

Physical and physiological aspects of submarine tower escape

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This work is being submitted in partial fulfilment of its requirements for the award of the degree of Doctor of Philosophy by Publication of the University of Portsmouth.

Abstract

My work has involved the investigation of physical and physiological issues related to submarine escape and rescue, including animal experiments using goats, human experiments, engineering and equipment based trials and also the development of a number of mathematical models for the prediction of equipment performance and physiological aspects of decompression. In addition to my published papers I have authored or made substantial contribution to over sixty reports funded by the United Kingdom Ministry of Defence (UK MoD).

Experiments in which I made significant contribution in terms of original conception, design, data acquisition and analysis have provided evidence for the efficacy of surface oxygen as a treatment for decompression illness following submarine tower escape and demonstrated that breathing raised partial pressures of carbon dioxide in a distressed submarine then switching to diving quality air in the escape tower is not likely to prevent successful escape.

The submitted work demonstrates an advance in our knowledge of the risks of decompression illness and a substantially improved level of confidence in the predictions of mathematical models of decompression illness for submarine tower escape. These are the first semi-empirical probabilistic models of decompression illness to combine animal and human decompression illness data using body mass as a scaling factor. Provision of more detailed information on risks of decompression illness and likely outcomes has allowed me to argue for a change in escape policy which has been accepted by the UK Royal Navy (RN). My suggestions for optimising tower escape are to be tested on board UK submarines in the future, prior to possible adoption by the RN. The iso-risk curves I developed for probability of decompression illness and predicted probability of survival following submarine escape have been included as advice in the latest update to [ATP-57, the NATO submarine search and rescue manual](#).

Statement

While registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this commentary are the work of the named candidate and have not been submitted for any other academic award.

A listing of the published work on which the application is based is presented here, with statements of the extent of my contribution to any of the submitted work which involves joint authorship or other type of collaboration. The statements are summarised at Table 1, page 5.

Throughout this work, references to the published articles on which this submission is based are indicated by their annex number [A]; Technical reports which I have authored or co-authored are designated [T] and do not form part of the submission. ***indicates a publication in a peer reviewed journal. Other listed publications are in conference proceedings:*

[A1] MG White, FM Seddon, GAM Loveman, KM Jurd, SL Blogg, JC Thacker. Severe Decompression Illness Following Simulated Rescue from a Pressurised Distressed Submarine. In: Operational Medical Issues in Hypo- and Hyperbaric Conditions. NATO Research and Technology Organisation, Meeting proceedings 62. Presented at the RTO Human Factors and Medicine Panel (HFM) Symposium held in Toronto, Canada, 16-19 October 2000.

I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A2] Bradley SR, Loveman GAM, Hall A, Martin R. The Physiology and Engineering of Submarine Escape. The Royal Institution of Naval Architects - Warship 2002 Symposium Naval Submarines 7, 2002; 109-120

I drafted a large section of the article, revised the article critically for important intellectual content and gave my approval of the version to be published.

[A3]** Blogg SL, Gennser M, Loveman GA, Seddon FM, Thacker JC, White MG. The effect of breathing hyperoxic gas during simulated submarine escape on venous gas emboli and decompression illness. Undersea Hyperb Med. 2003 Fall;30(3):163-74.

I made substantial contributions to acquisition and analysis of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A4] Loveman, G.A.M. Jurd K.M. Thacker, J.C. Stansfield, M.R. & Seddon, F.M. Iso-risk curves for escape from saturation in a distressed submarine. Proceedings of Humans in Submarines, Editor: H. Ornhagen, 2004.

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A5]** Blogg SL, Loveman GA, Seddon FM, Woodger N, Koch A, Reuter M, Gennser M, White MG. Magnetic resonance imaging and neuropathology in the goat nervous system following hyperbaric exposures. Eur Neurol. 2004;52(1):18-28. Epub 2004 Jun 22.

I made substantial contributions to acquisition and analysis of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A6]**Jurd K, Thacker J, Seddon F, Gennser M, Loveman G. The effect of pre-dive exercise timing, intensity and mode on post-decompression gas bubbles. Diving Hyperb Med 41(4):183-8. 2011

I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A7] Loveman, GAM. Optimising submarine tower escape. Proceedings of the 11th International Naval Engineering Conference, Edinburgh 2012.

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A8] Loveman, GAM. Optimising submarine tower escape, effects of submarine angle and shallow depth. Proceedings of PACIFIC 2013 International Maritime Conference, Sydney, October 2013

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A9]** Geoffrey AM Loveman, Fiona M Seddon, Julian C Thacker, M Graham White and Karen M Jurd. Physiological effects of rapid reduction in carbon dioxide partial pressure in submarine tower escape. Diving and Hyperbaric Medicine. 2014 June;44(2):86-90

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A10]** Seddon FM, Thacker JC, Fisher AS, Jurd KM, White MG, Loveman GAM. Decompression illness in goats following simulated submarine escape: 1993-2006. Undersea Hyperb Med 2014; 40(4):301-306.

I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A11]** Jurd KM, Seddon FM, Thacker JC, Blogg SL, Stansfield MR, White MG, Loveman GAM. Submarine “safe to escape” studies in man. Undersea Hyperb Med. 2014; 41(4):307-314.

I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A12]** Loveman GAM, Seddon FM, Thacker JC, Stansfield MR, Jurd KM. Submarine tower escape decompression sickness risk estimation. Undersea Hyperb Med. 2014; 41(4):315-329.

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A13]** Mikael Gennser, Geoff Loveman, Fiona Seddon, Julian Thacker, S. Lesley Blogg. Oxygen and Carbogen breathing following simulated submarine escape. Undersea Hyperb Med. 2014 Sep-Oct;41(5):387-92.

I made substantial contributions to acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A14]** Seddon F, Thacker J, Jurd K, Loveman G. Effects of Valsalva manoeuvres and the 'CO₂-off' effect on cerebral blood flow. Diving and Hyperbaric Medicine. 2014 December;44(4):187-92.

I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

[A15]** Loveman GAM, Seddon FM, Jurd KM, Thacker JC, Fisher AS. First Aid Oxygen Treatment for Decompression Illness in the Goat After Simulated Submarine Escape. Aerospace Medicine and Human Performance. 2015 December;86(12):1020-7.

I drafted the article. I made substantial contributions to conception and design, acquisition, analysis and interpretation of data. I revised the article critically for important intellectual content and gave my approval of the version to be published.

	A1	A2	A3 **	A4	A5 **	A6 **	A7	A8	A9 **	A10 **	A11 **	A12 **	A13 **	A14 **	A15 **
Drafted the article as first author				✓			✓	✓	✓			✓			✓
Conception and design	✓			✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
Data acquisition	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Analysis and interpretation	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Critical revision	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Publication approval	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 1: ✓ indicates my contribution to the published article; ** indicates a publication in a peer reviewed journal. Other listed publications are in conference proceedings.

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I would like to thank my PhD supervisor, Professor Mike Tipton, for your support and advice.

Our hyperbaric experiments involved the combined efforts of a team of dedicated scientists, engineers and technicians working long days and nights in the Submarine Escape Simulator and Deep Trials Unit on the Alverstoke site in Gosport over many years. Occasionally there was blood, usually there was sweat and frequently there were tears, mostly tears of laughter, but not all. Thank you, everyone.

I especially want to thank Karen Jurd, I learned from you that hard work truly is its own reward.

Melanie, Eve and Charlie, thank you, and sorry for the boring weekends xxx

In loving memory of my father.

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Annexed publications

- A1. Severe decompression illness following simulated rescue from a pressurised distressed submarine.
- A2. The physiology and engineering of submarine escape.
- A3. The effect of breathing hyperoxic gas during simulated submarine escape on venous gas emboli and decompression illness.
- A4. Iso-risk curves for escape from saturation in a distressed submarine.
- A5. Magnetic resonance imaging and neuropathology in the goat nervous system following hyperbaric exposures.
- A6. The effect of pre-dive exercise timing, intensity and mode on post-decompression gas bubbles.
- A7. Optimising submarine tower escape.
- A8. Optimising submarine tower escape, effects of submarine angle and shallow depth.
- A9. Physiological effects of rapid reduction in carbon dioxide partial pressure in submarine tower escape.
- A10. Decompression illness in goats following simulated submarine escape: 1993-2006.
- A11. Submarine “safe to escape” studies in man.
- A12. Submarine tower escape decompression sickness risk estimation.
- A13. Oxygen and Carbogen breathing following simulated submarine escape.
- A14. Effects of Valsalva manoeuvres and the ‘CO₂-off ’ effect on cerebral blood flow.
- A15. First aid oxygen treatment for decompression illness in the goat after simulated submarine escape.

1. Introduction

1.1 Statement of the problem

Evacuation of a UK Royal Navy submarine occurs via a small airlock, the escape tower. The crew may be exposed to raised pressure within the distressed submarine (DISSUB) and subsequently in the escape tower. Rapid return to normal atmospheric pressure puts the crew at risk of suffering decompression illness (DCI). Information on likely casualty levels and the severity and progression of DCI are required by rescue forces responding to a DISSUB event. Methods for the prophylaxis and/or mitigation of DCI and other hazards of submarine escape are also desired.

1.2 Literature review

Starting out in this area in 1993, I turned to the comprehensive textbook: Bennett and Elliott's Physiology and Medicine of Diving, now in its fifth edition [1].

At that time, the Internet was not available to me. My literature searches were conducted via The Defence Research Information Centre (DRIC) [2]. I later used Alta Vista and Google and also the U.S. Department of Defense Technical Information Centre (DTIC) and the Research Repository of the Rubicon Foundation. I refer to peer reviewed papers where possible; however, much information specific to submarine escape is contained solely within government technical reports. I keep up to date using Google Scholar, ResearchGate and journals such as *Diving and Hyperbaric Medicine*, *Undersea and Hyperbaric Medicine* and *Aerospace Medicine and Human Performance*.

Search terms I have used during the period covered by this work include: submarine escape; submarine rescue; DISSUB; decompression sickness; DCS; decompression illness; DCI; mathematical modelling; venous gas emboli; bubbles; Doppler.

1.3 Objective and Hypotheses

An over-arching objective of the work described here was to define a dose-response relationship, the dose being associated with decompression following exposure to raised pressure, and the response being the occurrence/absence of signs or symptoms of DCI. Of the experimental hypotheses listed below, only **H1** is directly related to the main objective. The remaining hypotheses relate to investigation of other hazards of submarine escape and interventions for the prophylaxis and/or mitigation of DCI.

- H1.** A pressure exposure of six hours is not sufficient for saturation of goat tissues with nitrogen [A10]; page 26.
- H2.** Breathing a raised partial pressure of carbon dioxide during saturation will affect risk of DCI in goats compared with breathing air [3, T4]; page 27.
- H3.** Breathing a hyperoxic gas (60/40 oxygen/nitrogen) during escape will reduce risk of DCI in goats compared with breathing air [A3]; pages 27 – 28.
- H4.1** Breathing oxygen following submarine tower escape will reduce risk of DCI in goats compared with breathing air [A13]; pages 27 – 28.
- H4.2** Breathing carbogen (95/5 oxygen/carbon dioxide) following submarine tower escape will reduce risk of DCI in goats compared with breathing air [A13]; pages 27 – 28.
- H4.3** Breathing carbogen (95/5 oxygen/carbon dioxide) following submarine tower escape will reduce risk of DCI in goats compared with breathing oxygen [A13]; pages 27 – 28.
- H5.** Divers are at risk of long-term central nervous system (CNS) damage from non-symptomatic hyperbaric exposure [A5]; pages 28 – 29.
- H6.** First aid oxygen administration (FAO₂) without recompression is efficacious in the treatment of DCI following submarine tower escape [A15]; pages 31 – 32.
- H7.** Timing, intensity and mode of exercise before diving will affect post-decompression production of venous gas emboli (VGE) [A6]; page 35.
- H8.** Adverse physiological effects from a rapid drop in inspired carbon dioxide partial pressure (PiCO₂) in the breathing gas will hinder or prevent submarine tower escape [A9]; page 36.
- H9.** Performing Valsalva manoeuvres following a switch from breathing raised PiCO₂ will exacerbate the drop in mean cerebral arterial velocity (MCAv) caused by the switch in breathing gas [A14]; page 36.

1.4 Research timeline

Year	Publications	Technical reports	Hypotheses	Animal experiments	Human experiments	Decompression modelling	Equipment trials and models
1993			H1 [A10]	6 h 'saturation' [A10]		Five compartment Hill dose-response model calibrated to animal data [T1]	
1994		[T1]		24 h 'saturation' [A10]			
1995		[T2]		'Saturation' and escape [A10]		Bubble model based on Tikuisis and Nishi [T3]	
1996		[T3]					
1997			H2 [T4]	'Saturation' at raised P_iCO_2 [T4]	24 h 'saturation' [A11]		DISSUB atmosphere model [T6, T7]
1998		[T4]	H3 [A3]	Accelerated decompression for submarine rescue [A1]		Symmetric and asymmetric EE models	Naval Escape Wait Time Software [T11]
1999		[T5, T6]					
2000	[A1]	[T7, T8]					
2001							
2002	[A2]		H4.1 [A13]	Magnetic Resonance Imaging and neuropathology [A5]	'Saturation' and escape [A11]	Probabilistic gas and bubble dynamics model based on Gerth and Vann	
2003	[A3**]	[T9, T10]	H4.2 [A13]				
			H4.3 [A13]				
2003			H5 [A5]	Beneficial effects of altered breathing gases [A3, A13]		LE model based on Thalmann et al with Hill based model of Lillo et al for high risk 'saturation' [A4, T13]	Carbon dioxide absorption unit performance [T9]
2004	[A4†, A5**]	[T11 - T14]	H6 [A15]	'Saturation' and escape with 50% risk of DCI [A10, A15]			Lithium hydroxide reactive polymer curtains performance [T14, T17]
2005		[T15 - T17]					
2006		[T18 - T20]		Surface oxygen for treatment of DCI [A15]		Re-analysis of historical animal DCI data [T24, T32]	Soda lime curtains model [T12, T16]
							Surface abandonment [T18]
2007		[T21 - T30]				LE model based on Thalmann et al with exponent on risk function scaled with body mass [A12, T37]	Lithium hydroxide curtains model [T31]
						Bootstrap based confidence limits on escape iso-risk curves [A12, T39]	
2008		[T31 - T36]	H7 [A6]		Exercise effects [A6]	Probability of survival following DISSUB tower escape [T36]	Fanfold lithium hydroxide curtains performance [T34]
2009		[T37, T38]					
2010		[T40 - T42]					
2011	[A6**]	[T43 - T49]	H8 [A9]		CO ₂ off-effect [A9]		Escape from DISSUB at angles [T42, T47, T65]
2012	[A7†]	[T50 - T52]					
2013	[A8†]	[T53]					
2014	[A9†**, A10**, A11**, A12†**, A13**, A14**]	[T54 - T60]	H9 [A14]		CO ₂ off-effect with Valsalva [A14]	Review of decompression tables for the NATO Submarine Rescue System [T54, T55, T59, T62]	Revised model of escape tower pressurisation [A7, A8]
2015	[A15†**]	[T61 - T63]					
2016		[T64 - T65]					
2017					Buoyancy during submarine escape	Prediction of signs/symptoms of DCS following submarine tower escape [T63]	Redefinition of escape tower acceptance tests [T51, T52]
							Optimised non-vented tower escape [A7, A8, T42, T47, T65]

Table 2: Timeline of publications, reports and corresponding studies; [A] indicates annex number of publication, † I was first or sole author, ** Peer reviewed journal publication; [T] indicates a technical report.

1.5 Ethical conduct of experiments

All human experiments were conducted in accordance with the principles of the declaration of Helsinki [4]. An ethical protocol was written for each study and reviewed and approved either by the QinetiQ Research Ethics Committee or the UK MoD Research Ethics Committee.

All animal experiments were conducted under UK Home Office License according to the Animals (Scientific Procedures) Act 1986. The experimental protocol for each study was reviewed by a DRA, DERA or QinetiQ Ethics Review Committee. The goats were maintained under the surveillance of a veterinary surgeon and an animal care welfare officer and certified in good health prior to use.

1.6 A note on units of pressure

Pressure units of bar are used in keeping with the usage in RN submarines, and refer to the absolute pressure. Other pressures are quoted in Pascals ($\text{N}\cdot\text{m}^{-2}$) or millimetres of mercury (mmHg).

It is assumed that a depth change of 10 metres of sea water is associated with a pressure change of 1 bar (100 kPa) and air pressure at sea level (0 m) = 101.325 kPa = 760 mmHg.

1.7 Background to submarine tower escape

Should a UK Royal Navy submarine be unable to surface, the preferred option for the survivors is to await rescue within the DISSUB. If environmental conditions within the DISSUB make waiting for rescue untenable then evacuation is made by donning a submarine escape immersion suit (SEIS – see Figure 1) and carrying out submarine tower escape. The escape procedure involves rapid pressurisation of one or two personnel at a time to the

ambient sea pressure – this pressurisation takes place in an airlock, the escape tower, a small chamber with hatches at the top and bottom (Figure 2).



Figure 1: *Man dressed in Submarine Escape Immersion Suit (SEIS)*

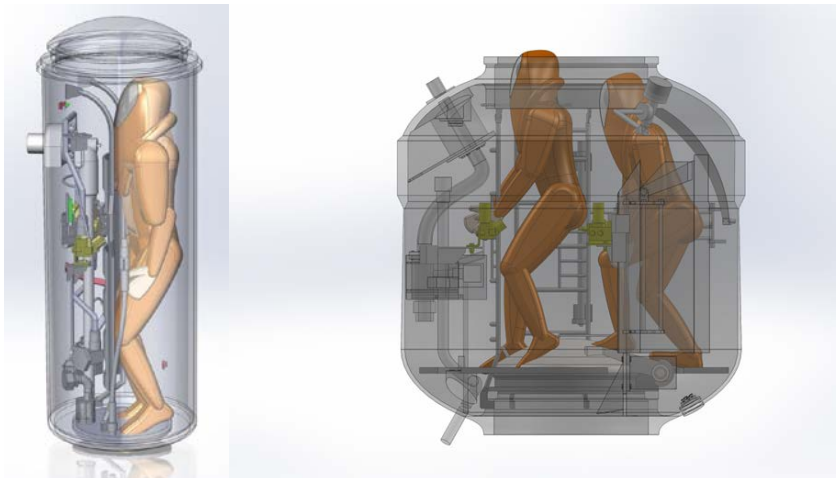


Figure 2: *Escape towers; drawings courtesy of DC Cosserat and JB Peckham*

The escapers enter the tower wearing SEIS and the lower hatch is shut. The SEIS is plugged into a hood inflation system (HIS) via a hose in the arm of the suit. The HIS supplies air for breathing and also acts to keep the hood and stole of the SEIS fully inflated during the flood and pressurisation phases of the escape. The tower is flooded with seawater. During this

phase, air may be allowed to vent from the tower into the submarine, such that the tower does not become pressurised. Once the seawater reaches the height of the vent, the vent is shut and continued flooding results in a rapid pressurisation phase. On equalisation of tower pressure with ambient sea pressure, the upper hatch opens and the men ascend to the surface due to the buoyancy of the SEIS. The escaper is not protected from the pressure associated with their depth in the sea, as they would be if rescued by submersible. On reaching the surface the escaper inflates and boards a single-seat liferaft that is supplied with the SEIS.

If the DISSUB has been subjected to flooding or escape of high-pressure air, the ambient pressure within the submarine will be raised. Thus, the escaper may already have been subjected to raised ambient pressure for some time prior to the escape exposure and the subsequent ascent to the surface.

1.8 Important physiological factors in submarine tower escape

The effects on man of exposure to raised ambient pressure and subsequent return to normobaric pressure are well documented [1]. The most important effects in terms of relevance to exposure in the DISSUB and subsequent tower escape are briefly described below.

Decompression Sickness

Breathing air at raised pressure causes an accumulation of dissolved gases (mainly nitrogen) in the body's tissues. Subsequent rapid return to surface pressure allows these gases to come out of solution, forming bubbles in the body. These bubbles can physically disrupt tissue or indirectly affect function by blocking the blood supply to cells or disturbing blood biochemistry. The range of signs and symptoms that may result from these processes are referred to specifically as decompression sickness (DCS) and may include fatigue, skin

irritation, joint pain, cardiopulmonary and/or neurological injury, the most severe of which can be fatal. DCS may be avoided by limiting the time spent breathing gases at raised pressure and through controlled or staged decompression. An excellent review has been made by Vann *et al* [5].

Nitrogen narcosis

Nitrogen narcosis occurs in air environments at raised ambient pressure. Symptoms may include impaired judgment, loss of coordination, unconsciousness and death. It can be detected in some susceptible people breathing air at 3.0 bar, and most people will display some performance decrement at 5.0 bar. Nitrogen narcosis is completely and rapidly reversible on decompression. A detailed review of nitrogen narcosis has been made by Clark [6].

Oxygen toxicity

Paul Bert [7] was the first to prove that excess oxygen is extremely toxic and can be fatal. All organs are susceptible to oxygen toxicity [8, 9]. At partial pressures of oxygen greater than 1.3 bar the brain is the first organ to show signs of toxic effects. These effects manifest as disturbances of vision, twitching, and grand mal seizures. Variability between and within individuals is high [10, 11].

For a given inspired oxygen partial pressure, the lung epithelium is exposed to the highest partial pressure of oxygen and is the most susceptible tissue when the partial pressure of oxygen is low (< 1.3 bar). Pulmonary oxygen toxicity (POT) was first described by Lorraine-Smith [12, 13], while trying to determine the threshold of central nervous system (CNS) oxygen toxicity. He subjected mice to 0.74 – 0.8 bar oxygen and noted an absence of seizures, but the animals became ill and eventually died after four days at this level of

exposure. Since then POT has been observed in all species tested and its symptoms and progression in humans are well-documented [8].

Exposure to oxygen pressures greater than 0.5 bar, such as during diving or oxygen pre-breathing prior to flight, is associated with the onset of POT symptoms. All mammalian species show a similar progression. First, there is an exudative phase that results in pulmonary oedema. Histological examination shows an increase in the width of the interstitial space. Lung diffusing capacity decreases leading eventually to hypoxaemia. After several days' exposure, if death from hypoxaemia has not occurred, a proliferative phase occurs leading to a chronic thickening of the alveolar membrane with a permanent decrement in lung diffusing capacity. Lung volume as estimated through forced vital capacity (FVC) decreases in a manner related to the dose. These changes are reversible on return to normoxia, but the time course to complete recovery is not known.

Barotrauma

The body is mostly comprised of fluid filled structures. Since fluids are highly incompressible, these structures are largely unaffected by exposure to raised ambient pressure. However, the air-filled structures of the body, namely the lungs, ears and sinuses may be subject to damage during changes in ambient pressure. Of primary concern in tower escape are injury to the middle ear and injury to the lung (pulmonary barotrauma - PBT). Although the inner ear is fluid filled, injury here is also possible; in particular, the round window membrane which separates the fluid filled inner ear space from the air filled middle ear can rupture.

Middle ear barotrauma

Equalisation of air pressure on either side of the tympanic membrane (eardrum) is made possible by the Eustachian tube, which connects the middle ear with the pharynx. Air passes along the Eustachian tube during swallowing with the direction of airflow dependent on the relative pressures of the middle ear and the mouth. Air can also be forced into the middle ear by performing a Valsalva manoeuvre.

During compression, the increasing pressure in the outer ear relative to that in the middle ear causes the eardrum to be pushed inward. Pressure is equalised by performing the Valsalva manoeuvre. Failure to equalise the pressure across the eardrum may result in injury to the eardrum and surrounding tissues. This injury may include rupture of the eardrum. Middle ear barotrauma is painful but generally heals well without complications [14].

Barotrauma can also occur in the ear if air becomes trapped in the outer ear due to a tight-fitting hood. Escape suit hoods are designed to prevent this, having perforations through the hood material, where the hood meets the pinnae.

Round window membrane rupture

The inner ear has two membranes which interface the air filled middle ear - the oval window and the round window. The oval window lies behind the third middle ear bone (the stapes). The oval window membrane vibrates with sound transmission via the stapes. This causes changes in pressure within the fluid of the inner ear. The round window acts to relieve the change in pressure, bulging outward (into the air space of the middle ear) as fluid pressure rises in the inner ear. Performing the Valsalva manoeuvre in an attempt to equalise pressure across the eardrum also causes a rise in the fluid pressure in the inner ear. Overly forceful attempts to equalise the middle ear can cause rupture of the round window membrane. This is

a serious injury which can result in symptoms of vertigo, nausea, tinnitus and deafness. Some symptoms can become chronic/permanent. It seems likely that vertigo and nausea would affect an escaper's chances of survival in the single-seat liferaft.

Pulmonary barotrauma (PBT)

Injury to the lung due to the pressure changes associated with tower escape may occur in a variety of ways and can lead to several severe outcomes. Given the likely scenarios in which tower escape would be attempted, PBT would likely lead to death of the escaper.

Compression pulmonary barotrauma (barotrauma of descent)

As the ambient pressure is increased, the escaper must inhale in order to equalise pressure in the lungs with the ambient pressure. A failure to do this will result in compression of the lungs, referred to as 'thoracic-squeeze' or 'lung-squeeze'. Thoracic-squeeze is a painful condition which may result in rupture of lung tissue and pleural detachment. A small injury to the lung during the pressurisation phase of escape would potentially have fatal consequences during ascent.

Pulmonary barotrauma during ascent

During ascent the air in the escaper's lungs is expanding as the ambient pressure decreases. If the escaper holds their breath or fails to breathe out for some other reason, the resultant over inflation of the lungs may result in rupture of the lung tissues.

Whether injury to lung tissue occurs during compression or ascent, the hazard to the escaper will present during the final stages of the ascent where the expansion of the air in the lungs will be greatest. This air may escape the lung with a range of possible outcomes including:

- Trapping of air in the thoracic cavity which may lead to difficulty in breathing and possibly death (depending on location of the trapped air this is described as pneumothorax or pneumomediastinum);
- Arterial gas embolism (AGE) – where air passes as bubbles into the blood via the vasculature of the lung. These bubbles are likely to pass through the heart and become trapped in the arterial vessels of the brain, leading to CNS damage and possibly death.

Other forms of barotrauma

In addition to the main problems caused by barotrauma, it is also worth noting that injury can occur to the sinuses, teeth and digestive tract due to the compression or expansion of air during changes in ambient pressure.

Terminology: Decompression Sickness (DCS) and Decompression Illness (DCI)

The symptoms of AGE as a result of PBT may be indistinguishable from neurological symptoms of DCS caused by the evolution of gas bubbles from the dissolved state. Such problems have led to the development of a terminology suitable for use in the clinical setting where the term 'Decompression Illness' (DCI) is used to encompass both decompression sickness (DCS) and barotrauma as described above.

2. The selected published works in context

Section 2.1 summarises early research which has formed the background to my own work, which I describe in section 2.2.

2.1 Early research and evolutionary development in submarine tower escape

Methods of submarine escape evolved through trial and error development since the 1930s. A review was made by Donald in 1970 [15, 16]. It was anticipated that DCI would limit the maximum depth that could be achieved and that risk of pulmonary barotrauma would limit maximum pressurisation and ascent rates. Experiments with animals, usually goats, were made prior to using men, in an iterative process allowing extension of maximum depth by increasing pressurisation and ascent rates, reducing time spent at raised pressure. Such an approach results in procedures that are known to work but does not imply optimality. Departure from the '*tried and tested*' pressure-profiles could result in raised incidence of injury. All experiments detailed by Donald involved escape from normobaric pressure. Donald concluded that exposure to raised pressure within the submarine prior to escape required investigation.

Circa 1962, Eaton and Hempleman investigated the effect of direct surfacing from raised pressure without any escape profile [17]. Goats were exposed to raised pressure for between 15 min and 6 h. At this time, 6 h was thought sufficient to saturate the goats' tissues with nitrogen at the exposure nitrogen partial pressure.

From their results, Eaton and Hempleman estimated the pressure/duration combinations which would result in DCI in 50% of animals. For a 6 h exposure, a pressure of 2.68 bar was estimated to result in 50% DCI. The experiments were designed such that any animal suffering DCI for a particular exposure was not subjected to the planned remaining exposures

of the same duration at higher pressures. Although not explicitly stated in their report, it can be deduced from Eaton and Hempleman's results that they assumed any animal displaying signs of DCI for a given pressure exposure would also have suffered DCI had it been exposed for the same duration to some greater pressure, or to a repeat exposure at the same pressure. Thus, the number of subjects for each combination of pressure and depth was artificially increased.

The assumption that an individual animal removed from the experiment due to suffering DCI would also have suffered DCI for any exposure to greater pressure or for repeat exposures is false since an individual may have different reactions to the same exposure on different occasions (intra-individual variability). Also, if some animals are more susceptible to DCI than others due to inter-individual variability, then the removal of susceptible animals at less risky exposures would leave a group of less susceptible animals to be tested at the higher risk exposures. A population risk model calibrated against such data would underpredict risk of DCI for higher risk exposures. This effect would be exacerbated if acclimation were also taking place. I discuss the possibility that such effects might be present in these historical data at section 2.2.

The first submarine escape experiments where subjects were exposed to raised pressure prior to escape were conducted between 1971 and 1973. Eaton and Hempleman exposed goats to pressures of between 1.7 and 3 bar for 6 h prior to escape from simulated depths of 140 to 240 m. Details of these experiments were not published at the time but appear in a paper published in 1984 by Bell, Burgess, Summerfield and Towse after they had conducted further work in this area [18]. Bell et al exposed 37 goats to 'saturation' exposures (16 to 18 hours) with simulated submarine escape following the saturation period. The experiments aimed to establish combinations of saturation pressure and escape depth resulting in 50% of subject animals suffering DCI. The 50% points were estimated by extrapolation. The full details of

the method of extrapolation are not made clear, and no estimation of confidence regions is given. Bell et al drew a curve through the 50% DCI goat data which is reproduced as the dashed line shown in Figure 3. They then predicted a '0% bends-curve for men' based on the shape of the 50% DCI curve drawn for the goat and the best guesses they could make, for man, of the maximum safe escape depth and the maximum safe saturation pressure for direct return to normobaric pressure. The resulting curve is shown as the solid line in Figure 3. This curve and succeeding versions have been generally referred to as the '*safe-to-escape*' curve, performing escape from any pressure/depth combination within the area of the curve being regarded as 'safe'.

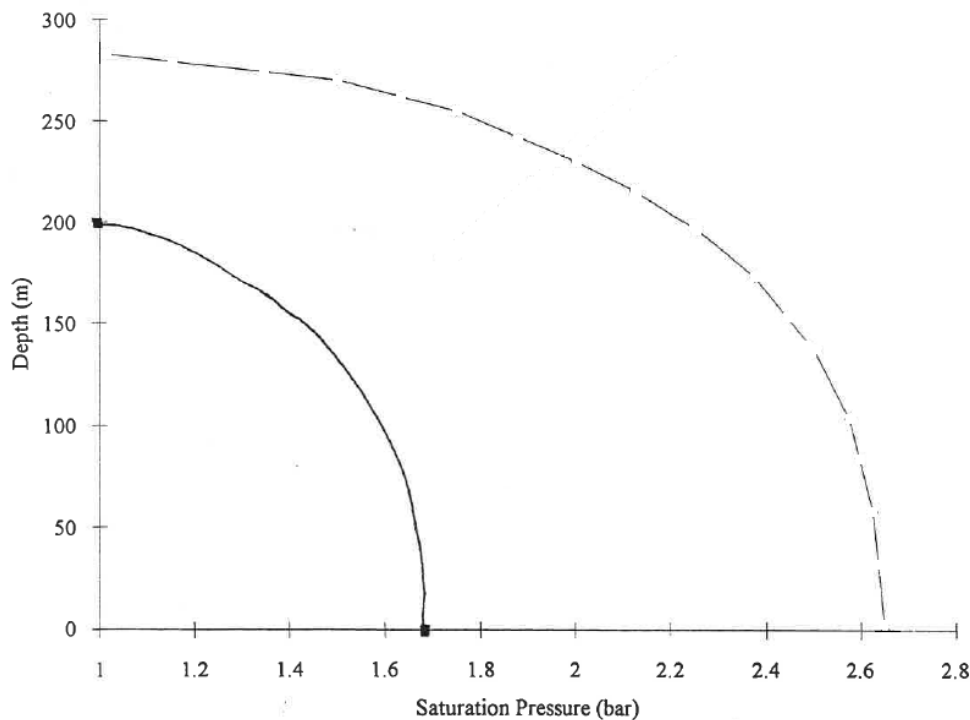


Figure 3: 50% DCI curve based on goat data (dashed line) and '0% bends curve for men' – the '*safe-to-escape*' curve (solid line) (after Bell et al, 1984)

After the study of Bell et al was completed, investigation of the safe-to-escape curve was postponed during construction of a purpose-built hyperbaric chamber for investigating submarine escape: the Submarine Escape Simulator (SES), described in [A2].

In 1990, White recalibrated the Bühlmann ZH-L₁₂ decompression model [19] against the data from Bell et al to generate a safe-to-escape curve [20]. The resulting curve is shown in Figure 4, along with the original curve after Bell et al, and a curve produced in a subsequent modelling study carried out in 1992/93 by Denison and Bridgewater at The Royal Brompton Hospital using a five tissue-compartment model of their own design which I refer to as the ‘Brompton model’ [21].

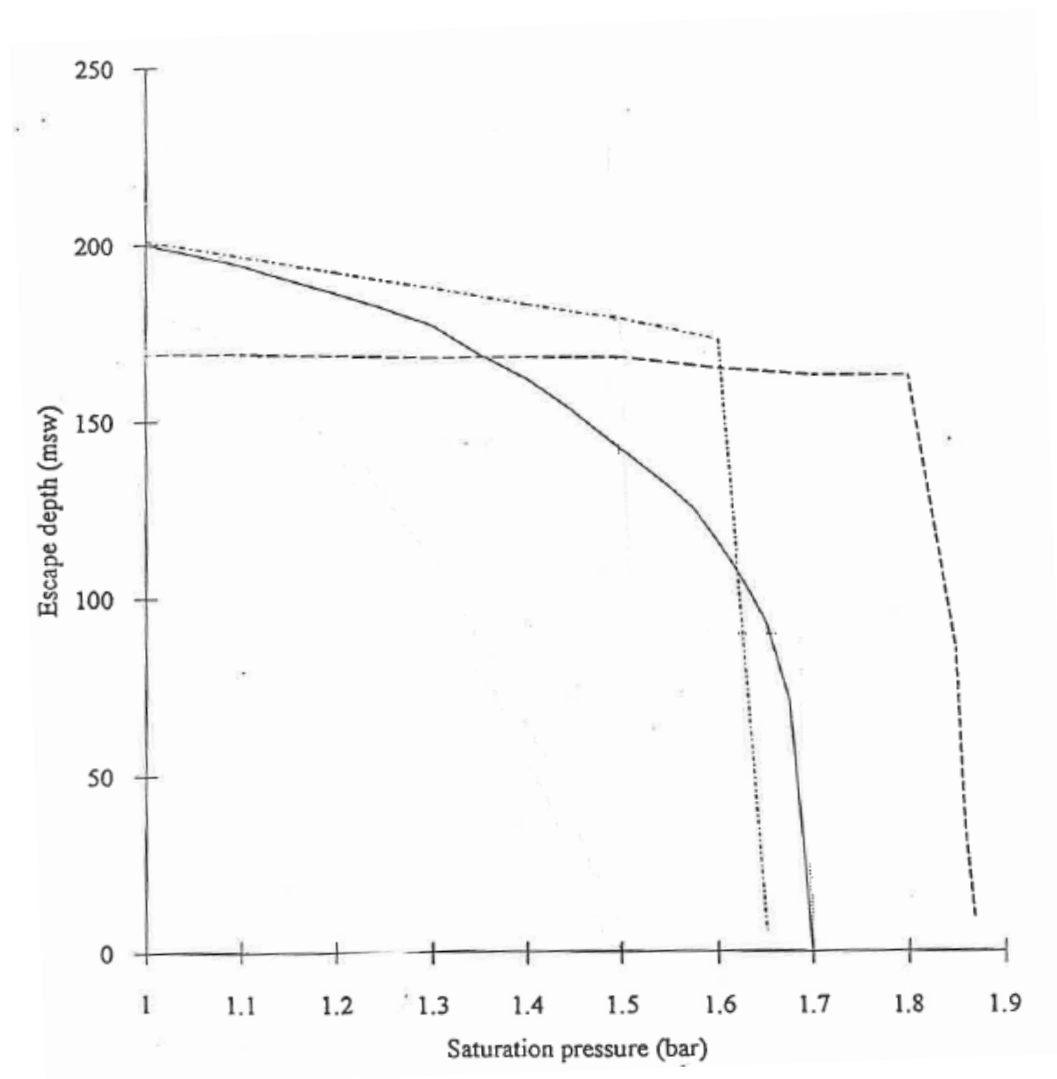


Figure 4: ‘0% bends curve for men,’ after Bell et al, 1984 (solid line); ‘5% bends curve,’ after White et al, 1990 (dotted line); ‘Less than 5% DCI,’ after Denison and Bridgewater, 1993 (dashed line)

In 1993, White and Seddon reviewed historical data from experiments on goats carried out since 1951, generating a database with two main objectives: to ascertain which exposures should be carried out in the newly completed SES, and to identify data that might be used in calibration of future mathematical models [22]. White and Seddon concluded that further experiments were required to establish whether 6 h was a sufficient duration for a goat's tissues to reach saturation. The first experiments to be carried out in the SES would test **H1**, comparing the rate of DCI following 6 h and 24 h 'saturation' exposures. At this time, I was employed to progress the mathematical models and to assist with the experiments in the SES.

2.2 A summary of my work

1993 – 1994 On being introduced to the concept of the safe-to-escape curve I felt there were several issues to address:

- The use of the word 'safe' implies no risk to the escapee;
- Definition of an acceptable 'safe' risk level is unlikely to take into account the range of symptoms and pathologies of DCI and is therefore likely to be misleading;
- The assumption that safe and unsafe regions can be clearly demarcated by a single curve is not logically justifiable;
- The crew are assumed to be saturated at the DISSUB escape compartment internal pressure – the curve is therefore conservative in the estimation of safe escape depth for escape where the crew has not been exposed to raised pressure for long enough to become saturated with inert gas.

A more informative figure would comprise a set of curves, each indicating a particular risk of DCI. Rather than 'safe-to-escape', these might more properly be referred to as '*escape iso-risk curves*'. I realised that deterministic models of DCI would likely always produce an almost 'rectangular' safe to escape curve with a sharp elbow as shown in Figure 4. I

converted the Brompton model from a deterministic to a probabilistic model, applying a Hill dose-response model to the supersaturation ratio in each of the five tissue compartments of the model and optimising the Hill model parameters to give the best fit to the existing DCI data of Bell et al [18]. This allowed me to produce the set of iso-risk curves for submarine tower escape for the goat reproduced at Figure 5 [T1]. This model was limited, providing no method to generate predictions for man.

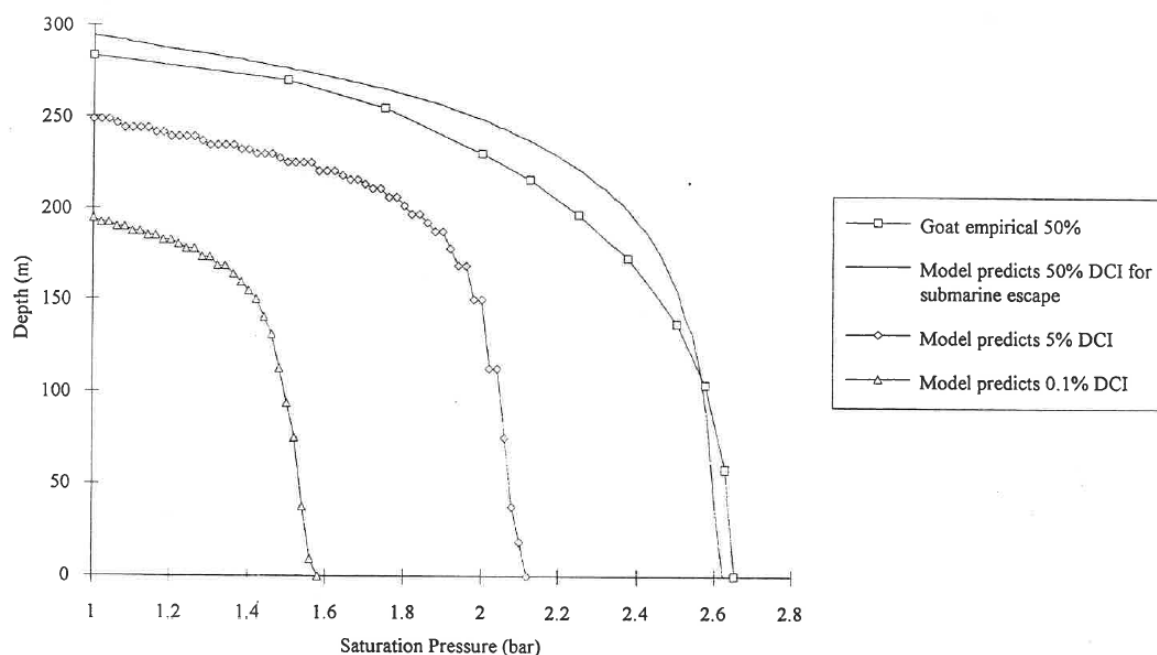


Figure 5: *Escape iso-risk curves generated using a modified version of the Brompton model*

1994-1996 I completed Institute of Biology training courses for personnel working under the Animals (Scientific Procedures) Act 1986; I completed UK HSE training for the role of Diver Medical Technician allowing me to act as an attendant in Hyperbaric Oxygen Therapy; I passed four modules at M.Sc. level at Cranfield College covering Fundamentals of numerical analysis, Approximation and data fitting, Mathematical modelling in the physical sciences and Optimisation and minimisation; I attended a short course in Doppler techniques in radiology and vascular diagnosis and taught myself the C programming language.

To use a model better reflecting mechanistic aspects thought to contribute to DCI, I implemented, in C, a more complex model previously described by Tikuisis and Nishi simulating bubble formation and resolution in a number of parallel tissue compartments [23]. Tikuisis and Nishi used maximum likelihood methods to fit their model to DCI data, employing the Levenberg-Marquardt algorithm to optimise parameter values of the model. Use of these methods in decompression modelling had previously been described by Weathersby et al and Tikuisis et al [24, 25]. Using the same method, I calibrated my implementation of their model against the growing set of DCI data from our ongoing experiments in the SES and generated new escape iso-risk curves. As before, I had no method of scaling predictions to man. However, the predicted curves were generally more conservative than those in Figure 5, due to the inclusion of the accumulated animal data [T3].

By February **1997**, our team had carried out 481 animal exposures in the SES with goats breathing air throughout. Of these, 60 were of duration 6 h and 88 were of duration 24 h with no simulated escape. These experiments were used to test **H1** [A10]. If the goat's tissues are not saturated at six hours, then increasing the duration of the exposure should increase the incidence/severity of DCI. Goats were subjected to 1.9 bar for 6 h or 24 h and then decompressed over approximately 60 s. Two animals of 24 in the 6 h group and seven animals of 24 in the 24 h group showed signs of DCI following decompression. Interpretation of DCI signs in the goat is discussed at section 3.2. These results were not significant ($P \approx 0.07$, one-sided Fisher's exact test) though the data suggest six hours may not be sufficient for saturation of goat tissues with nitrogen. At the time, we used Fisher's exact test; however, Barnard's unconditional test could be regarded as more appropriate in this case. We also measured higher Doppler bubble counts in the 24 h group and on that basis decided that all further 'saturation' exposures should be of at least 24 h duration.

During this time, we also tested **H2** [3, T4]: We had conducted 72 exposures in the SES with goats breathing air with 2.5 kPa carbon dioxide, I analysed the results from these experiments which demonstrated an increase in rates of DCI in goats exposed to the raised partial pressure of carbon dioxide.

The remainder of the experiments carried out by this stage involved escape: 153 escape exposures from 1 bar and 180 escapes following 24 h 'saturation'. All experiments from 1993 to 1997 were summarised in a report by Seddon [3]. During experiments I was responsible for acquisition of pressure and temperature measurements, sound level measurement and observation and care of animals before, during and post-exposure, which involved noting signs of DCI, phlebotomy, Doppler bubble-scoring using the Kisman-Masurel scoring system [26] and assisting in recompression therapy of goats suffering DCI.

During **1996** and **1997** we conducted the first manned experiments in the SES. These were a series of 24 h 'saturation' exposures with direct ascent from either 1.5 or 1.6 bar, there were no cases of DCI in 38 exposures.

In **1998** I worked with members of the Standing Committee on Submarine Escape and Rescue, producing a plan for progressing manned experiments investigating escape from raised pressure [T4]. Between **1999** and **2003** we conducted 344 man-exposures at 'saturation' pressures between 1.0 and 1.6 bar and escape depths between 30 and 120 m. There were 2 cases of DCI following exposures at 1.6 bar with a 90 m simulated escape. These are the only 'saturation' and escape exposures that have been conducted in man.

During this period, we worked collaboratively with Dr Mikael Gennser of the Swedish Defence Research Agency (FOI) on studies involving the use of different breathing gas mixtures prior to, during or following simulated submarine escape in goats. This work tested hypotheses **H3**, **H4.1**, **H4.2** and **H4.3** [A3, A13]. We anticipated that oxygen breathing

would be beneficial since the gradient for inert gas washout is increased, as is the level of inherent unsaturation due to the ‘oxygen window’ [27]. The numbers of animals used in each experiment were too small to expect a statistically detectable effect based on rates of DCI. Levels of Doppler detectable bubbles were used to give an indication of benefit (this is discussed further in section 3.3). We showed breathing a raised partial pressure of oxygen at any stage (pre-escape, during or post-escape) to be beneficial in terms of reduced duration of circulating bubbles, although only oxygen pre-breathe reduced initial (maximal) bubble grades [A3, 28, 29, A13]. Additionally, pre-breathing ‘carbogen’ (2.5% carbon dioxide in oxygen) followed by breathing a hyperoxic gas (60% O₂-40% N₂) during escape resulted in convulsions in 2 of 8 animals, which we attributed to CNS oxygen toxicity. This suggests breathing a hyperoxic gas during escape may be dangerous since the DISSUB atmosphere is likely to have a raised partial pressure of carbon dioxide.

During this same time, Graham White obtained funding via the ONR/NavSea/Undersea Biomedical Research Program for a collaborative project between ourselves (using the goat), the University of Wisconsin (using sheep) and the US Naval Medical Research Institute (using pigs) to investigate decompression profiles for submarine rescue. I designed the decompression profile used in our study. White later presented this work at a meeting of the NATO Research and Technology Organization [A1].

At this time, we had a large number of animals that had been used in repeated pressure exposures over several years. This afforded an opportunity to look for neuropathological changes in these animals, thus testing **H5**. We carried out magnetic resonance imaging (MRI) of thirty goats used in experiments between 1993 – 1998 and six naïve to pressure exposure. I worked with Lesley Blogg and Fiona Seddon on methods for achieving MRI of goats. MRI was conducted by Alliance Medical in a portable scanner at our establishment in Alverstoke. The scans were examined by Andreas Koch of the German Naval Medical Institute and

Michael Reuter of the Diagnostic Radiology and Neurosurgery Department of Christian Albrechts University. Neuropathology was carried out by Nick Woodger at the Cambridge University Department of Veterinary Medicine. Lesley Blogg wrote up this work, I performed some of the data analysis [A5].

Also in **1999 – 2000**, I designed a spreadsheet to determine the partial pressure of carbon dioxide in the DISSUB at which escapes must commence [T6, T7]. Following this I acted as a technical advisor to a team who developed my spreadsheet into a Windows-based application. In **2002** I was promoted to technical lead for the Submarine Escape, Rescue, Abandonment and Survival (SMERAS) research team which by that time was part of the privatised firm, QinetiQ.

2002 – 2003 Anthony and Blatherwick had shown the performance of the DISSUB Carbon Dioxide Absorption Unit (CDAU) was reduced at low temperature and at raised pressure [30]. Working with Matt Evans, we showed the CDAU would not effectively remove carbon dioxide in some DISSUB scenarios [T9]. Subsequently, I designed and ran equipment trials [T14, T17, T34] and wrote models for simulating performance of atmosphere control systems [T16, T31] including Micropore™ lithium hydroxide reactive polymer curtains which were determined to be the most suitable replacement and are now installed aboard all UK RN submarines.

Between **1999** and **2003**, I implemented various formulations of DCI models. These included symmetric and asymmetric exponential-exponential models (EE), a bubble model described by Gerth et al [31] and the linear-exponential (LE) model as described by Thalmann et al [32]. None of the models were markedly superior in terms of achieving goodness of fit to the DCI calibration data. Derivation of the LE model as described by Thalmann et al is given at Appendix A.

The LE model possesses several useful qualities, not least that linear gas washout approximates the predictions of models using full simulation of bubble evolution while avoiding the numerical computation issues. Thus, evaluations of DCI probability can be made rapidly in comparison with models such as that of Tikuisis and Nishi [33]. However, the LE model as calibrated by Thalmann et al underpredicted the rate of DCI for high risk exposures [34]. Despite this, or rather, since there was no preferable model, the LE model was used by Parker et al to estimate DCI risk for submarine escape [35]. I recalibrated the LE model using data from our submarine escape experiments in man and goat and included data made publicly available by Weathersby et al [36]. I considered scaling between goat and man as had been carried out by Ball et al for sheep [34]. Ball et al had not used body mass as a scaling factor since there was not a marked difference in body mass between the sheep and humans in their data sets. At that time, I could not reconcile the scaling method they applied with my perception of the ‘lumped parameter’ nature of the model and the methods used for parameter optimisation. At this stage I opted to treat the goat and man as if there were no difference between the two species. A comparison I made of the predictions of my recalibrated LE model with a fit made to human saturation exposure DCI data by Lillo et al [37] suggested that underprediction of risk was still present. I decided to combine the predictions of the recalibrated LE model with the fit made by Lillo et al and generated a set of iso-risk curves for submarine escape [T13]. Subsequently I presented this work at the Humans in Submarines conference in **2004** [A4]. My inclusion of the Hill-based model meant the resulting model could only be used for prediction of risk where the crew were saturated at the DISSUB internal pressure, i.e. the model was no use where escape from raised DISSUB pressure occurred within a few hours of an initial incident.

To further the modelling work, I decided to select, from the available data, only exposures directly relevant to generation of the escape iso-risk curves. My reasoning was that by

leaving out all lower-risk exposures containing staged decompression, a model could be calibrated to better fit the data important to submarine escape, recognising that such a model would be of little use for any other kind of pressure exposure. Also, I wanted to include body mass as a risk factor in the model. Body mass data had not been included in the calibration datasets from the outset. We sifted approximately 10,000 pressure exposures in man, goat, sheep and pig to generate files specific to submarine escape and rescue, adding body mass data where available.

I reassessed the historical data previously reviewed by Seddon and White [22]. I found evidence suggestive of acclimation within the historical data. It was not possible to determine whether increase in risk observed for longer between-dive intervals in subsets of the data was due to higher pressure of those exposures or whether it might have been partly due to ‘de-acclimation’ effects. There was evidence that the manner in which experiments were designed strongly influenced the levels of DCI observed in the data such that the historical data taken as a whole were not suitable for the calibration of population-based mathematical models for DCI prediction. I concluded that the use of the first pressure exposure for each animal was an acceptable method for inclusion of the historical data. Of the 7309 exposures in the historical dataset, 389 were usable for model calibration [T24].

At this point I felt it was not useful for our group to conduct more manned experiments in submarine escape breathing air: in observing two cases of DCI we had already established the boundary of what we would be able to achieve without putting people at even more serious risk. We moved on to test **H6** [A15]. Mitigation of DCI signs/symptoms remained as deserving further investigation. However, the wide confidence limits of model-based predictions of the likelihood of DCI meant that detecting the effect of any prophylactic or mitigating measure would be difficult. The most effective way to narrow the confidence limits, in terms of using the least number of animal exposures, was to generate more data in

the region where we expected 50% DCI. Since we could test any mitigation measure that was applied after DCI was observed without affecting that observation, that meant the data could be used for further model calibration. It made sense to test the efficacy of treatment of DCI with surface oxygen since the Submarine Parachute Assistance Group (SPAG) were already equipped to administer this but how much effect it would have was unknown. We conducted experiments that I designed to address these issues between **2004** and **2006**. At this time, we were asked not to publish any further details of animal experimentation. This was a decision we fought for several years. I was eventually able to submit a paper on this study in **2015** [A15].

2005 – 2006 I conducted an on-paper study into surface abandonment from submarines, this included modelling personnel evacuation times and a review of current and potential procedures and equipment for abandonment and surface survival. This was reported in 2006 [T18]. During this time I also wrote a 30 year strategy for future research in SMERAS-related topics.

2006 – 2009 Having prepared the set of submarine escape relevant data, I began recalibration of the LE model. I altered the risk function to include a factor which allowed DCI risk to scale with body mass. I also added an exponent to the instantaneous risk function believing there is no reason to expect instantaneous risk to vary linearly with tissue supersaturation level. The model was unable to achieve a good fit to the pig or sheep data; I excluded those species and recalibrated the model [T37]; (I later discovered the pig and sheep datasets contained replicated data for reasons which made sense to the authors of those datasets but we had not appreciated this at the time). As in previous modelling efforts, I obtained estimated confidence limits on the optimised parameter values using the constant Chi-square boundary method. This is a similar approach to that followed by Thalmann et al [32]. However, I had concerns over the appropriateness of this method since the likelihood

surface is not smooth. I implemented a bootstrap-based method to estimate confidence limits on both the parameter estimates and for the predicted P(DCI) from the models [T39]. I was eventually able to submit the work for publication in 2014 following submission of two papers detailing the simulated escape experiments that we had conducted in the goat and in man [A10, A11, A12]. I refer to the recalibrated version of the LE model as ‘5C’. The escape iso-risk curves are shown in Figure 6. The bootstrap estimated confidence regions are omitted for the sake of clarity but are given in the published paper.

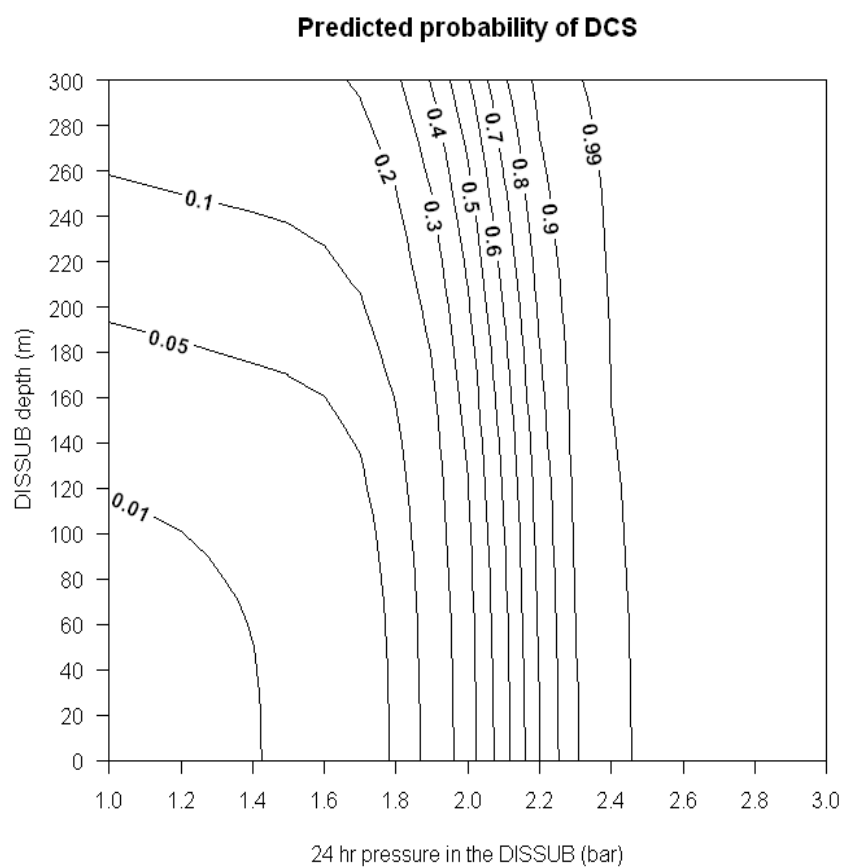


Figure 6: *Iso-risk curves for an 80 kg individual for escape following 24 h at raised DISSUB pressure [adapted from A12]*

One of my early concerns was the fact that the safe-to-escape curve gave no indication of severity. This is an issue for two main reasons: firstly, we had shown that saturation exposures are more likely to produce limb pain DCI whereas escape exposures are more

likely to cause more serious neurological problems. This means that exposures with equal likelihood of DCI may have very different outcomes in terms of the severity of symptoms and likelihood of survival. Secondly, most submariners are not divers and may not fully appreciate what the likelihood of DCI means, when considering submarine tower escape. Rather than iso-risk curves for DCI, I wanted to generate 'Probability of survival curves.' For this I needed to be able to predict the rates of different DCI symptoms rather than simply the overall rate of DCI. We went back through our data and specified the type of DCI as one of limb-pain, neurological or respiratory (cardiopulmonary) DCI. I then calibrated logistic regression models against each symptom type in the DCI data [T33]. I ran a workshop with attendees from our group and representatives of the Institute of Naval Medicine. By combining the predicted likelihood of the different DCI symptoms with the subject matter expert 'guesses' for the effect of each symptom type on chances of surface survival, I was able to generate the probability of survival curves for submarine tower escape shown in Figure 7 [T36]. I have since argued that the safe-to-escape curve was too conservative and provided an argument to the MOD for use of escape limits that are predicted to give a survival rate of better than 90% [T56].

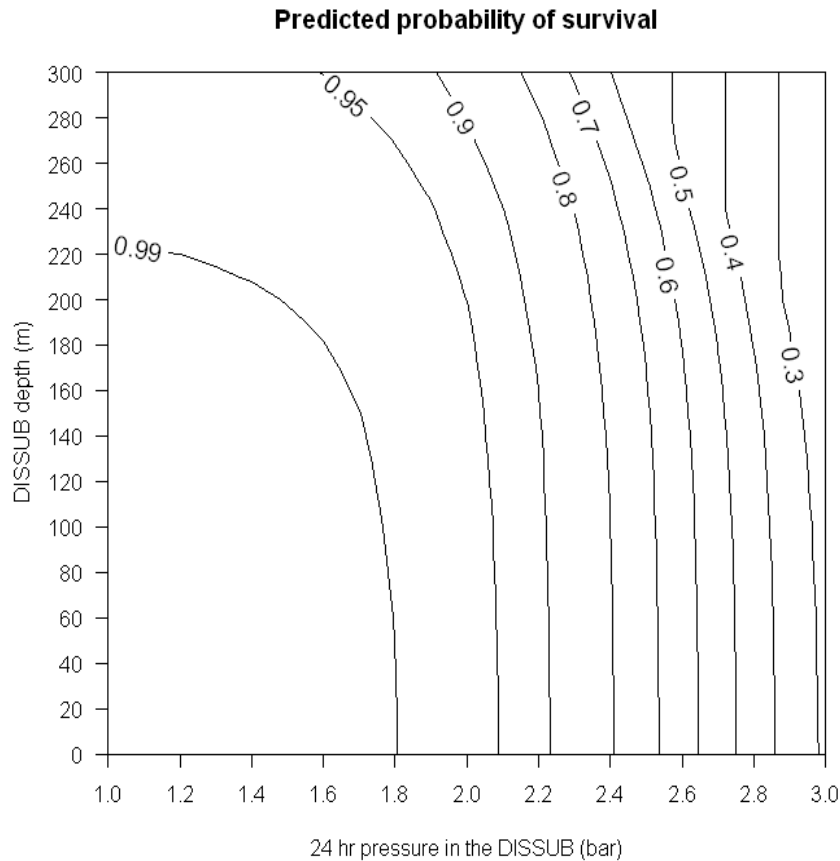


Figure 7: *Probability of survival curves for an 80 kg individual for escape following 24 h at raised DISSUB pressure [adapted from T36]*

During this same period, we conducted two experiments investigating the effect and mode of exercise on Doppler detectable bubbles as an investigation of **H7** [A6]. For the first study [38] I helped with the randomised design and data acquisition set up, including writing software to allow us to use a mass spectrometer for VO_2 max testing. However, I didn't have much further input as we were short on participants so I volunteered. For the second study I wanted the form of exercise to be something that could be practicably carried out in a DISSUB and this corresponded with the idea of investigating a mode of exercise with higher impact. The study was written up for publication by Karen Jurd [A6].

In **2007** I presented 'Parameter estimation in DCS' as a problem to the Mathematics in Medicine Study group at Southampton University [39]. Following this I applied for funding

through the EPSRC for a PhD student to investigate applying Bayesian techniques to this problem. I acted as the ‘Industry PhD Supervisor’ for the selected student while Professor Jon Forster acted as the supervisor for the University of Southampton Dept. of Mathematics.

2009 – 2010

In 1939, Alexander et al had reported that switching from breathing a hypercapnic gas (6% carbon dioxide) to 100 kPa oxygen resulted in nausea and vomiting in some participants [40]. I pushed for our group to investigate this issue because, as is pointed out by Donald [16], this situation is directly relevant to submarine escape. Our group conducted a manned experiment to investigate **H8** [A9]; I presented the results at the EUBS meeting in 2011 [41] and wrote up the study for publication [A9].

We followed this up by testing **H9** [A14]: that the effect of the gas switch might be exacerbated by a submariner attempting to ‘clear their ears’ using the Valsalva manoeuvre. The study was written up by Fiona Seddon for publication [A14]. A criticism that could be levelled at these experiments is that we did not immerse the participants or expose them to an actual pressurisation profile. Immersion would partially ameliorate the reduction in cerebral blood flow that we observed [42]. However, this assumes that the escape tower will be flooded to a level where hydrostatic pressure will have a non-negligible effect on blood pressure. Only in some scenarios will the escape tower be flooded to this level prior to the upper hatch opening. Rapid pressurisation has been shown to result in expiratory hypoventilation leading to hypercapnia. This would also act to mitigate against any reduction in cerebral perfusion [43]. For these reasons, a non-immersed participant that is not exposed to pressurisation might be taken to represent the worst case. This reinforces the finding that any CO₂-off effect is unlikely to result in incapacitation in submarine escape. This statement

is subject to the other points I make in the paper with respect to chronic exposure and partial pressures of carbon dioxide above 5 kPa.

2010 – 2013 During a discussion between myself and colleagues, I realised the correct functioning of the escape system in terms of rate of pressurisation in the tower was predicated on an assumption that the DISSUB would come to rest on the seabed with no angle of pitch or roll. That is to say, the escape tower had to be ‘upright’ to function in the expected way. In looking into this problem I went back to an analytical solution for the rate of pressurisation of the escape tower derived by Ackles et al [44]. I had used this solution in the first model I wrote in 1994. With the benefit of greater experience, I realised that use of the Hagen-Poiseuille formula by Ackles et al was inappropriate, although their calibration against actual trials data meant the output of the model was approximately correct. I derived an analytic solution based instead on orifice-flow which takes into account Bernoulli’s principle. This enabled me to demonstrate that it should be possible to successfully pressurise the tower at any DISSUB angle by shutting the tower vent prior to flooding the tower, with appropriate adjustment of the flood orifice plate which controls the rate of flooding. I have written a number of reports on this subject, defining a new performance envelope for escape towers and revising the method by which escape towers are tested. [T42, T47, T51, T52, T57]. Based on this work, I have presented two conference papers on the optimisation of submarine tower escape [A7, A8].

2013 – 2016 My recent work has involved issues related to decompression of survivors following submarine rescue [T55, T62]. I am mentoring a new employee in calibrating models for prediction of DCI by symptom type [T63, 45]. We are also investigating the relationship between grip strength and an individual’s ability to maintain their connection to the hood inflation system during submarine tower escape.

3. Methodologies in submarine tower escape research

In this section I discuss methodologies used in the research described above. I cover only critical points that are not discussed in the previous section or the published papers, and points due to more recent studies by other authors.

3.1 Animal testing and use of the goat in decompression studies

Novel pressure exposures can produce unexpected results: dives that were expected to produce bone necrosis were shown to produce respiratory DCI in sheep [46]. It is therefore necessary to proceed with caution. We used goats to provide some notion of the risks that might apply to man for the more dangerous saturation and escape profiles.

Berghage et al describe a relationship between body mass (and therefore metabolic rate and rates of tissue-blood perfusion) of an organism and the pressure from which that organism can be safely decompressed to the surface. To select a species for use in testing pressure profiles proposed for use in man, it is sensible to choose an animal with a body mass similar to that of man's [47].

Experience suggests that use of animals such as goats, sheep or pigs will provide useful results in terms of applicability to man without resorting to use of non-human primates. Pigs have been shown to be a useful model of neurological DCI in man [48, 49] and for analysing the formation of circulating bubbles [50]. However, the body mass of adult pigs is markedly greater than humans and for this reason, infant pigs have often been used in experiments.

Since sedation/anaesthesia results in reduced metabolic rate and therefore alters gas kinetics, we used fully conscious animals during pressure exposures. Goats and sheep are easy to handle and to keep, and do not tend to become restless when kept in a hyperbaric chamber for long periods. The large volume of previous work performed using goats [16, 46] afforded us

a useful background on the response of the goat to decompression, enabling experiments to be performed with the minimum number of initial exploratory exposures.

The use of animals in experiments can establish basic concepts, principles and trends but cannot be used to provide data that directly apply to man without qualification. Obviously, there are many physiological differences between man and goat and some might be expected to directly affect the aetiology of DCI.

As with other ruminants, goats produce large quantities of gas in the digestive tract in comparison to humans [51]. Hydrogen and methane diffuse from the gut into the blood and have been shown to contribute to levels of DCI observed in rats and pigs [52, 53]. In the goat, fermentation takes place primarily in the rumen rather than the hind-gut. Chief by-products are carbon dioxide and methane and a proportion of these are absorbed through the rumen wall. However, this process is not fully understood, the carbon dioxide tension in the rumen is higher than the capillaries indicating that diffusion is limited in some way [54]. Nevertheless, it is plausible that gases generated as a by-product of digestion may have an increased role in DCI in the goat compared with man and this remains untested.

Bovidae have a raised breathing frequency relative to body mass in comparison with other mammals. However, this is not thought to be due to a metabolic difference but perhaps due to the large rumen of these animals placing increased elastic load on the respiratory system. [55].

The blood supply to the goat brain passes through a fine network of blood vessels, the rete mirabile caroticum [56]. This network acts as a heat exchanger, cooling the blood on its way to the brain. Since the rete is absent in man, there is a possibility that this anatomical difference may cause disparity between results for goat and man in situations where gas exchange in the brain and CNS is important, such as submarine escape. Gas exchange

between afferent and efferent vessels at the rete is expected to be low since the supply of oxygen to the goat's brain would otherwise be limited and carbon dioxide retention would also occur [57]. Therefore any disparity between man and goat caused by the presence of the rete in the goat in terms of uptake/elimination of gases is probably negligible. Another possibility, however, is that the rete could act as a bubble filter, which could have some protective effect against neurological DCI.

Despite the differences described above, we have observed that the goat dose-response curve for decompression from saturation shows good agreement with that for man, see for example Figure 4 in my paper [A15]. The case for decompression from the short duration submarine escape pressure profile is less clear, partly because the greatest escape depths that have been tested in the goat resulted in less than a 20% incidence of DCI and of course no comparable escape has been tested in humans.

3.2 Interpretation of DCI signs and pulmonary barotrauma in the goat

It is generally thought that DCI events in animal models may be missed, since minor symptoms of DCI may not present as signs noticeable to an observer. This would result in the dose-response curve for a goat being shifted to the right of that for man. However, as described above, the goat dose-response curve for saturation decompression shows good agreement with that for man.

Diagnostic criteria we used for assessing signs of decompression illness (DCI) in the goat are given in [A10]. Of these, it is worth discussing the diagnosis of pulmonary barotrauma (PBT) in some extra detail.

In the clinical setting, the symptoms of arterial gas embolism (AGE) as a result of PBT may be indistinguishable from neurological symptoms caused by the evolution of gas bubbles

from the dissolved state. In our animal experiments we observed 14 cases of apparent PBT for escape breathing air; in these instances, animals usually showed severe signs including collapse and loss of consciousness immediately or within two minutes of surfacing, sometimes accompanied by distension similar to the bloat which often affects ruminants. Since 12 of the 14 cases of PBT occurred following escape without pre-saturation, it seems unlikely that bloat could be the cause since there would not be time for bloat to develop during the rapid escape procedure. PBT occurred generally on deeper escapes and it seems unlikely that the increased pressure of the deeper escapes was the problem *per se* because it is only in the shallowest part of the ascent that Boyle's law results in the greatest expansion of gases in body cavities. There is a more plausible explanation in that the wide temperature swing observed in the SES during pressurisation (when temperatures reached as high as 130 °C) and subsequent depressurisation (where temperatures fell as low as – 40 °C) may have caused the goats to hold their breath, resulting in either barotrauma of descent or barotrauma of ascent. Note that these extremes of temperature were transient, lasting only seconds. In manned escape, the temperature swing is mitigated to a great extent by the expansion of hood inflation system air into the hood of the escape suit.

Barotrauma of descent may also occur if pressurisation is too rapid. As the ambient pressure is increased, the escaper must inhale in order to equalise pressure in the lungs with the ambient pressure. A failure to do this will result in compression of the lungs. Calculation using Boyle's law shows that this would result in serious injury to breath-hold divers attempting to dive beyond 50 metres. In fact, some breath-hold divers have been able to descend to depths greater than 150 m without serious injury. This may be possible due to redistribution of blood into the heart and chest [58]. However, it has been shown that breath-hold divers do suffer pulmonary oedema (fluid on the lung) and haemoptysis (coughing up of blood) [59, 60]. These injuries are unlikely to result in fatality in breath-hold diving, since

there is only sufficient air in the lungs for them to be fully inflated (and not over-inflated) on returning to the surface. This is not the case for an individual performing submarine escape.

There could be other mechanisms by which injury to the lung might occur during very rapid pressurisation: small regions of the lung may be partially blocked by cysts or blebs – these can be asymptomatic, causing no problem during normal breathing. During pressurisation, flow to these regions may be choked causing collapse in the localised region – the collapsed region may be damaged or injury may occur to the surrounding lung tissue as it expands into the collapsed region.

Inspiratory flow limitation has been observed in healthy divers breathing gas at raised density, with dynamic compression of the trachea being suggested as a possible cause [61]. This effect would limit an escaper's ability to maintain inflation of the lungs during overly rapid pressurisation.

Although barotrauma during the pressurisation phase is possible, it would seem unlikely (but not impossible) that this would result in an injury sufficiently debilitating to prevent the escaper from exiting the tower. However, a small injury to the lung during the pressurisation phase would likely have fatal consequences during ascent.

Thus, there are several possible causes for PBT in these animals. We were able to recognise cases of PBT as being distinct from neurological DCI mainly due the presence of distension in these animals. However, it remains possible that the occurrence of neurological DCI during decompression might, in some cases, cause an animal to hold its breath, perhaps due to pain and this in turn could lead to PBT. I excluded cases of apparent PBT from my modelling efforts and therefore there is a chance that a small number of cases of neurological DCI were missed from the calibration data.

3.3 Doppler based bubble detection

Methods of most physiological measurements taken during our studies are well documented elsewhere. The use of Doppler ultrasound to assess levels of venous gas emboli warrants some discussion.

In our experiments, we used the Kisman-Masurel bubble scoring system which relies on observer judgement and is therefore subjective. It is not parametrically scaled and does not have a clearly defined relationship to likelihood of DCI. Nor can the bubbles detected through ultrasound be said to be the cause of any observed symptoms; in fact, since the bubbles that are detected are generally in the venous circulation, it is almost certain that they are not responsible for provoking DCI symptoms other than respiratory DCI. However, levels of Doppler detectable bubbles may be indicative of general gas loading in the tissues and therefore of decompression stress [62].

A recent study has shown that the effect of any condition such as oxygen breathing would have had to be very large for us to detect using Doppler based methods. The study investigated the power of experiments to detect effects using Doppler bubble scoring as a measure and showed that at least 50 paired measurements are needed [63]. Neither our animal or manned experiments have had this number of subjects/participants. In running power tests to determine subject/participant numbers in preparation of ethical protocols for these experiments, I always assumed that we would only be interested in a very large effect. This is because any procedure would need to show a marked beneficial effect in order to be considered practicable for use in a DISSUB scenario. This means I accept a reasonable chance of failing to detect small effects.

More recently a number of different bubble scoring methods have been developed, some of which allow parametric and/or more objective measurement [64]. Some of these methods

could be applied retrospectively to our data but many use ultrasound imaging as their basis, rather than continuous wave audio Doppler.

Doppler bubble score has been used in model calibration [65] and a bubble model has been shown to adequately predict the extent and duration of decompression bubbles following submarine escape [66, 67]. A scaled measure of response to the pressure exposure dose gives the parameter estimation process more leverage on parameter values than the binary response of DCI. However, it is prediction of DCI occurrence rather than prediction of bubbles that is needed and the processes by which bubbles cause DCI are not fully described. This statement is often more succinctly put as ‘Bubbles do not equal DCI,’ see, for example, Møllerlækken et al [68].

3.4 Mathematical modelling of DCI and model selection

Deterministic and Probabilistic methods

Deterministic methods prescribe fixed limits on model variables assumed to be indicative of decompression stress. If, during simulation of a pressure exposure, the prescribed limits are exceeded, the exposure is deemed unsafe. The limiting values for these variables are generally defined based on DCI data from experience with human and animal pressure exposures. Limiting values may be pressure and compartment-dependent (e.g. Workman’s “M-values” [69]) or dependent on compartment time-constant only (e.g. Bühlmann’s ZHL series of models in [19]). Deterministic methods have generally been adopted for staged decompression as used in diving decompression tables and dive-computers. Since deterministic models do not attempt to compute actual risk of DCI, decompression tables developed in this way may contain recommended exposure limits which are quite variable in terms of actual levels of DCI risk, with some exposures within a set of tables being highly conservative whilst others may pose more significant risk. Limiting values of a model’s

variables are often altered, once the tables are in use, if particular exposures are found to result in an unacceptable level of DCI. When the parameters of different deterministic algorithms are gradually refined to produce successively more conservative decompression schedules, then the fact that the models are based on different algorithms becomes less important. The determination of one conservative model as being in some way superior to another, in terms of rates of DCI, becomes practicably impossible when thousands of exposures would be needed in order for any cases of DCI to be observed.

There are, therefore, fundamental differences between the requirements of designing a model for the avoidance of DCI, which is an objective in diving, and designing a model to predict the rate of DCI following a dive, a diving accident or submarine escape.

Probabilistic methods use some form of risk function based on variables within the model assumed to be indicative of decompression stress to define a likelihood of DCI. Only through probabilistic methods can a risk of DCI be estimated for a given exposure. For this reason, I adopted probabilistic methods from the outset.

Empirical and mechanistic models

Empirical models do not simulate the aetiological processes of DCI. They use pre-defined mathematical functions which are fit to data using statistical methods such as logistic regression. Empirical models cannot be used in extrapolation beyond the bounds of the data upon which they are based with any confidence since they do not model the physical/physiological processes involved. Where I have used empirical models such as Hill dose-response or logistic regression models, this necessarily required the reduction of pressure profile information to a set of predictor variables: saturation pressure, escape depth, body mass etc. Any such model is then limited to calibration against and prediction of risk for

pressure profiles that can be summarised by the same predictor variables. In order to account for more complex pressure profiles, some form of mechanistic model is needed.

Mechanistic models attempt to simulate the physical and physiological processes that result in DCI. Not all of the processes involved in the aetiology of DCI, nor their relative importance, are known or fully understood. Therefore, it is not possible to state categorically which elements of the relevant physics and physiology need to be described through detailed algorithms or those which may be approximated or ignored. These models generally contain parameters, the values of which have not been determined through experiment but are estimated to give the best fit of the model to some DCI data. For these reasons, mechanistic models of DCI are sometimes referred to as 'semi-empirical' or 'quasi-physiological.' The models may give reliable results when used in interpolation and might be looked to for improved predictions over empirical models when used in short range extrapolation.

Mechanistic models usually represent the body as a group of tissue compartments in which inert gas kinetics are tracked. Compartments may be in parallel, serial or more complicated arrangements.

Differences between tissue compartments are related to their rate of blood supply, or 'perfusion,' some compartments may be poorly perfused and gas kinetics here may be dominated by diffusion rates. In some models perfusion is ignored, in some diffusion is ignored. In any case, parameters of the model determine the rate at which inert gases are taken up or eliminated from tissue compartments. Where partial pressures of inert gases in tissue compartments are raised above the ambient pressure by some degree, that tissue compartment is said to be in a supersaturated state and risk of DCI may be assumed to accumulate over time. The risk of DCI may be based upon the level of supersaturation of the tissue with inert gas or, for bubble models, a certain level of supersaturation will drive bubble

growth and risk of DCI may be based on size or numbers of bubbles present [31]. Once a bubble has formed, kinetics for elimination of gases from the tissue are altered. In some models the formation of bubbles is not described but altered gas kinetics are assumed above a given level of supersaturation, thus approximating the effect of the presence of bubbles [32].

Some models assume risk of DCI only accumulates for certain tissue compartments or weight certain compartments as having a higher risk of causing DCI symptoms than others for the same level of decompression stress. A model by Goldman allows certain compartments to act as ‘sinks’ – storage areas where inert gas may be present without causing stress to that tissue, but may result in stress when gas passes from the sink tissue into the surrounding tissues [70].

In general, bubble models ignore difficulties associated with the modelling of spontaneous formation of bubbles in solutions; rather, it is assumed that tiny bubbles, ‘micronuclei,’ exist within the body and that these act as ‘seeds’ for the formation of bubbles when conditions of tissue supersaturation exist [71]. In some bubble models, the growth and resolution of a single bubble from a micronucleus of a fixed size is tracked in any given tissue compartment [31]; in others, a population of micronuclei may be tracked where only a proportion will grow to become bubbles dependent on the conditions within the tissue and on physical properties of each micronucleus assumed to vary over the population [72, 73].

In summary, mechanistic models have been designed with a number of differing structures and assumptions. However, no model has been conclusively shown to be superior in terms of goodness of fit to DCI data. My selection of the LE model for most of the modelling effort described in section 2.2 was therefore based as much on its inherent lower computational requirement as its ‘quasi-physiological’ mechanistic elements.

Form of instantaneous risk function

Lack of a full description of how supersaturation leads to bubble formation and consequent DCI means that the appropriate form of risk function to adopt is unknown. Since there seemed to be an issue in prediction of higher risk decompression from saturation in the original calibration of the LE model, I added an exponent to the supersaturation ratio model to allow the model more freedom. It was possible for the exponent to be set to a value of 1 by the optimisation routine allowing for the situation that the original form of the risk function was already optimal. In fact, this did not occur. It is sometimes tempting to attempt to draw some kind of physically meaningful conclusions about the values that gave the best fit of the model to the data; this is not necessarily useful or even sensible in a model with lumped parameters where it is known that the model falls short of representing reality in more than a loose approximation.

Unfortunately, introduction of an exponentiated supersaturation ratio meant there was no analytic solution for integration of the risk function: numerical solution was needed and the computational advantage of the LE model over bubble models reduced to some extent.

Weathersby and Gault have also used an exponentiated supersaturation ratio in modelling of higher risk exposures [74]. In their model the authors used the square of the supersaturation ratio rather than allowing the parameter to be optimised. Following on from this, Hada and Howle have investigated the use of other forms for the risk function. A full paper has not been published but their published abstract suggests that exponentiating only the numerator of the supersaturation ratio may provide a better fit [75].

On the structure of the '5C' model

In recalibrating the LE model to generate model 5C, I made two important changes: the alteration of the risk function and the re-selection of the calibration data to utilise only pressure exposures relevant to submarine escape. The optimal model that I found had five tissue compartments, none of which used the linear washout functionality of the LE model, that is, the 5C model is an exponential-exponential (EE) model. This means that the model never uses that part of the LE model that emulates the existence of bubbles.

The original LE model needed only three tissue compartments to adequately describe its calibration data. It may be that parameter values exist for a model using LE kinetics that would give a better fit to the submarine escape data and I simply failed to find these. There is no guarantee that a global optimum will be located in the optimisation process. It is notable that in the original LE model, only one of the three tissue compartments uses the linear-washout functionality, the fastest and slowest compartments are both EE only. Given the semi-empirical basis of these models, offering a physical explanation for this finding would be purely conjectural.

Physiological elements that could be included in a more fully mechanistic approach

Examples of relevant processes that are ignored in the simple models I have used include:

- Nucleation (Chappell and Payne have modelled bubble growth in crevices [76])
- Bubbles lodging in vessels - models of ischaemia
- Endothelial damage
- Effects of pharmaceuticals, heat stress
- Effects of age, fitness, smoking
- Damage and repair - inflammation processes leading to late onset of DCI
- Effects of metabolic gases
- Effects of other toxic gases
- Other breathing gases
- The role of the lymphatic system
- The role of blood constituents, red and white blood cells, platelets and plasma

Some pressure exposures result in DCI occurring with a delay after surfacing of as much as 24 hours or more. Late symptoms may not be due to the presence of bubbles at the time of symptom occurrence, but perhaps due to a chain of physiological events triggered by the presence of a bubble at an earlier time, for example inflammation or reperfusion injury following ischaemia. In the models I have used, risk of DCI is based on the presence of a certain degree of supersaturation. Since processes such as inflammation and ischaemia are not modelled, in order to allow the prediction by the model of late occurrences of DCI symptoms, the calibration process forces the requirement for at least one tissue compartment with a very long halftime for inert gas uptake and elimination. Models for these individual processes do exist and could be combined in a predictive model for DCI. However, at present these would remain as exploratory models since the full aetiology is not understood.

4 Contribution to knowledge

The submitted work demonstrates an advance in our knowledge of the risks of DCI and a substantially improved level of confidence in the predictions of mathematical models of DCI for submarine tower escape.

I have introduced a method for scaling risk of DCI using a lumped parameter approach which incorporates body mass. These are the first semi-empirical probabilistic models of DCI to combine animal and human DCI data using body mass as a scaling factor.

Experiments in which I made significant contribution in terms of original conception, design, data acquisition and analysis have provided evidence for the efficacy of surface oxygen as a treatment for DCI following submarine tower escape, and demonstrated that breathing raised partial pressures of carbon dioxide in the DISSUB then switching to diving quality air in the escape tower is not likely to prevent successful escape.

5 Impact of the work on professional practice

Provision of more detailed information on risks of DCI and likely survival outcomes has allowed me to argue for a change in escape policy which has been accepted by the UK RN.

My suggestions for optimising tower escape to use the non-vented method are to be tested on board UK submarines in the future, prior to possible adoption by the RN.

The iso-risk curves I developed for probability of DCI and predicted probability of survival following submarine escape have been included in ATP-57, the NATO submarine search and rescue manual, a reference used by all submarine operating NATO nations [77].

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7 List of technical reports

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Appendix A - Derivation of the Linear-Exponential model

This appendix describes the linear-exponential (LE) model as developed by Thalmann, Parker, Survanshi and Weathersby [22]. An expression is derived for the instantaneous risk function of the LE model. Subsequent modifications to the instantaneous risk function to produce the 5C model are described at Annex 12 [A12].

In the simplest formulation of the LE model, the possibility of using helium or other rare gases in the breathing mixture is ignored. The ambient air or breathing mixture is assumed to be composed entirely of oxygen and nitrogen. Any inert gases other than nitrogen that might be present, such as argon, are not considered as variables within the model but are assumed to contribute to the nitrogen partial pressure. Throughout the model, it is only necessary to track the partial pressure of nitrogen. The partial pressures of the constituent gases of the atmosphere being breathed, $P_{atm}N_2$ and $P_{atm}O_2$, are assumed to sum to the ambient pressure, P_{amb} , according to Dalton's law. Since it is usually $P_{atm}O_2$ that is measured, then $P_{atm}N_2$ is determined as shown in **Equation 1**:

$$P_{atm}N_2 = P_{amb} - P_{atm}O_2 \quad \text{Equation (1)}$$

The atmospheric nitrogen partial pressure is reduced to its inspired partial pressure, P_iN_2 , due to the presence of water vapour. The reduction in partial pressure occurs in proportion to the fraction of inspired nitrogen, $(P_{atm}N_2/P_{amb})$. Inspired, alveolar and arterial nitrogen tensions (P_iN_2 , P_AN_2 and P_aN_2 respectively) are then assumed to be equal:

$$P_aN_2 = P_AN_2 = P_iN_2 = \frac{P_{atm}N_2}{P_{amb}} \cdot (P_{amb} - PH_2O) \quad \text{Equation (2)}$$

Where PH_2O is water vapour pressure at 37 °C, taken to be 47 mmHg (6266 Pa).

Tissue tensions of oxygen (P_vO_2) and carbon dioxide (P_vCO_2) are assumed to be fixed at typical mixed venous levels: $P_vO_2 = 46$ mmHg (6133 Pa); $P_vCO_2 = 53$ mmHg (7066 Pa).

The model represents the body as a set of n independent and parallel perfused tissue compartments. The tissue nitrogen tension in the i^{th} tissue compartment (PN_{2tiss_i}) is related to the concentration of nitrogen within that tissue (CN_{2tiss_i}), as:

$$PN_{2tiss_i} = CN_{2tiss_i} \cdot \frac{1}{\alpha_{t_i}} \quad \text{Equation (3)}$$

Where α_b and α_{t_i} are the solubility coefficients of nitrogen in the blood and tissue respectively. The values of the solubility coefficients are not explicitly defined within the model but are 'lumped' together with the tissue blood perfusion rate (Q_i) in a parameter τ_i , the values of which are determined for each tissue through fitting of the model to DCI data.

$$\tau_i = \frac{1}{Q} \cdot \frac{\alpha_{t_i}}{\alpha_b} \quad \text{Equation (4)}$$

For any given pressure exposure, tissue nitrogen tensions in each compartment are tracked according to:

$$\frac{\partial PN_2 tiss_i}{\partial t} = \frac{1}{\tau_i} \cdot (P_a N_2 - PN_2 tiss_i) \quad \text{Equation (5)}$$

Equation (5) is a separable ordinary differential equation. For a constant value of $P_a N_2$ and initial tissue nitrogen tension $PN_2 tiss_{i(t0)}$, the solution may be written:

$$PN_2 tiss_i(t) = P_a N_2 + (PN_2 tiss_{i(t0)} - P_a N_2) \cdot e^{-\frac{t}{\tau_i}} \quad \text{Equation (6)}$$

Thus, nitrogen uptake and elimination within each tissue compartment follows exponential kinetics with time constant τ . For $P_a N_2$ varying linearly with time, **Equation (6)** becomes:

$$PN_2 tiss_i(t) = P_a N_{2(t0)} + (PN_2 tiss_{i(t0)} - P_a N_{2(t0)}) \cdot e^{-\frac{t}{\tau_i}} + \frac{\partial P_a N_2}{\partial t} \cdot \left(t + \tau \cdot \left(e^{-\frac{t}{\tau_i}} - 1 \right) \right) \quad \text{Equation (7)}$$

It is assumed that a gas phase (bubbles) may form if the sum of the tissue gas tensions exceeds ambient pressure by some amount P_{Xoi} , the ‘cross-over’ parameter, the value of which will be determined through fitting the model to DCI data. That is, a gas phase will form if:

$$PN_2 tiss_i + P_{fixed} \geq P_{amb} + P_{Xoi} \quad \text{Equation (8)}$$

Where

$$P_{fixed} = PH_2O + P_VO_2 + P_VCO_2 \quad \text{Equation (9)}$$

It may, perhaps, be helpful to consider P_{Xoi} as being representational of those pressures (other than ambient pressure) which tend to cause gas bubbles to shrink, due to the action of, for example, surface tension and tissue elastic forces. While the condition shown in Equation (8) remains true, $PN_2 tiss_i$ may be thought of as the tissue nitrogen tension which would exist if the gas phase were forced back into solution; the tissue nitrogen washout rate is then assumed to be independent of $PN_2 tiss_i$, and to follow linear, rather than exponential kinetics, according to (for $P_a N_2$ and P_{amb} varying linearly with time):

$$\frac{\partial PN_2 tiss_i}{\partial t} = \frac{1}{\tau_i} \cdot \left(P_a N_2 - (P_{amb} + P_{Xoi} - P_{fixed}) + \left(\frac{\partial P_a N_2}{\partial t} - \frac{\partial P_{amb}}{\partial t} \right) \cdot t \right) \quad \text{Equation (10)}$$

The solution to **Equation (10)** is:

$$PN_2tiss_i =$$

$$PN_2tiss_{i(t0)} + \frac{1}{\tau_i} \cdot \left((P_aN_{2(t0)} - P_{amb(t0)} - P_{Xoi} + P_{fixed}) \cdot t + \left(\frac{\partial P_aN_2}{\partial t} - \frac{\partial P_{amb}}{\partial t} \right) \cdot \frac{t^2}{2} \right)$$

Equation (11)

The degree of supersaturation within a tissue compartment may be expressed as the relative supersaturation ratio:

$$\frac{PN_2tiss_i + P_{fixed} - P_{amb}}{P_{amb}}$$

For each compartment a threshold pressure, Thr_i , is defined as the total tissue gas burden that the compartment can withstand with no accumulation of risk of DCI symptoms. The instantaneous risk function for DCI for each compartment is then taken as:

$$r_i = G_i \cdot \left(\frac{PN_2tiss_i + P_{fixed} - P_{amb} - Thr_i}{P_{amb}} \right) \quad \text{Equation (12)}$$

Where G_i is a weighting factor, usually termed the ‘gain’. The instantaneous risk function, $r(t)$, is the sum of the r_i over the n compartments.

Thus, for each compartment there are four parameters: τ_i , P_{Xoi} , Thr_i and G_i .

In survival analysis theory, the instantaneous risk function is also referred to as the ‘hazard function’ and represents the instantaneous rate at which DCI symptoms develop (the ‘failure’ rate) among individuals who do not yet have DCI (the ‘survivors’).

Following survival theory, the instantaneous risk function may be defined as:

$$r(t) = \frac{f(t)}{S(t)} = \frac{f(t)}{1 - F(t)} \quad \text{Equation (13)}$$

Where $f(t)$ is the failure probability density function and $S(t)$ is the survival function, that is, $S(t)$ is the complement of the failure cumulative distribution function, $F(t)$. Since $f(t)$ is, by definition, the derivative of $F(t)$ with respect to t , it follows that:

$$r(t) = \frac{f(t)}{S(t)} = \frac{1}{S(t)} \cdot \frac{d}{dt} F(t) = - \frac{1}{S(t)} \cdot \frac{d}{dt} S(t) \quad \text{Equation (14)}$$

Solving Equation 14 for $S(t)$ gives an expression for the probability of survival, the complement of which is the probability of developing symptoms of DCI between two timepoints, T_1 and T_2 :

$$P(DCI)_{T1,T2} = 1 - S(t)_{T1,T2} = 1 - e^{-\int_{T1}^{T2} r \cdot dt} \quad \text{Equation (15)}$$

The model can be used to calculate a predicted likelihood of the actual measured outcome of a pressure exposure as follows: If there is no DCI on an exposure, the predicted likelihood, L , of the actual outcome is the calculated probability that DCI will not occur, that is:

$$L = 1 - P(DCI)_{0,\infty} = e^{-\int_0^{\infty} r \cdot dt} \quad \text{Equation (15)}$$

Note that, in practice, only positive values of $r(t)$ are considered which usually requires evaluation of the integral for only the first 48 h following the pressure exposure.

If DCI does occur following an exposure, the predicted likelihood of the actual outcome is the product of the calculated probability that DCI will not occur before T_1 and the probability that DCI will occur in the interval $T_1 - T_2$:

$$L = (1 - P(DCI)_{0,T_1}) \cdot P(DCI)_{T_1,T_2} = (e^{-\int_0^{T_1} r \cdot dt}) \cdot (1 - e^{-\int_{T_1}^{T_2} r \cdot dt}) \quad \text{Equation (16)}$$

A likelihood value can be computed for an entire dataset of pressure exposures as the product of the calculated likelihoods of all the exposures in the dataset. This value is generally a very small positive number and is more conveniently expressed by its logarithm, the log-likelihood (LL), which is therefore negative. Values of the parameters (τ_i , P_{Xoi} , Thr_i and G_i) of the model are selected using optimisation methods to maximise the LL given the data.

Annex 1.

MG White, FM Seddon, GAM Loveman, KM Jurd, SL Blogg, JC Thacker.

Severe Decompression Illness Following Simulated Rescue from a Pressurised Distressed Submarine. In: Operational Medical Issues in Hypo- and Hyperbaric Conditions.

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Severe Decompression Illness Following Simulated Rescue from a Pressurised Distressed Submarine

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Summary

If adequate transfer under pressure or recompression assets were not available after rescue from a pressurised Disabled Submarine, the rescuees may suffer from severe or fatal decompression illness (fDCI). Effective methods of reducing the risk of fDCI require characterisation. This study uses a large animal model (goat) to estimate the dose (pressure) response (fDCI) relationship. It also addresses the putative intervention measures of breathing oxygen after surfacing or slowing the rate of decompression, as much as the operational cycle time of the rescue vehicle will allow.

The efficacy of interventions was determined by exposing a group of twelve animals to the LD₇₅ pressure. After surfacing at the standard rate, oxygen was delivered by oro-nasal mask for one hour. Alternatively, animals were decompressed through a slow, stepped decompression profile, designed to prevent any microbubble formation on ascent to the surface. Animals were observed for signs of decompression illness (DCI) for up to 10 hours post decompression. They were then humanely killed for necropsy. Animals showing continuously declining vital signs were considered to be dying and were humanely killed.

It was shown that respiratory DCI is the most likely cause of death after rapid decompression from deep air saturation. Interventions, such as slowing the rate of decompression, which reduce the bubble load on the lungs on surfacing are likely to be the most effective. Non-recompression therapies, which target improving gas exchange in the lungs, should also improve the outcome.

Introduction

The submarine's primary role is to deliver its payload to the selected target. This requires it to be covert, fast and manoeuvrable. Constraints are present which prevent the designer from building a totally reliable boat and despite the emphasis on design for high reliability, equipment failures can and do happen. The Russian submarine KURSK highlights the most recent example of such an incident. The covert nature of the submarine's role also makes it vulnerable to collision when at or near the surface, e.g. the Peruvian boat PACOCHA (Harvey, 1989). In both of the cases cited above, further complications occurred when flooding raised the ambient pressure within the boat, increasing the likelihood of rescuees developing serious decompression illness (DCI) on reaching the surface.

If the pressure is greater than about 1.7 bar for more than 24 hours, the survivors will require a controlled decompression to avoid DCI (Bell *et al*, 1986; Eckenhoff *et al*, 1986). Logistical constraints to operators of submarines with large crews (>80), may mean that rescue vehicles arrive at the scene prior to the arrival of the transfer under pressure facility. If the conditions in the submarine are deteriorating, then the on-scene commander will have to consider commencing the rescue operation without the means to control the decompression or to treat the survivors for DCI.

Limb pain only decompression illness has frequently been shown to respond to delayed therapy (Bennett and Elliott, 1993), with little risk of long term adverse health effects. Experience of diving accidents has shown that severe 'missed' decompression can cause permanent neurological damage or even be fatal. The rescue teams require advice to allow the best decisions to be made under such adverse circumstances.

Obviously these "bad outcomes" need to be avoided if at all possible. There is a lack of information upon the relationship between pressure exposure and risk of a bad outcome, which needs to be elucidated. Additionally, any non-hyperbaric methods of reducing the risk of a bad outcome (i.e. prophylactic measures) for a given pressure exposure would be of great advantage and also warrants thorough investigation. Obvious ethical considerations prevent the execution of this study with human volunteers. Therefore, the US Navy has sponsored a three Centre study using large animal models to provide the best data on which to base the advice to be given to on-scene commanders.

Methods

The goat has been used in our laboratory for many years, having been shown to be a good model for human decompression illness (Boycott *et al*, 1906; Seddon, 1997). The species has been found to be slightly more resistant than man to DCI arising from long near saturation exposure. Previous work has demonstrated that for practical purposes 24 hours exposure to raised pressure is sufficient to achieve saturation (Seddon, 1997). The protocols used here were approved by our local animal use review board.

Dose Response Curve

To determine the dose response curve, 48 adult female and male castrated goats were exposed in groups of three to an ambient pressure in the range of 55-85 fsw for 24 hours. Mean body mass was 48 kg, with a range 36 - 62 kg. No animal was exposed to pressure in the preceding 4 weeks to avoid risk of acclimation hyperbaric exposure. If an animal had experienced DCI in a previous study it must have been shown to have fully recovered, following a single hyperbaric treatment on USN Table 5 (RN Table 61), before entering the present study. The animals were exposed to 2.67 – 3.58 bar (55 - 85 fsw) for 24 hours, with compression on air at 1.0 bar/min, inside a 14m³ chamber. Environmental gases were such that CO₂ <0.2 kPa, O₂ = 20.9±0.2% (v/v) and CH₄ < 0.1 kPa throughout the exposure. The ambient temperature remained at 15 - 22°C, except during pressure moves upon initial compression and decompression to the surface. Food and water were given to the animals *ad libitum* up to 8 h prior to decompression, then food alone was withheld. Decompression following the 24 h exposure occurred at 1.0 bar/min (except in 9 animals at 3.46 bar (82 fsw) where decompression occurred over 15 min; there was no difference in outcome in these cases).

Although goats are hardy, feral animals, they do express discomfort strongly, either through vocalisation or altered body language. A protocol for managing pain was developed in the early stages of the experiment. Intra-venous (IV) Torbugesic was administered within 5 min of surfacing. Subsequently Benzodiazepam was given by slow IV injection to sedate the animals if required. The animals were observed for up to four hours after surfacing. If at 4 hours the animals were showed no signs of terminal cardiorespiratory or CNS damage, it was assumed that they would survive. The following clinical signs were recorded:

- Presence of limb pain
- Motor control
- Respiratory rate, pattern and end tidal gases
- Heart rate
- Arterial oxygen saturation by pulse oximetry
- Cyanosis
- Blood gases (CO₂, O₂ and pH)

The Kisman – Masurel (KM) method was used to detect intra-vascular gas bubbles.

Trans-thoracic 2-D imaging was also conducted on an opportunity basis. The carotid artery and jugular veins were also observed for the presence of bubbles.

Animals were considered to be “bad outcomes” if their vital signs were poor (respiratory rate > 50 and heart rate > 180) and continuing to decline over a 20 min period. Such signs were occasionally accompanied by strong visceral pain, which could not be relieved. It was assumed that these animals too would be bad outcomes, and were killed humanely. Clear indications of cerebral damage were also assumed to be fatal and the animals were killed humanely. Examples included convulsions or nystagmus.

These observations were made at 15, 30, 60 minutes after surfacing and at 30minute intervals thereafter up to four hours. The time of any significant changes was also recorded. A gross post mortem was conducted at about 5.5 hours after reaching the surface in this component of the study.

Intervention methods

Two possible prophylactic DCI interventions were tested; post exposure O₂ breathing and a four hour decompression. The estimated lethal dose 75% (ED₇₅) point of 3.35 bar (see Figure 2 for dose response curve) was taken as the standard saturation depth. The animals were compressed in the same way as in the dose response study, and the environmental parameters were also maintained as previously. These animals were either decompressed to the surface at 1 bar/min followed by 1 h O₂ breathing or a staged decompression taking 4 h.

Twelve animals were exposed to this pressure exposure in each test and if the incidence of DCI fell to 33% the intervention would be accepted as effective.

Post exposure oxygen breathing

The effect of oxygen breathing at the surface was tested. 100% oxygen was administered by oro-nasal mask for one hour after surfacing. A limit of one hour on oxygen post surfacing was set, as the provision of unlimited oxygen to 100 plus rescues by open circuit requires vast quantities of bottled oxygen, and is unlikely to be practicable. Also, the gradient of the dose response curve predicts that only a small reduction of gas load is required to produce significant benefits.

In this set of studies, observations continued on the subjects for up to 10 hours (rather than 4 h) depending on the condition of the goat. Animals were sent for post-mortem the following day.

Four hour decompression

A four hour decompression profile was also tested following the 24 h saturation period at 3.35 bar. The objective of the decompression profile was to prevent the formation of gas bubbles that would slow further gas washout. To be sure that bubbles had not formed, the first stop had to be at least two hours duration, which would allow KM Doppler scores to be observed. The aim was for a supersaturation ratio ($PN_{2\text{tissue}}/P_{\text{ambient}}$) as close as possible to 1, though stop times and depths were refined by common sense to avoid confusing decompression rates. A single tissue compartment model (based on previously obtained saturation data) with a half-life of 106 minutes was used to calculate the profile (see Figure 1).

Again, the animals were watched for a period of up to 10 h post surfacing, then humanely killed and sent for post-mortem the following day.

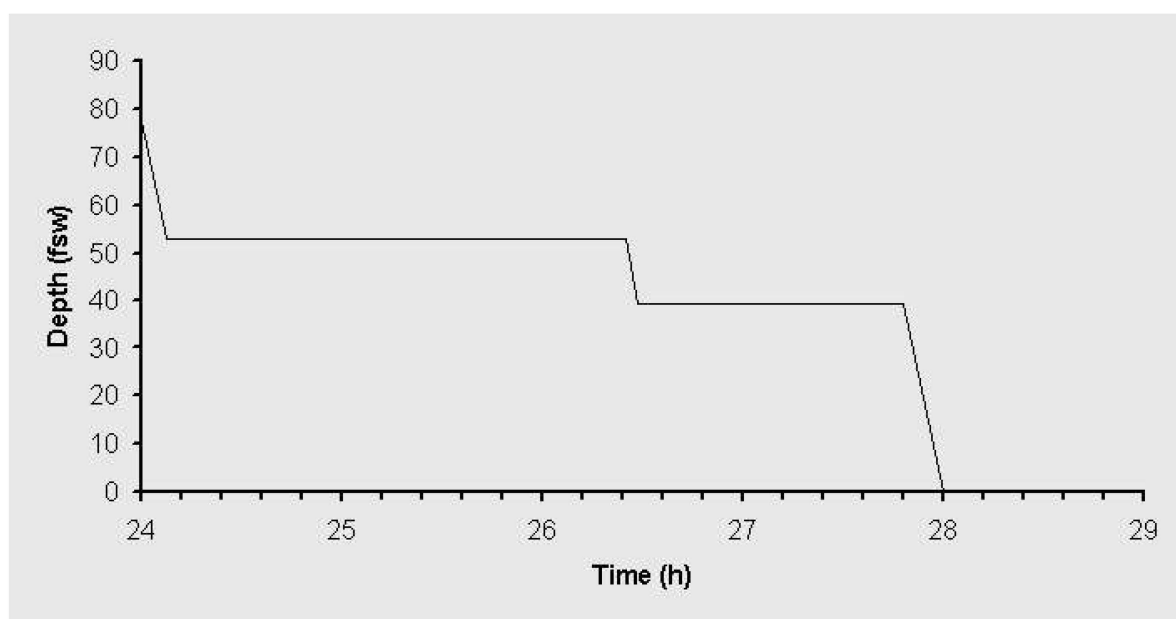


Figure 1 – Slow decompression profile calculated to avoid bubble formation.

Results

Dose response curve

All 48 animals presented with limb pain affecting one or more limbs. All animals also presented with respiratory decompression illness (chokes) to varying degrees. Those least affected had an increased resting respiratory rate, while those most severely affected had severe tachypnea, were hypo-ventilating and were cyanosed. Measurement of venous blood gases showed an elevated PCO_2 and a depressed PO_2 . Three animals presented with central nervous system signs and were diagnosed as bad outcomes. Figure 2 shows the spread of bad outcomes related to depth, producing the dose response curve. From this curve it was estimated that ED_{75} saturation depth was 3.35 bar (~75 fsw).

Venous gas emboli were present at Kisman-Masurel score of four at all observations. 2D imaging showed relatively few bubbles in the periphery compared with the pulmonary artery. No bubbles were observed in the left ventricle or the carotid artery.

Common examples of post mortem findings are:

- Pulmonary oedema.
- Foam in bronchi.
- Gas in major vessels.
- Haemorrhage in brain/mid-brain/spinal cord (C1 - T5).
- Excess Cerebrospinal Fluid in C1 - T5 area.
- Pale brain and coning (compression).

There were no obvious post mortem differentiating signs between the bad outcome group and those that survived.

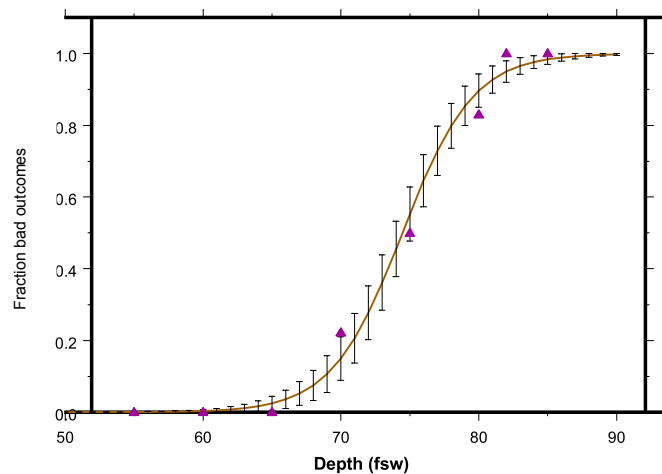


Figure 2 - Showing the derived dose response curve for bad outcomes. The error bars are the predicted 95% confidence intervals on the mean.

Post exposure oxygen breathing

In this case, there were five bad outcomes. This was significant at the $P=0.06$ level indicating a strong trend to a significant benefit. One animal was completely asymptomatic; the 11 remaining animals all exhibited limb bends, while 5 had chokes (chokes being defined as increased respiratory and heart rates) and were deemed to be bad outcomes. One of the latter also suffered from severe CNS complications. All animals in this part of the study exhibited KM pre-cordial Doppler ultrasound scores of four at the surface.

The general pathology on post mortem was as in the dose response part of the study.

Four hour decompression.

In this trial, the number of bad outcomes dropped to 2 out of 12 (17%, $P>0.002$ – a significant improvement on the ED_{75}). No bubbles were detected during the decompression, fulfilling the aim of the model, however KM scores at surface were still four. Some of the animals were affected by respiratory compromise, but not as severely as the controls. There was only one case of cerebral involvement. Again, the general pathology was the same as the earlier parts of the study.

Discussion

It would seem that bad outcomes are largely due to respiratory decompression illness, with a few due to cerebral damage. Therefore, to decrease the risk of a bad outcome, the insult to the lungs needs to be reduced. Oxygen administered post decompression showed a beneficial trend. In addition, anecdotal evidence indicates that oxygen post decompression is effective at reducing the incidence of symptoms following diving accidents. Oxygen administered during decompression should be of even greater benefit as is found in diving and acute altitude exposure. However, at the onset of this study none or very few rescue submersibles are equipped with an oxygen delivery system.

It is accepted that slowing the decompression will be effective, but what is practical? Assuming that the commander wished to evacuate the DISSUB quickly, the Deep Submergence Rescue Vehicle operators have advised that up to four hours could be required to recycle the submersible for its next flight. This would make a four hour stepped decompression to avoid DCI an eminently suitable method of treatment.

Fatalities occurred in the goat model at pressures greater than 2.8 bar saturation. The predicted ED_{50} is 3.25 bar with 95% incidence at 3.5 bar. Other work is in progress to establish the likely figures for man. This work has shown that slowing the decompression will reduce the risk; oxygen breathing is showing a trend to reducing the risk and it can be inferred that measures to improve gas exchange could also improve the outcome. As respiratory DCI is complicated by

pulmonary oedema, a diuretic may be beneficial as a prophylactic measure, and this option should also be investigated in a further study. All of these three options address different mechanisms; they accelerate gas washout, decrease bubble formation and reduce pulmonary oedema, and therefore combinations of the above may be more effective than any alone. Future work will address this question.

In summary this study has confirmed that severe missed decompression can be fatal but the risk of fatalities may be reduced without immediate need for recompression facilities. Although acute symptoms of missed decompression may be alleviated by the varying intervention methods discussed, the gross pathology of all groups showed a similar level of decompression insult. This indicates that post intervention, rapid hyperbaric therapy should be carried out as soon as practicable to reduce the likelihood of chronic DCI.

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Annex 2.

Bradley SR, Loveman GAM, Hall A, Martin R.

The Physiology and Engineering of Submarine Escape.

The Royal Institution of Naval Architects

Warship 2002 Symposium: Naval Submarines 7, 2002; 109-120.

THE ENGINEERING AND PHYSIOLOGY OF SUBMARINE ESCAPE

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SUMMARY

Submarine Escape has become topical since the loss of the Russian Federation Navy submarine K141, KURSK. This paper considers the systematic integration of physiological research and engineering development to improve the process of escaping from a disabled submarine. Almost immediately after the sinking of a submarine, the crew can conduct escape without external assistance. The alternative to escape is rescue by a small submersible that can mate to the disabled submarine, but this process requires a significant period of time while the crew waits for rescue assets to be brought to the scene. Time is a luxury that is not often afforded to those involved in a submarine incident. The process of escape involves compression to the ambient sea pressure, egress from the submarine, ascending to the surface then surviving to reach shore and return to a normal life. At the present time the escape system with the deepest operating envelope is that in service with the UK RN which is rated for escapes from a depth of 180 metres. In an ideal world escape would only be limited to the collapse depth of the submarine pressure hull. QinetiQ Ltd is pursuing lines of research and development that will push the boundaries of escape closer to that ideal.

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Andrew Hall holds the current position of senior technician at QinetiQ Ltd (Alverstoke). His current responsibilities include evaluation of submarine escape and diving systems and has previous hydrodynamic experience.

Ramsey Martin is an engineering consultant to QinetiQ Ltd. Since 1973 his experience includes deep diving operations in support of offshore oil activities, manned submersibles, design and build of saturation diving systems and evaluation of submarine escape systems.

NOMENCLATURE

DISSUB Disabled Submarine
DCI Decompression Illness
HIS Hood Inflation System
RN Royal Navy
SEIE Submarine Escape Immersion Equipment
SEIS Submarine Escape and Immersion Suit
SES Submarine Escape Simulator
SRS Submarine Rescue System
SPAG Submarine sunk Parachute Assistance Group

USN United States Navy

1 INTRODUCTION

On 18 March 1904 HMS A1 failed to surface following a collision with the SS Berwick Castle. This was the first fully commissioned naval submarine to be lost at sea. There were no survivors.

On the 12 August 2000 K141 KURSK of the Russian Federation Navy sank in approximately 110 metres of water following two explosions in the torpedo compartment. This was the most recent naval loss at sea. There were no survivors.

In the span of time covering these two incidents approximately 290 naval submarine losses have occurred due to accident or error resulting in over 7000 fatalities.

This paper considers the systematic integration of physiological research and engineering development to improve the process of escaping from a disabled submarine (DISSUB).

2 ESCAPE OR RESCUE

Should a UK Royal Navy (RN) submarine be unable to surface, the crew can either await rescue by small submersible or they can escape. The escape procedure for each submariner involves a rapid pressurisation to the ambient sea pressure in a specially designed escape tower airlock, followed by buoyant ascent to the surface wearing submarine escape immersion equipment (SEIE). The escaper is not isolated from the pressure associated with his depth in the sea, as he would be if rescued by submersible.



Figure 1 A man wearing Submarine Escape Immersion Equipment (SEIE) exits a submarine via an escape hatch

If the crew can safely wait until a rescue submersible is brought to the scene they may be rescued without the need for escape. However, there remain several environmental factors that are outside of the control of the crew which may force the crew to attempt escape before rescue becomes an option. Within the DISSUB, temperature is likely to drop within the first day close to that of the sea, which may be as low as two to four degrees Celsius; condensation due to the cold will mean that the crew will be in wet conditions even if there has been no flooding. There may have been outbreaks of fire that produce carbon monoxide and other toxic gases. In nuclear submarines there is also the risk of exposure to radiation. Prevailing conditions outside the DISSUB may make successful operation of a rescue submersible impossible. In general, these small submarines are unable to mate with a DISSUB in strong currents or where the DISSUB has come to rest at a large angle from the horizontal. Weather conditions at the surface may also make rescue difficult. Any or a combination of these factors may force the crew to have to escape.

There is a great deal of discussion on the relative merits of Escape as opposed to Rescue. The authors contend that the decision to escape will be forced by circumstances in most DISSUB scenarios.

3 UNDERSTANDING THE PHYSIOLOGY OF SUBMARINE ESCAPE

The limiting physiological factor to the safety of submarine escape is Decompression Illness (DCI), often referred to as “the bends”. When exposed to raised pressure, the body’s tissues begin to absorb the gases being breathed. In the case of an air atmosphere the majority of the absorbed gas is nitrogen. The tissues will continue to absorb these gases until equilibrium is reached between the concentrations of gases in the lungs and the concentrations of gases in the body tissues. The gases are dissolved in the tissues and remain harmless

while in this state. If the body is slowly returned to a lower pressure (decompressed), the excess gas will be carried in the blood in this dissolved state and breathed out via the lungs. However, if the body is rapidly decompressed, the excess gas in the body can come out of solution and form bubbles. DCI is believed to be initiated by the formation of gas bubbles in the body’s tissues. These bubbles can directly disrupt tissue function by their physical presence or indirectly by blocking blood supply to cells or by disturbing blood biochemistry.

The signs and symptoms of DCI are manifold. Their significance can vary from minor irritation, joint pain through severe pain, to disruption of the nervous system (central nervous system (CNS) DCI) resulting in permanent paralysis or other neurological disability and in extreme cases, death.

It is not possible to open a hatch on the DISSUB against the weight of water pressing down on that hatch without first equalising the pressure below the hatch with that of the seawater outside. Therefore, any escape attempt will involve exposure of the crewmen to the pressure of the sea associated with the depth at which the DISSUB has come to rest. Breathing air for any lengthy exposure to the ambient sea pressure at depths of more than a few tens of meters followed by direct ascent to the surface would result in severe DCI and likely death. Therefore, either the exposure to this high pressure must be made sufficiently short such that the amount of inert gas absorbed by the escaper whilst at depth is not great enough to cause DCI, or, if the exposure is to be long, the escaper must be able to stop at various points during the ascent and wait for the absorbed inert gas to leave his body at a safe rate before progressing toward the surface.

4 DEVELOPMENT OF ESCAPE EQUIPMENT

In Britain at the end of WW2 the Admiralty set up a committee under the then Captain Philip Ruck Keene CBE DSO, later Admiral, to review escape from submarines and to investigate alternatives.

Up until the formation of the “Ruck Keene Committee”, traditional escape thinking had been driven by the fear of Decompression Illness (DCI), therefore provisions for escape reflected traditional diving practice. Equipment tended to bear a resemblance to diving apparatus. A typical example was the Davis Submerged Escape Apparatus (DSEA) developed in the UK between the first and second world wars. The apparatus uses oxygen in order to provide the maximum safety with regards to DCI, but this then imposes a severe depth restriction due to the toxic nature of oxygen at increased pressure. The DSEA apparatus was successfully used for escapes from HMS POSEIDON (1931) at a depth of approximately 38 metres (125 ft). For safety in normal diving operations today, the use of pure oxygen is limited to a depth of 9

metres in water and a pressure equivalent to 18 metres inside a decompression chamber.

There are generic similarities between the DSEA, the German Tauchretter, and Russian systems up to 1941. All of these systems relied on pure oxygen as the breathing gas.

The United States Navy (USN) Momsen Lung is similar in principle but is supplied from shipboard oxygen storage rather than having its own independent supply.



Figure 2 DSEA Equipment



Figure 3 Russian Escape Equipment

Since the 1940s the diving apparatus approach has been developed further in other countries such as Russia. The Russian system in figure 3 uses gas mixtures to extend the escape limit to greater depths than can be tolerated breathing pure oxygen. Following the traditional diving technology approach increases the complexity of equipment worn by the escaper. The escaper dons full diving equipment including breathing apparatus and is pressurised at normal diving rates. Russian submarines are equipped with escape towers configured for this slow compression technique. The slow compression technique also offers the possibility of using the torpedo tubes for egress. (Russian submarines have the benefit of being outfitted with 65cm (25.6 inch) torpedo tubes in addition to the 53.3cm (21 inch) universal standard).

At depths greater than 30 metres, depending upon an individual's susceptibility and acclimatisation, the nitrogen in normal breathing air becomes progressively more narcotic resulting in the individual feeling and acting as if he were intoxicated by alcohol. In order to avoid this potentially lethal narcosis at depth, it is necessary to breathe a less narcotic gas, commonly a mixture of helium and oxygen. The relative percentages of these gases in the mixture have to be different for different depths. Therefore, diving safely at these depths is a highly complicated and technical operation. In order to avoid DCI following the slow compression, during which time the escaper's body has absorbed much gas, he must perform several stops on his way to the surface. In order to achieve this he ascends to the surface following a rope with knots to indicate his depth. Depths at which he needs to stop and the duration of the stops to allow gas to safely leave his body must be calculated using complicated tables based on initial escape depth and time at depth. It must be remembered that many of the crew will not be trained divers and for them this operation will be highly taxing, even trained divers occasionally make mistakes when using decompression tables. The crew will be stressed, probably tired, cold and exhausted, therefore this will reduce the probability of effecting a safe escape without making mistakes, any of which could be fatal.

The bulky equipment and complex procedures of the modern Russian escape system are therefore the result of following diving tradition.

The Ruck Keene Committee broke this mould and set in train a path of development based upon limiting the encumbrance on the escaper to a minimalist personal equipment that is practical to use in disaster conditions.

The resulting system developed by the UK Royal Navy (RN) exploits the delays in physiological response by only allowing very short exposure to the ambient sea pressure, thus preventing the body from taking on significant levels of inert gas. The careful scientific exploitation of this physiological window of opportunity permits the development of simple escape equipment.

The original concept as conceived by the Ruck Keene committee was that of a tower holding one man, which could be pressurised rapidly, the man then ascending buoyantly to the surface with his head inside a bubble of gas contained within a hood.



Figure 4 UK RN SEIE Mk10

The escaper's personal equipment comprises an immersion suit to protect from hypothermia on the surface, a lifejacket and a simple hood, open at the bottom, to hold a bubble of gas around the escaper's head. This is the elegant simplicity of the UK RN SEIE concept. The UK RN SEIE Mk 10 also contains a one man liferaft for deployment on surfacing.

UK RN submarines are fitted with one man or two man escape towers or a combination of both. The crew must therefore wait their turn before ascending into the tower one or two men at a time to perform the escape procedure.

The UK RN Escape Tower releases an escaper into the water equipped with the means to complete the ascent and survive for a reasonable period of time on the surface.

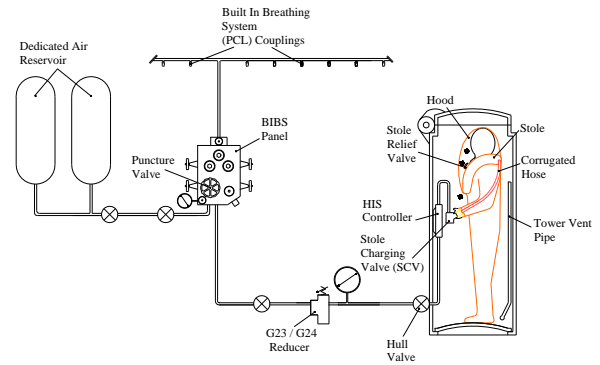


Figure 5 Single Escape Tower Schematic.

The escape tower is integrated into the submarine and also provides man and stores access when the submarine is on the surface alongside. Figure 5 illustrates how the support equipment is all concentrated on the submarine and the escaper does not need any gas cylinders or other diving equipment and is encumbered by no more than the bare essentials that comprise the SEIE.

Each escaper in turn climbs into the tower and the lower hatch is closed. The escaper holds onto a ladder within the tower and plugs his suit into the Hood Inflation System (HIS) via a hose attachment which passes from the stole in the lifejacket to a connector situated at the left wrist of the suit.

Once the stole is charged to a pre-set pressure, air vents into the hood through two pressure relief valves mounted in the stole.

The escape cycle for a tower escape is primarily split into two phases: the flood phase and the compression phase. During the flood phase a valve is opened allowing seawater to flood in. The air in the tower passes down a vent pipe into the escape compartment below. The diameter of the vent pipe should be sufficiently large that the occupant is not subjected to an increase in ambient pressure. Once the water level reaches the top of the vent pipe, a valve is closed and the compression phase starts. During the compression phase the HIS maintains the inflation of the stole in the lifejacket of the suit. The tower occupant is subjected to a rapid elevation in pressure until the internal tower pressure equals that of the ambient seawater, this compression phase takes around twenty seconds and the upper hatch is sprung to open upon pressure equalisation. The escaper is likely to take four seconds to leave the tower and the buoyancy of his escape suit will carry him to the surface at around 2.75 m.s^{-1} . A typical escape pressure profile is shown in figure 6.

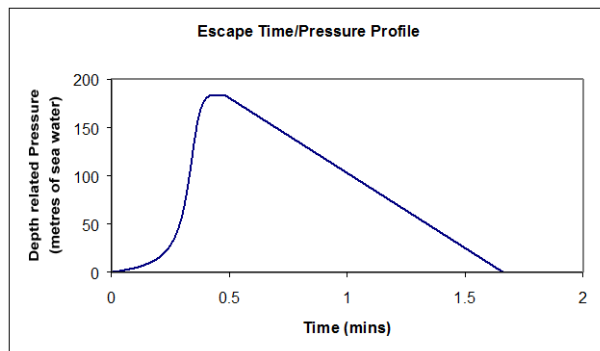


Figure 6 180 metre Escape Profile

In order to give some idea of the extreme rates of pressure change involved in this submarine escape technique it is useful to compare the rates of pressure change experienced in conventional diving. Speaking very generally a diver would be unlikely to descend (compress) at rates greater than 30 metres per minute and unlikely to ascend faster than 15 metres per minute.

The very short duration of exposure to pressure means that slow decompression is not required. However, the compression rate in the tower is so great that the escaper may have difficulty in clearing his ears. Although a nose clip is provided to allow a hands-free Valsalva manoeuvre, for many people the rapidity of compression results in rupture of the eardrums (otitic barotrauma). The pain of this is acute but passes rapidly. Healing and full recovery of hearing is generally attained within weeks.

The greater danger to the escaper is posed by the gas within his lungs. During the ascent the ambient pressure is rapidly decreasing causing the gas in the escapers lungs to expand. The escaper must exhale this expanding gas in order to prevent rupture of the fragile alveolar membrane of the lungs. Pulmonary Barotrauma (PBT) is the general name given to the group of conditions pertaining to lung tissue damage induced by pressure change. In everyday life, minor lung ruptures are not uncommon and are relatively harmless, healing rapidly. However, the consequence of gas trapping during ascent, which can be caused by breath-hold, coughing, sneezing or even hiccupping can lead to pulmonary rupture through over pressure. Fatal conditions can ensue from air filling the cardiac cavities and air entering the pulmonary venous blood from ruptured alveoli, causing arterial gas embolism (AGE). In a trained individual the chances of lung rupture occurring due to inadequate exhalation are low. As part of their training submariners are advised on the dangers of breath holding and the best means of exhalation during ascent. Because of this, the problems of pulmonary barotrauma should be avoided. The experience of PBT in the Royal Navy's Submarine Escape Training Tank (SETT) shows an incidence of pulmonary barotrauma of 7.5 per 10,000 ascents from 30 m. Unfortunately since training began in 1954, six men have died as a result of DCI, probably cerebral arterial gas embolism; of which two were hooded ascents, (3 per

100,000 ascents), the most recent being in 1995. One of the fatalities may have been due to an operational error, the cause of the remainder is not obvious. A large proportion of human PBT cases occur among inexperienced submariners, a review from submarine escape training shows the incidence of PBT among initial trainees is almost double that of requalifiers and fear or panic is thought to be a contributing factor.

The lifejacket stole and the gas within the hood provide the buoyancy for the ascent. During the ascent the gas inside the stole expands and relieves into the hood. The gas in the hood relieves into the water via a simple flap port at the bottom of the hood. The stole effectively acts as a reservoir to provide clean gas to flush through the hood during the ascent. At the surface the relief valves are gagged to maintain the stole as a life jacket buoyancy aid.

The current designs of tower are provided with fixed geometry flooding systems and a HIS that is responsive to pressure and pressurisation rate. The top hatch is driven through a manpowered freewheeling gearbox. On equalisation the hatch can open freely or be provided with supplementary "follow up" assistance. Following each escape it is necessary to close the top hatch, depressurise the tower, drain down and open the bottom hatch to permit the next escaper to gain access. Flood and vent control is normally conducted from inside the submarine. There is also provision of a "last man" facility that provides override control to start the flood and close the vent from within the tower.

The simplicity of the entire escape technique combined with a small degree of training is highly likely to result in a successful escape, even under great stress.

5 SURVIVING ON THE SURFACE

Submariners escaping from a DISSUB on bottom will normally be arriving at the surface with significant time intervals between individuals and will be widely dispersed by the combination of tide and wind.

During wartime an escaper coming to the surface will be considered to be of value to the forces that have sunk his submarine and may be rescued from the water after a very short period of immersion.

During peacetime, provided a submarine can release its indicator buoy, it is anticipated that rescue services would be rapidly deployed to the area to provide support. To this end the UK RN maintains a "Submarine sunk Parachute Assistance Group", (SPAG) that can be deployed very rapidly and air dropped to support the escaping submariners coming to the surface.

Many submarine incidents are the result of a collision with a surface ship. In such an event one could

reasonably expect that rescue and support services would be alerted quickly. The record shows otherwise. From the loss of HMS A1 (1904) to the loss of the PACOCHA (1988) there are a significant number of incidents where the vessel involved in a collision has failed to assess the situation correctly and continued on its way without putting out an alert.

It is therefore necessary to provide for the situation where the escaper will arrive at the surface, at night, in poor weather conditions. Possibly injured and beginning to suffer the onset of DCI. He would then have to survive on his own efforts for a considerable period of time. The problems he may face are:

- Motion sickness
- Hypothermia or heat stroke depending on the latitude.
- Dehydration, possibly exacerbated by sickness.

There are two SEIE surface survival concepts in use at the present time. One, as represented by the UK RN SEIE Mk8, is that the escaper remains in the water solely protected by his suit. The suit's thermal protection is enhanced by a double skin construction that can be inflated with carbon dioxide to provide insulation. The other, as in the case of the UK RN SEIE Mk10, is to provide a one-man liferaft attached to the SEIE. The liferaft is similar to the type provided for aircrew ejecting over the sea. The UK RN has now completely re-equipped with the SEIE Mk10 but the SEIE Mk8 and its generic clones remain in service with other navies.

There are other escape systems in service around the world that are only in the form of a hooded lifejacket or jerkin. These provide no environmental protection other than the lifejacket buoyancy aid function on the surface.

While the initial tendency is to consider cold water survival there are problems associated with survival in tropical waters. Insufficient cooling, exposure to the sun and dehydration can combine to create conditions that limit survival time. There are potentially further problems due to sea life attack but these are secondary to surviving the ascent and environmental conditions.

6 SUBMARINE ESCAPE RESEARCH

In 1987 a successful escape trial was conducted from a RN submarine at a tower depth of 180m (600feet). The escaper was breathing air at a depth that would be considered impossible using conventional diving techniques. A fast compression followed by a rapid, non-stop, free ascent to the surface with no decompression stops, again a method considered impossible when using techniques driven by conventional diving technology.

Prior to these trials, research work conducted at what is now QinetiQ Ltd. (Alverstoke), confirmed that it is

safe to escape at a depth of 180 metres, using fast compression profiles, from a submarine compartment in which the ambient pressure is 1 bar. Since that time further research has increased the fund of knowledge indicating that the physiological limits lie beyond those conditions.

7 SUBMARINE ESCAPE SIMULATOR AND DEEP TRIALS UNIT

The Submarine Escape Simulator (SES) and the Deep Trials Unit (DTU) located at Alverstoke provide a unique research and development facility for QinetiQ Ltd. to service the needs of the submarine community and to develop escape and rescue techniques and equipment. The facilities can be used for both manned and unmanned test purposes.

The DTU can simulate environmental conditions likely to be experienced inside a flooded pressurised DISSUB for testing atmosphere control, breathing apparatus and the depressurisation sequences that would pertain to long term survival and rescue by a submersible.

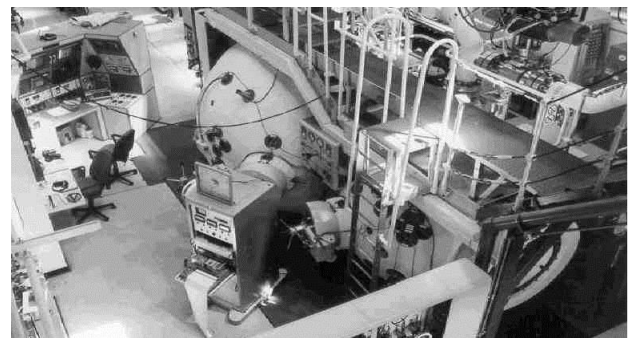


Figure 7 The SES at Alverstoke

The SES is a system designed for dynamic control of rapidly changing pressure. Safety is of prime consideration because the system is subjecting test subjects to physiologically extreme conditions.

The control system is designed and rated for safety critical manned use utilising a triplex computer control system which employs a majority voting logic. The system can simulate the pressurisation / depressurisation profiles of all existing and envisaged escape systems. The SES is a unique facility that is further enhanced by the existence of the DTU on the same site.

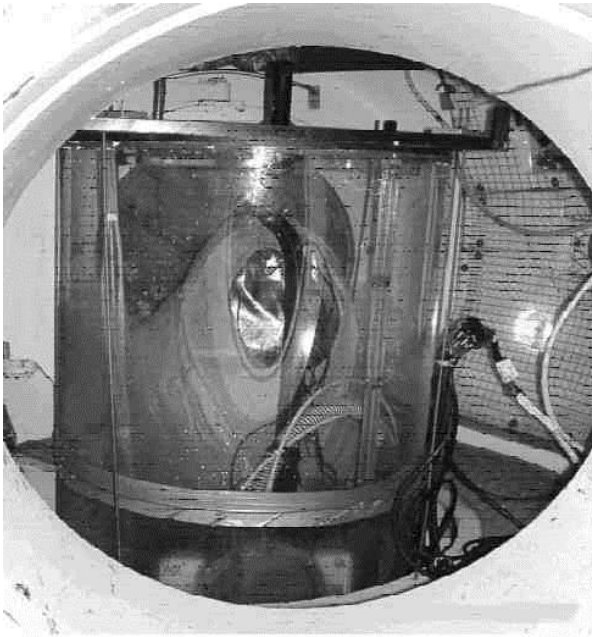


Figure 8 SEIE Mk10 under test in the SES on a mannequin.

The SES facility has been operational since August 1995 and to date has performed in excess of 2000 simulated escape profiles. The trials have ranged from SEIE and HIS equipment testing for both the UK RN, commercial equipment suppliers and other navies, to the use of volunteer submariners from the UK RN, the Royal Australian Navy (RAN), the Swedish Navy and civilian staff of QinetiQ.

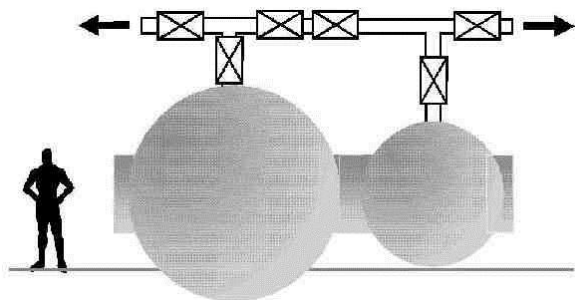


Figure 9 SES Outline

The SES comprises two spheres rated to 150bar with an interconnecting manway. The pressure rating of 150 bar, equivalent to 1490 metres of sea water (msw) means that it has a performance potential stretching beyond the deep diving depth of the majority of naval submarines.

The system can be used for simulating escapes from elevated submarine compartment pressures: test subjects can be exposed to a period at raised pressure and altered atmosphere composition while living in the larger sphere. The subjects transfer into the smaller sphere at the elevated compartment pressure and the interconnecting manway door is closed.

Escape pressurisation / depressurisation profiles are simulated in the smaller sphere. An overview of the process is as follows.

- The larger sphere is precharged with gas.
- The controlled decanting of gas from the larger sphere to the smaller sphere simulates the compression phase of the profile.
- The “on bottom” hold (usually 4 seconds) is simulated by closing off the gas transfer.
- Exhausting the smaller sphere to atmosphere via a substantial silencer simulates the ascent phase.

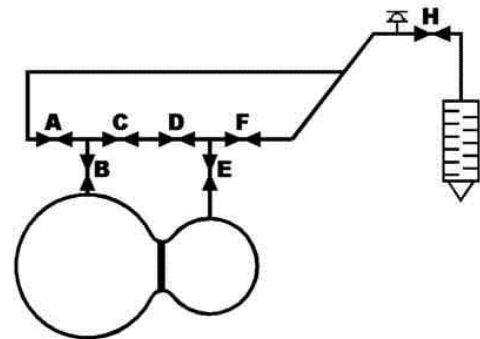


Figure 10 SES schematic

Escape profile simulation involves pressurisation rates that can vary from 0.3 msw s^{-1} in the case of deep diving type technology to rates peaking in excess of 30 msw s^{-1} for the latest developments of the UK RN type technology.

Ascent rates can vary from $<0.3 \text{ msw s}^{-1}$ to $>3.0 \text{ msw s}^{-1}$ with the ability to introduce stops as required

The SES can simulate the compression and ascent profiles of any submarine escape system in use today and has the potential to simulate escapes outside these limits.

8 THE ESCAPE IMPERATIVE

Submarines normally sink because they are damaged. The likelihood of establishing a stable pressure environment in the face of flooding is small. Other than in the most favourable scenarios, the only practical response is to escape immediately.

In order to determine the relative importance of escape as a means of surviving a DISSUB incident we need to look to history and what it can tell us for future planning.

Since the first properly commissioned naval submarine went into service in 1900 there have been many

accidents. Taking the loss of HMS A1 (1904) as the starting point, the history that we are aware of is summarised in table 1:

Submarine Losses		
Enemy Action	1148	80%
Accident / Error	290	20%
Total Losses	1438	100%

Table 1 Submarine Losses

There have been in excess of 7000 fatalities in respect of submarine losses resulting from Accident/Error. The largest single loss of life due to this cause was 18 February 1942 when the French submarine SURCOUF sank with the loss of all 159 crew following a collision with the American freighter THOMSON LYKES. Although the incident occurred during wartime, it was a simple collision with a non-combatant vessel.

During war, irrespective of the cause of the loss, it will not normally be possible to mount large scale rescue operations other than in exceptionally favourable circumstances, such as a loss in enclosed waters close to salvage facilities (e.g. HMS K13, Gareloch, 1917).

The records show that even in wartime when the loss is due to enemy action it is still possible to have survivable conditions conducive to making escapes.

Our figures are based upon full scale fighting submarines and do not include civilian incidents such as the rescue of Pisces III with its two man crew off Southern Ireland in 1973.

It should be noted that the majority of DISSUB incident survivors have abandoned ship while their stricken vessel was still on the surface, this is referred to as "Surface Abandonment." History (table 2) has shown it to be by far the best option if at all practicable but it is still fraught with danger; the rate of survival on the surface is poor. In high latitudes this is mainly due to hypothermia. In the case of the K278 KOMSOMOLETS incident, the reports indicate that only 23 of 64 (36%) evacuees survived. In tropical waters the problem is reversed, heat stroke together with dehydration becomes the major risk.

Escape from DISSUB on Surface		
Scenario	Survivors	Incidents
Surface Abandonment	>4000	Unknown

Table 2 surface abandonment statistics

The figures for submerged escape and rescue, as shown in table 3, relate to a total of 38 incidents, which amount to only 2% of the total submarine losses.

Survival from Sunken DISSUB		
Scenario	Survivors	Incidents
Salvage from bottom	98	5
Assistance to DISSUB	104	3
Submarine Rescue System	33	1
Through Water Escape	>140	29

Table 3 submerged escape and rescue

"Salvage from bottom" covers incidents where either one end or the whole submarine has been raised to the surface by salvage operation intervention.

"Assistance to Submarine" covers external intervention to assist a DISSUB that has managed to present either the bow or stern above water by its own efforts. These figures are not necessarily complete; there is anecdotal material suggesting that this procedure has also been carried out in respect of two Japanese submarines.

"Submarine Rescue System" (SRS). In general, rescue systems can only operate successfully in a narrow range of environmental conditions. So far the only successful non-exercise SRS deployment has been the use of the McCann bell during the USS SQUALUS incident, in which all 33 men surviving the initial event were rescued. However, in the case of the loss of the Turkish submarine DUMLUPINAR, the McCann bell was also used but despite being deployed to the DISSUB more quickly than in the USS SQUALUS incident, the rescue attempt failed and there were no survivors.

"Through Water Escape" covers emerging into the water column both with and without escape equipment. Note that this method of survival has been attempted with some level of success in a high proportion of the sunken DISSUB incidents where there were any survivors. To the best of our knowledge the deepest survivor of a through-water ascent made his escape from approximately 73 metres (240 ft) when U1199 was sunk during the Second World War. Incidents such as the loss of Soviet K429 (1983/84?) are not included in our survivor figures due to unreliability of the details. Our information varies between "no survivors" and anecdotal evidence recently obtained which suggests that as many as 30 - 40 men may have made a through water escape.

When we review the record of through water escape, table 4, the record has been less than one in three getting out of the submarine and reaching the surface alive. Of those making it to the surface it appears that hardly better than one in two has survived until rescue. Once the surface is reached, hypothermia / drowning are major risks unless supported by effective equipment.

Through Water Escapes	
Scenario	Numbers
Number Attempting Through Water Escape	>600
Deaths before/on leaving submarine	>300
Deaths on Surface	>100
Survivors	140

Table 4 through water escape statistics

The presentation of the numbers reflects the uncertainty as to exactly where the deaths occurred. Although the figures look bad it must be remembered that without attempting escape, all would have died.

From the details related above it is apparent that efforts made to increase survival rates of DISSUB incidents would be most profitably aimed at the further development of procedures and equipment to improve chances of survival during surface abandonment, through water escape and survival on the sea surface.

9 WAITING FOR RESCUE – TIME UNDER PRESSURE

Here we take two recent cases, the Peruvian submarine PACOCHA (1988) and the Russian submarine K141 KURSK (2000).

The Peruvian submarine PACOCHA sank in 43 metres (140 ft) and the initial response was to await a McCann rescue. Due to conditions inside the submarine deteriorating at a rate that precluded further waiting, a decision was then made to use escape as the fallback option.

The escape equipment available for use on the PACOCHA was the USN Steinke Hood. This is a hooded lifejacket.



Figure 11 USN Steinke hood.

Apparently some of the escapers chose to keep the hood open and come to the surface with their faces exposed to the water, using the Steinke equipment purely in the lifejacket mode for buoyancy.



Figure 12 USN Steinke hood. Hood unzipped.

The long exposure to elevated pressure during the wait for rescue, in addition to the use of a slow compression escape system, resulted in a high incidence of DCI, in one case fatal, in another resulting in paraplegia.

In the case of the K141 KURSK incident, the response was again to wait for rescue. On 12 August 2000 the KURSK sank in approximately 110 metres of water following two explosions in the fore-ends. The explosions caused failure of the pressure hull and the relatively light 10 bar rated bulkheads between the compartments forward of the reactor bulkhead. Compartments forward of the reactor bulkhead were first subjected to an air blast wave followed by rapid flooding from the hull rupture in the forward compartment.

The forward escape hatch was located in compartment 1, the seat of the explosion. The escape capsule in the fin was accessible from compartment 2 but the bulkhead between compartments 1 and 2 was ruptured. The aft escape hatch located in compartment 9 remained intact and accessible to a number of personnel.

It is reasonable to suppose that conditions physiologically conducive to making an escape never existed in the part of the submarine forward of the reactor bulkheads. Aft of the reactor bulkheads survivable conditions existed for a limited period of time. There was a 10 bar rated bulkhead between compartment 9 and 8, but compartment 9 aft of this bulkhead was flooding, possibly via the shaft seals.

A note written by Capt Lt Dmitri Kolesnikov indicated that 23 men were alive, an addendum indicated conditions were poor. Another note attributed to Capt Lt Rashid Ariapov mentioned increasing pressure.

As previously mentioned, the Russian escape system is based upon slow compression and slow ascent following a traditional diving profile. Escape was written off as being impossible due to “the pressure”. Whether or not that decision was taken in respect of the ambient pressure inside the compartment or the external seawater pressure is difficult to understand from the information available.

It would appear that, when approximately half flooded, the compartment suffered a flash fire, probably due to the potassium superoxide life support system getting wet.

An Illushin IL-38 overflew the area in a search pattern approximately 6 hours after the incident. If escape had been conducted immediately using a Royal Navy system and the Mk10 SEIE some of those 23 men may have been found alive on the surface.

A simple effective escape system that permits rapid escape and promotes surface survivability can make a significant impact on the typical morbidity rates traditionally seen in submarine incidents.

Ideally the DISSUB should be configured to provide an adequate temporary secure refuge that will allow a respite sufficient to mount a viable escape. Only high quality refuge bulkheads could ensure that conditions remained tenable for long enough to await rescue.

10 DEVELOPMENT OF CURRENT AND FUTURE ESCAPE TECHNOLOGIES

There is, of course, a cost implication in the provision of escape and rescue systems. The installation of such equipment also has an impact on the ability of the submarine to perform its primary function as a warship. The current UK RN system is a model for maximising

effectiveness while minimising costs and intrusion upon the submarine. Future escape concepts must also meet these constraints whilst striving for the ideal escape system.

When considering the future of DISSUB escape technologies, it should be recognised that engineering development must go hand in hand with current and future developments in knowledge of the physiology of escape, it is with this intent that the following is presented.

10.1 SURFACE ABANDONMENT

The majority of the world’s ocean floors lie beyond the collapse depth of naval submarines. The only option for development here is to maximise the potential for escape and survival through surface abandonment. The requirements are to maximise the time that the submarine can be held at the surface, possibly through redesign of the ballast tanks, and to minimise the time required to evacuate with adequate survival aids and stores. Provision of multi-man life rafts would enhance chances of survival on the surface.

10.2 PERSONAL LIFE SUPPORT SYSTEMS

The first stage of escape is to reach the point of egress. This involves moving through the submarine and possibly queuing in line. If the atmosphere were contaminated some form of life support system is required. Personal equipment offers greater mobility than systems that are built into the structure and there are several types of such equipment that could be assessed for applicability in the DISSUB scenario.

10.3 SECURE REFUGE

Much has been made of the secure refuge concept. In the case of escape the security is only required for a limited period of time. In the case of waiting for rescue then security must be maintained for many days.

This demands high integrity compartments where submariners can take refuge secure from flooding and continued pressurisation. It should be noted that if security cannot be provided for the purposes of escape then there is no chance of waiting for rescue.

A few rudimentary calculations indicate the severity of the problem. If for example we consider a hypothetical incident in 180metres. The submarine has an escape compartment with a volume of 1000 m³. Let us suppose that flooding elsewhere in the submarine raised the pressure from 1bar to 1.25bar before the transfer of personnel was complete and escape compartment hatches were closed.

If we consider that a flood level of 65% of diameter makes the compartment untenable then the compartment

becomes untenable in 100 hrs with an equivalent hole diameter of 6.5mm. The 1% DCI limit of 1.5 bar for escaping at 180metres may be reached significantly before that. One hundred hours is likely to be an optimistic assessment of the time to mobilise rescue resources and complete the process of rescuing a significant number of men trapped in a large submarine.

In the immediate aftermath of a submarine accident the atmosphere may have become contaminated and the pressure inside compartments may be rising. There are a wide range of short and long term threats to life. The short-term threats are typically combustion products and increased partial pressure of carbon dioxide. The long-term threats are elevated partial pressure of oxygen, loss of thermal balance and dehydration.

It will be necessary to develop improved long-term life support systems to be able to take full advantage of the benefit provided by secure refuges

Development of knowledge of the physiological constraints of escape may determine requirements for prophylactic measures to be carried out prior to making an escape. For example, in some scenarios, breathing raised partial pressures of oxygen prior to escape may increase the chances of survival. Significant measures such as this will require time, which in turn demands some form of temporary secure refuge.

The structure of the secure refuge is the preserve of the hull designer.

10.4 SUBMARINE ESCAPE IMMERSION EQUIPMENT

The SEIE is a multifunctional garment. It provides both the means for escape and survival for up to 24 hours in a single package.

The possibility of the provision of extended survivability would bring a succession of needs including water and food rations which could be included in the SEIE. Since the SEIE is a long term sealed package with a nominal life of 10 years, and water and food are short-term stores with a life of one year, packaging issues would have to be addressed such that short term stores could be replaced without breaching the integrity of the long-term package containing the SEIE and its life raft.

10.5 TOWER ESCAPE

The technology developments for escape should be carried out in an interactive programme where the physiological constraints are defined first. The physiological research will be seeking to identify optimised compression / ascent profiles that minimise the physiological risks of long term damage associated with escape.

The physiologists at QinetiQ (Alverstoke) have now accumulated sufficient experience and data to be confident that the escape limit breathing air can be pushed significantly deeper than 180 metres. Models indicate that with alternative gas mixtures and the right equipment, there is the potential for successful escape from greater depth.

It is possible that altering the compression and ascent rates during tower escape may result in lower levels of DCI and this is also under investigation. If the result of this work is a requirement for changes to these rates, this could necessitate tower and/or SEIE redesign.

Once the physiological requirements are defined to adequate tolerances it becomes possible to define the operating characteristics for an ideal tower escape system. Ergonomic considerations must be addressed fully at this time in order to optimise the operability of the system under adverse conditions. Once the operating characteristics are determined these will form the Basis of Design (BOD) criteria for new Tower Escape systems.

Much of the original concept for escape systems defined by the Ruck Keene committee still hold good today. A slim single man tower with a clean interior is still the ideal so that nothing can snag and so that the escaper should leave the tower irrespective of whether or not he is still conscious. The outfitting inside the tower should be limited to the air supplies and flooding arrangements. The towers can either be welded into the pressure hull or flanged to mate with a larger diameter opening to provide for machinery access.

Modifications to towers could provide multiple simultaneous release of escapers without risk of a collapsed or panicking escaper causing a tower blockage.

Liquid breathing is a concept that has been discussed in diving research for many years. It theoretically has the capability of offering a great depth rating and freedom from decompression problems. Unfortunately it is unlikely to become a practicable option. Therefore, a gas breathing system appears to be the only option for the near term. Inert gas cannot be readily stored chemically. For the foreseeable future, storage as compressed gas appears to be mandatory. Gas systems will require high maximum flow rates to maintain SEIE hood volumes at the high compression rates necessary to minimise the pressure – time exposure.

10.6 CAPSULE ESCAPE

Ideally, in view of the uncertainty of rescue assets being deployed in time, the ability to escape should only be limited by the collapse depth of the submarine pressure hull itself.

The percentage of the world's ocean floor lying between 180 metres and the depth at which a submarine hull collapses are small, but still measurable.

A significant number of Russian Federation Navy submarines and two submarines operated by the Indian Navy are fitted with capsules, these can provide escape from incidents occurring in waters down to the collapse depth of the submarine hull.

Escape capsules are of necessity designed to the same pressure rating as the submarine hull. Collective (i.e. multi-man) capsule escape will limit pressure exposure to the maximum encountered in the submarine during the disaster. Once the capsule surfaces a controlled decompression can be conducted. Thermal balance is unlikely to be a major problem. Once decompression is complete the capsule can be ventilated from the atmosphere with limited power expenditure.

Escape capsules are best designed into the submarine from the outset, a retrofit programme to install an escape capsule would require a major engineering exercise. Conversely the retrofitting of escape towers into existing submarine hulls as the RN did in the late 1960's is a considerably simpler option. The use of a capsule presupposes that it will survive the incident and remain accessible to those surviving the initial incident. Escape capsules are of necessity located on the upper parts of the submarine and therefore vulnerable in the event of collision with surface shipping or hostile fire on the surface. In view of this potential vulnerability, capsules cannot completely replace individual through water escape. The authors therefore envisage two separate requirements. Firstly a retrofit programme based upon escape tower technology to outfit existing submarines and current build programmes. Secondly a fully integrated tower and capsule system for future programmes.

To ensure that a capsule remains accessible it will be necessary to develop the concept of providing a secure refuge compartment within the submarine from which access may be gained.

Individual (i.e. one-man) capsule escape is unlikely to be practical other than in the case of a large submarine with limited manning.

10.7 HYBRID ESCAPE SYSTEMS

The main element in a hybrid escape system would be a flexible pressure vessel in which the escaper would be pressurised to the escape depth as in a tower escape. However, the vessel would then rise to the surface buoyantly whilst maintaining the escaper at a predetermined pressure above the ambient, allowing a slow decompression capability. This concept has the potential to exploit the advantages of the RN system

minimising the decompression requirement and additionally providing a decompression facility for extreme exposures.

The use of currently available flexible pressure vessel technology would present a greatly increased storage overhead when compared with SEIE.

A limited manifestation of the hybrid system would be an enclosed SEIE that could sustain an internal pressure of approximately 0.5 bar above ambient. This would permit a fast ascent followed by an automatic slow bleed decompression from the equivalent of 5 metres once the surface was reached. This would make a significant impact on DCI in the marginal areas of the safe-to-escape curve.

11 CONCLUSION

Other than in the most favourable scenarios, the only practical course of action for the crew of a disabled submarine is to escape immediately. There is no "cure all" solution for surviving a submarine incident, however, surface abandonment, wherever possible, is the preferred option. Efforts made to increase survival rates of DISSUB incidents would be most profitably aimed at the further development of procedures and equipment to improve chances of survival during surface abandonment, through water escape and survival on the sea surface. A simple effective escape system that permits rapid escape and promotes surface survivability can make a significant impact on the typical morbidity rates traditionally seen in submarine incidents. The escape equipment must be simple and require minimal training. Current submarine escape technology has not yet reached the ultimate boundaries of physiology. The UK RN concept is capable of extension to provide a significantly deeper escape capability. In an ideal world, escape would only be limited to the collapse depth of the submarine pressure hull. QinetiQ Ltd is pursuing lines of research and development that will push the boundaries of escape closer to that ideal.

When devising engineering solutions to the problems of DISSUB escape, it is useful for the following statement to be borne in mind:

"It seems essential that a life-saving apparatus must have exceptional qualities if it is not to be superfluous ballast in the restricted space of a submarine."

Bernard Dräger. 1911.

This quotation by one of the foremost pioneers of breathing apparatus is as true today as it was ninety years ago when he was addressing the very problem we are still solving today.

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Personal Discussions

Annex 3.

Blogg SL, Gennser M, Loveman GA, Seddon FM, Thacker JC, White MG.

The effect of breathing hyperoxic gas during simulated submarine escape on venous gas emboli and decompression illness.

Undersea Hyperb Med. 2003 Fall; 30(3):163-74

The effect of breathing hyperoxic gas during simulated submarine escape on venous gas emboli and decompression illness.

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Blogg SL, Gennser M, Loveman GAM, Seddon FM, Thacker JC, White MG. The effect of breathing hyperoxic gas during simulated submarine escape on venous gas emboli and decompression illness. *Undersea Hyperb Med* 2003; 30(3): 163-174 - Raised internal pressure in a distressed submarine rapidly increases the risk of decompression sickness (DCS) following submarine escape. The hypothesis that breathing a hyperoxic gas during escape may reduce the risk of DCS was tested using goats. Shallow air saturation and simulated submarine escape dives were carried out either singularly or in combination (saturation, escape, or saturation followed by escape) using air or 60% / 40% oxygen (O₂) / nitrogen (N₂) mixture as breathing gas during the escapes. Post-surfacing, animals were observed for signs of DCI and O₂ toxicity. Precordial Doppler ultrasound was used to score venous gas emboli (VGE) using the Kisman Masurel (KM) scale. Following escape from 2.5 MPa, the rate at which VGE disappeared in the hyperoxic group (n = 8) was significantly faster (p < 0.05) than the air group (n = 7). One case of pulmonary barotrauma with arterial gas embolism occurred in the air group, but no cases of DCS were observed. After saturation at 0.18 MPa followed by escape from 2.5 MPa, DCS occurred in four of 15 animals in the air group and in two of 16 animals in the hyperoxic group. The rate of disappearance of VGE was significantly faster (p < 0.01) in the hyperoxic group. O₂ toxicity was not discernible in any of the animals.

decompression illness, submarine escape, hyperoxia, oxygen toxicity, saturation, venous gas emboli.

INTRODUCTION

The current submarine tower (alternatively known as lock or trunk) escape method has been shown to be successful at depths down to 180 meters of seawater (msw) (1.9 MPa) from normobaric pressure in the submarine (1). However, it is most likely that escape will have to be made from a disabled submarine (DISSUB) with raised internal pressure (the Pacocha and the Kursk are recent examples). Increasing pressure in a DISSUB rapidly increases the risk of decompression sickness (DCS) (2).

The possibility of using oxygen-enriched gas mixtures to reduce the risk of DCS was suggested by Donald, Davidson, and Shelford (see 1). A few successful escapes (without prior saturation) were carried out with a 34% O₂ / 66% N₂ mixture from 300 feet of seawater (fsw) (1 MPa), using a slow profile that had caused a high incidence of bends in air breathing animals. However, no full scale series comparing air and hyperoxic escape gas was carried out.

During decompression from saturation, an increased decompression rate can be balanced by an increased PO₂ in the inspired gas (3). However, the beneficial effect of increased O₂ is probably less in deeper and shorter dives (4). Vann (5) noted that breathing 100% O₂ from 18 msw (0.28 MPa) to surface reduced decompression time by 40%. Working on this basis, Leitch (6) suggested that 40% O₂ breathed during escape might reduce decompression time by 10%, though the theory remained untested. In addition to the possible benefits of breathing a high PO₂ gas during decompression, there is also a possibility that survivors may be vulnerable to O₂ toxicity. Modelling indicates that most of the N₂ loading in the tissue takes place during the deepest part of the ascent (1, 7), so to be beneficial, the highest concentration of O₂ needs to be present at the start of the escape, consequently increasing the risk of toxicity.

Another potential problem is that high concentrations of O₂ may increase the risk of DCS. It is tempting to think of O₂ purely as a metabolic gas, rather than having the potential to act as an inert gas, like N₂, when supersaturation occurs. In fact, O₂-induced DCS has been reported (8). Recent modelling has factorised the contribution of O₂ as an inert gas and also its capability to alter inert gas kinetics (9) in order to estimate its effect on DCS development. The results showed that elevated levels of O₂ do contribute to the risk of DCS, although to a lesser degree than the equivalent amount of N₂ (9).

The present study compared the effect of breathing hyperoxic gas during submarine escape upon the evolution and time course of venous gas emboli (VGE) in a range of scenarios, including escape without prior hyperbaric saturation and escape following hyperbaric saturation. The subjects were also closely monitored for signs or symptoms of AGE and O₂ toxicity.

MATERIALS AND METHODS

The initial trials reported on here, involving saturation dives (24 hours at depth) or saturation immediately followed by simulated escapes, were executed to determine a submarine 'safe-to-escape' curve for the Royal Navy (RN). Subsequent studies involving hyperoxic breathing gas involved collaboration between the United Kingdom (UK) Defence Evaluation Research Agency (DERA) and the Swedish Defence Research Agency (FOI).

The goat was chosen for this series of studies because it historically has been used as a model for decompression research, and there is an extensive comparative database of goat exposures. The animals were females or castrated males having a mean weight of 45.8 kilograms (kg) \pm 7.7 (range 36 - 64 kg, n = 67). There was no significant difference in weight between experimental groups (Table 1). All trials were conducted according to the regulations of the UK Animals Act (1986). Prior to pressure exposures, all animals were familiarized with the Submarine Escape Simulator (SES), trained to stand in restraints, and wear oro-nasal masks.

Table 1. Summary of subject details, profile protocols and results

Breathing gas (#)	Mass (Kg)	Sat depth (MPa)	Escape depth (MPa)	Compression time (s)	Maximum KM-score (median)	DCS/n
Air (n=20)	48±8.6	0.18	-	-	3	0/20
Air (n=7)	43±8.1	0.10	2.5	24	3	0/7*
Hyperoxic (n=8)	42±7.0	0.10	2.5	24	3	0/8
Hyperoxic (n=16)	46±6.2	0.18	2.5	30	4	2/16
Air (n=15)	47±8.3	0.18	2.5	30	4	4/15

* An eighth animal developed AGE after pulmonary barotrauma and is not included in the statistics.

Saturation period - 24 h

Time at depth during all escapes - 4 s

Ascent time for all escapes - 87 s

Pressure exposures took place within the SES, which consists of two spherical chambers (one of 3 m diameter and one of 2 m) joined via an interconnecting door, with doors to the outside at both ends. The SES allows the rapid pressure changes commensurate with submarine escape to be simulated precisely by transfer of gas from larger to smaller sphere via a computer-controlled valve system. Saturation phases took place in the 3 m sphere, while simulated escapes were conducted in the 2 m sphere. During all saturation phases, the goats were free in the 3 m sphere with free access to water. All food, apart from hay, was withheld for 24 h before the dive, but concentrated pelleted food was available for the first 12 h of the saturation in the 3 m sphere. The animal's behavior could be monitored at all times via an array of video cameras. A 24 h saturation period was used, which is sufficient for all tissues to be saturated in the goat (3, 10). In prior studies using goats (10), it was shown that 0.18 MPa was the final incremental saturation pressure at which no cases of DCS or AGE occurred. Therefore, all saturation phases took place over 24 h at 0.18 MPa. The saturation pressure was maintained to ± 0.5 kilopascals (kPa) by addition of air, while carbon dioxide (CO₂) was measured by infrared spectroscopy (ADC) and kept below 0.5 kPa. O₂ levels were measured with an analyser (Servomex) and maintained at 21 kPa \pm 0.3 kPa by an automatic injection system (Analox). The chamber atmosphere was scrubbed by an external life support system containing activated charcoal, silica gel and soda lime to remove organic gases and excess water vapor. Simulated submarine escapes were made from 2.5 MPa, based upon previous experience (1, 10). At 2.5 MPa, it was expected that VGE would evolve, but that life-threatening DCS would not occur.

A computer decompression model predicted that 60% O₂ was the lowest concentration to allow safe ascent from 250 msw (2.6 MPa) after saturation at 10 msw (0.2 MPa) for 24 h (11). Therefore a mixture of 60% O₂ and 40% N₂ was used as breathing gas during the escape phases.

Prior to compression control Doppler ultrasound measurements were made using the Kisman Masurel (KM) scoring system (12) and the audio output recorded onto digital audiotapes (DAT) using DAT recorders (Sony). Continuity of measurement was maintained throughout the studies by using the same Doppler operators. Any peculiarities in an individual goat's gait were noted so that limb 'bends' (joint DCS) could be differentiated from normal posture or movement.

SATURATION PROTOCOL

0.18 MPa saturation

Goats ($n = 20$) were placed in the chamber, the doors secured, the chamber was pressurised to 0.18 MPa at a rate of 0.05 MPa per min. After 24 h, the chamber was brought to the surface at a rate of 0.05 MPa/s and the animals were moved to a holding pen where they were observed closely for 2 h. Doppler recordings were taken immediately on surfacing, and at 15 min, 30 min, 1 h, 1.5 h and 2 h post surfacing, then again at every hour until two successive measurements detected no VGE or eight hours had passed.

ESCAPE PROTOCOL

2.5 MPa escape on air or hyperoxic gas

Pairs of goats were placed in restraints in the 2 m sphere and oro-nasal masks were placed over their snouts and secured behind their heads. One mask had a sample line inserted near the nostrils that lead to a mass spectrometer outside the chamber so the breathing gases could be monitored. Both the air control ($n = 8$) and hyperoxic ($n = 8$) groups wore masks to eliminate differences caused solely by the mask. Breathing gas was supplied to the masks via the hood inflation system (HIS). The HIS (which provides breathing air and buoyancy in the escape suit) in SES replicates that of UK submarines. Once the animals were settled in the restraints, the chamber doors were sealed and the 3 m sphere was compressed to the backing pressure necessary to complete the 2.5 MPa escape profile. During this period of around 30 min, the 2 m sphere remained at atmospheric pressure with the animals breathing air. Once the backing pressure was reached, in the case of the hyperoxic group only, the HIS gas supply was switched to a mixture of 60% O₂ / 40% N₂ one to two minutes before the compression began. Gas from the 3 m sphere was then rapidly transferred to the 2m sphere, effecting a compression to 2.5 MPa in 24 s. Following a short hold at depth (4 s bottom-time), the 2 m sphere was decompressed to surface at a rate of 2.75 meters of seawater/second (msw/s) (0.0275 MPa) and breathing gas switched back to air (Figure 1). The remaining backing gas was emptied from the 2 m sphere and the goats taken from the 2 m sphere into holding restraints. They were held in restraints for 30 min., during which time Doppler recordings were made every five minutes. Expired CO₂ and O₂ were monitored intermittently and recorded using a sample line connected to an oro-nasal mask and a capnograph (Datex-Ohmeda). At the end of this period, the goats were placed in an observation pen and Doppler monitoring continued as described above.

SATURATION + ESCAPE PROTOCOLS

AIR - 0.18 MPa saturation followed by 2.5 MPa escape on air

Goats ($n = 15$) were introduced to the chamber. Following 24h saturation, two attendants 'locked down' to 0.18 MPa in the 2 m sphere and transferred the goats from the 3 m sphere into holding restraints within the 2 m sphere via the interconnecting door. The attendants then moved into the 3 m sphere, locked the middle door and were brought back to surface. The subjects remained in the 2 m sphere for around 30 min. before the escape, while the 3 m sphere was

charged with gas to perform the 2.5 MPa escape profile. The escape involved a computer controlled rapid compression to 2.5 MPa over 30 s, followed by a short hold at depth (4 s) then decompression to surface at a rate of 2.75 msw/s (0.0275 MPa) (Figure 1). Once at surface, the goats were removed from the restraints and transferred into an observation pen for 2 h and monitored for any signs of DCS or O₂ toxicity. Precordial Doppler measurements were made using the same schedule as in the saturation protocol.

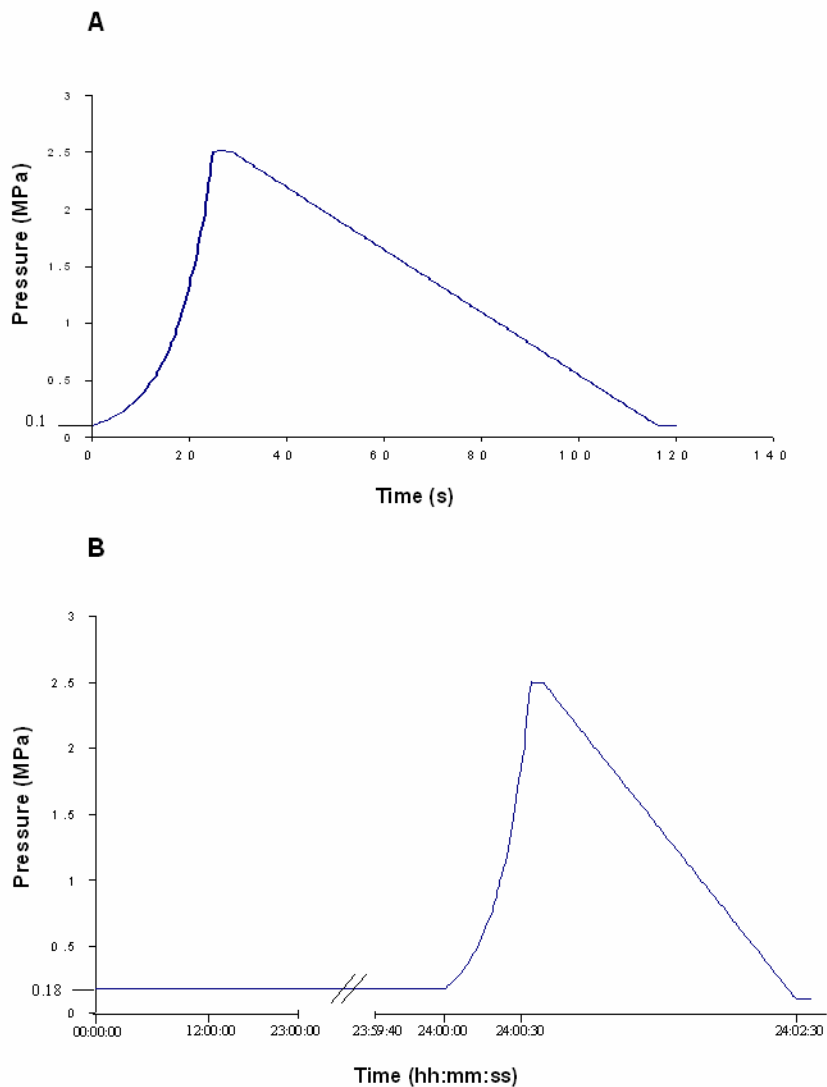


Figure 1. Plot A shows the computer generated profile used for escape only protocol (compression time 24 s), while plot B describes 24 h saturation at 0.18 MPa followed by escape (compression time 30 s). Note that in B, the x-axis (time scale) is interrupted to accommodate the entire dive period.

HYPEROXIC GAS- 0.18 MPa saturation followed by 2.5 MPa escape on hyperoxic gas

This trial followed the protocol for escape on air, as described in the preceding paragraph. However, once the animals ($n = 16$) were settled into the restraints in the 2 m sphere following post-saturation transfer, oro-nasal masks were fitted to deliver hyperoxic breathing gas during the escape phase. Again, a sample line was attached in order to verify that the animals breathed gas during escape of the correct composition (60% O₂/ 40% N₂). The escape profile and subsequent protocol was performed as described for saturation and escape with air.

STATISTICS

Mann Whitney U tests were employed for the analysis of KM Doppler scores. Further information on statistical testing is provided in the results section.

RESULTS

A summary of results is provided in Table 1.

SATURATION - 0.18 MPa

Of the 20 goats subjected to this dive profile, none showed any signs or symptoms of DCI post-surfacing. However, VGE were detected on first measurement in every animal. At this point (15 minutes post-surfacing) the lowest KM score was 1-, the median was 2 and the maximum 4-, spanning almost the full range of the KM scale (12). Figure 2 shows the median Doppler scores for each time point up to 8 h post-dive. The median onset time to maximum Doppler score was 60 minutes. The median values were calculated and plotted by converting the KM scores to a numerical scale, where a "+" value added 0.33 and a "-" value subtracted 0.33.

ESCAPE - 2.5 MPa escape on air or hyperoxic gas

Eight goats initially entered the 2.5 MPa escape trial on air. However on bringing one pair to surface, one animal was found to have suffered from a serious barotrauma (cerebral air embolism) and was immediately euthanised. Of the remaining seven, none showed any signs or symptoms of DCS or barotrauma. All showed normal ventilatory patterns and respiratory gas exchange. At 5 minutes post-surfacing, the median Doppler score was 3 (see Figure 2 and Table 1), which was also the maximum Doppler score noted for this dive series. At 4 hours post-surfacing, no precordial VGE were detectable by Doppler ultrasound.

Eight goats were also used for the 2.5 MPa escapes using hyperoxic breathing gas. All of these animals completed the escapes and did not show any signs of O₂ toxicity during the dives. On surfacing, none of the goats showed any signs or symptoms of DCI, or had respiratory problems. The median Doppler score of 3 was reached at 5 min., as was the maximum Doppler score (see Figure 2 and Table 1). However, unlike the air group, bubble evolution had ceased in all of the animals by 60 min. This rapid cessation, when compared with that of the air group, is shown in Figure 2.

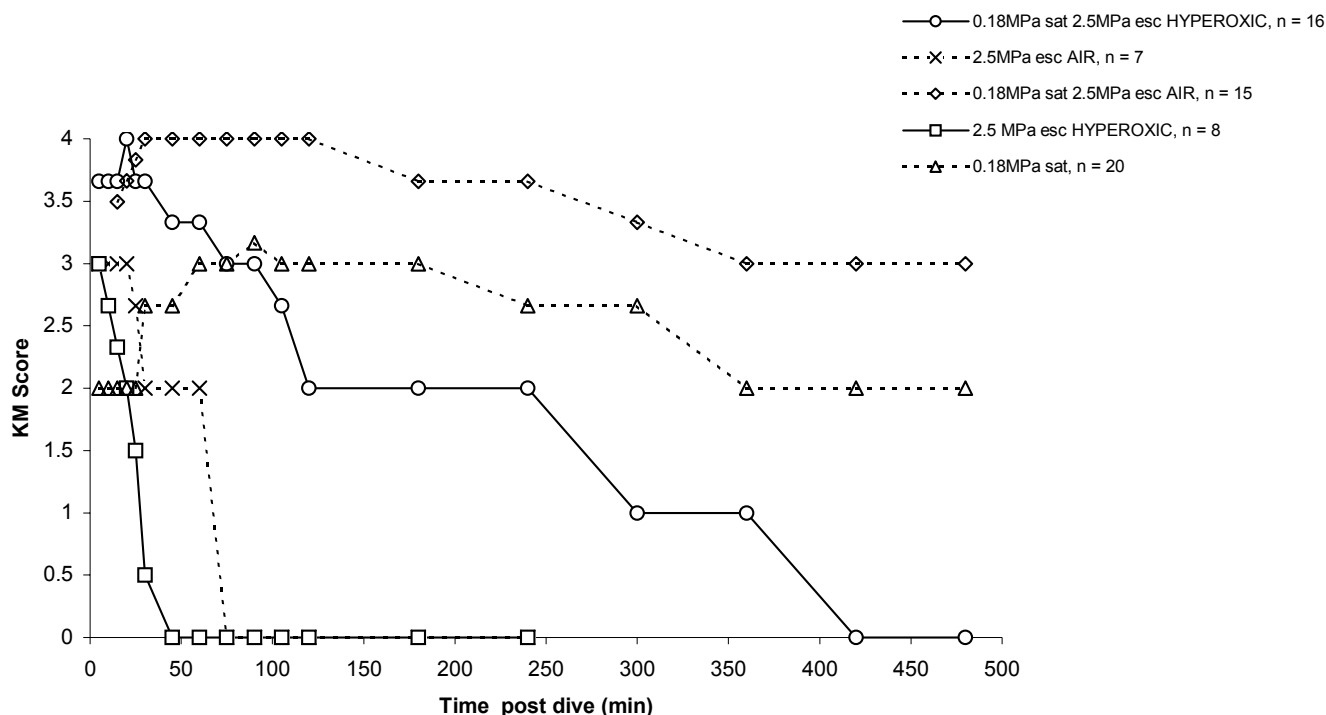


Figure 2. Time course of post-dive detectable precordial venous gas emboli (VGE) for each dive profile. Values are converted (see Table 2) median Kisman Masurel (KM) Doppler scores.

Sat = saturation

Esc = escape

HYPEROXIC = group breathing 60% / 40% O₂/N₂ during escape

AIR = group breathing air during escape profile

Dotted line denotes entire dive conducted only on air

Solid line denotes escape profiles conducted using hyperoxic HIS gas

To describe more fully the relationship between bubble cessation and the type of gas breathed, Figure 3 shows a box and whisker percentile plot describing the range of KM scores for each time point for both the air and hyperoxic groups. Although a good deal of overlap occurred in the magnitude of KM scores in the early stages post-escape, it can be seen that precordial VGE evolution and the range of KM scores fell in the hyperoxic breathing subjects much sooner than in the air group.

A modified Mann Whitney U test was utilized to determine any significant difference between the air and hyperoxic groups, in terms of disappearance of VGE. Tests were performed across the time period from which animals in the hyperoxic group had started to score KM zero (no precordial bubbles found), to the point at which all animals in this group had ceased to bubble and had zero scores. Therefore, paired data at four points, 25, 30, 45 and 60 minutes post surfacing, were tested. Consequently, the significance level of the test was reduced from 0.05 to $p < 0.0125$ ($0.05/4$) to compensate for repeated testing. Data of the 45 and 60 minutes time points showed that $p < 0.01$, therefore from 45 minutes onwards, the amount of circulating bubbles was significantly lower in the group of animals that had been breathing hyperoxic gas during the

escape, than in the air breathing group. The median time for all VGE to disappear was significantly shorter in the hyperoxic group ($p < 0.05$).

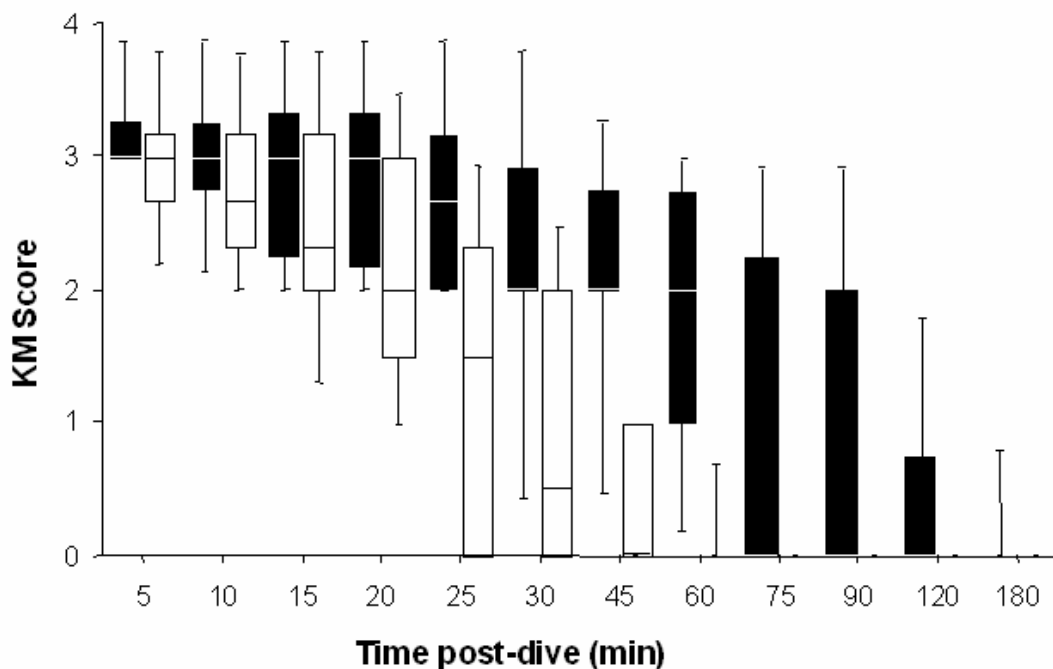


Figure 3. Box and whisker percentile plot comparing the range of precordial KM Doppler scores against time for both the hyperoxic and air groups following 2.5 MPa simulated escape.

Black bars denote group breathing air during the escape
 Open bars denote group breathing 60% / 40% O₂/N₂ during escape
 Boxes show the extent of the 25th to 75th percentile
 Whiskers show the extent of the 10th to 90th percentile
 Black or white lines within the box denote the median values

SATURATION + ESCAPE

0.18 MPa saturation followed by 2.5 MPa escape on air or hyperoxic gas

15 animals were subjected to 24 h at 0.18 MPa (8msw) followed by escape from 2.5 MPa while breathing air. Four of these suffered from DCS after return to surface. One case of central nervous system (CNS) DCS occurred, with the symptoms (spinal involvement) presenting almost immediately on surfacing (5 min.). The remaining three cases were single limb DCS; one presented at 1 hour post-surfacing (right fore-leg pain), the second at 1h 20 min. post surfacing (left hind-leg) and the third at 1h 25 min. post surfacing (right hind-leg). All four animals were treated for DCS. The remaining 11 animals showed no signs or symptoms of DCI.

At 15 minutes post-surfacing (the earliest time point measured in this section of the study), the median Doppler score was 3+ (see Figure 2), ranging from 3+ to 4. The circulating VGE then increased to a median KM of 4, which was maintained for the next 90 minutes. At 8 h post surfacing, all of the animals were still producing precordial bubbles and the median KM Doppler score at this time was 3. The full range of KM scores for each time point can be seen in Figure 4.

Sixteen animals entered the study of 24 h air saturation followed by escape using hyperoxic breathing gas. Of these, two suffered from DCS. One animal suffered from severe CNS DCS on reaching the surface and was immediately euthanised. The second case was also CNS DCS (staggering and loss of co-ordination) and presented at 17 minutes post surfacing. None of the other animals showed any signs or symptoms of DCI throughout the 8 h observation period and their respiratory signs were normal. At five min. post-surfacing the median Doppler score was 4 -, and then peaked at 20 min. post-surfacing at KM 4. However, this peak was only maintained for five min.; the Doppler scores then started to decrease gradually. At 4 h post-surfacing, a KM score of zero was recorded in one animal and by 8 h, all but three goats had a score of zero. Figure 4 shows the rate of decline in terms of Doppler scores for the hyperoxic group in comparison to that of the air group, who, as noted previously, retained high KM scores right through to 8 h.

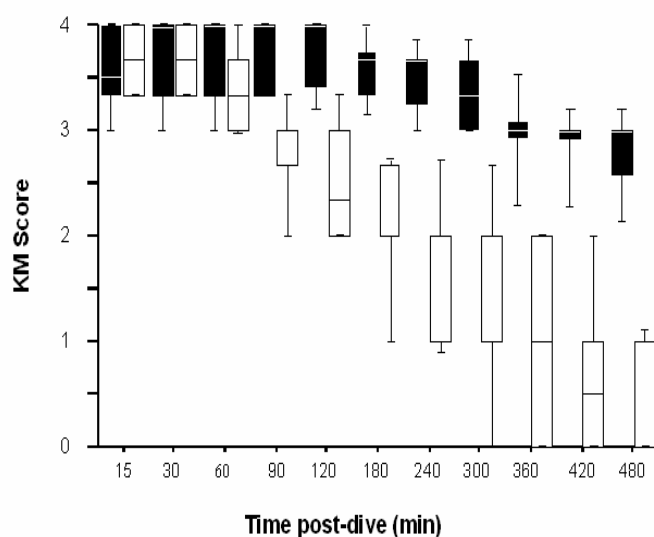


Figure 4. Box and whisker percentile plot comparing the range of precordial KM Doppler scores against time for both the hyperoxic and air groups following 0.18 MPa saturation and 2.5 MPa simulated escape. Black bars denote group breathing air during the escape. Open bars denote group breathing 60% / 40% oxygen/nitrogen during the escape. Boxes show the extent of the 25th to 75th percentile. Whiskers show the extent of the 10th to 90th percentile. Black or white lines within the box denote the median values.

Again, a modified Mann Whitney U test was used at five time points (240, 300, 360, 420 and 480 min.) over which time this hyperoxic group's KM scores reached zero. The significance level of the test was reduced to 0.01 (0.05/5). At every point tested, $p \leq 0.01$, showing that the rate at which the Doppler scores of the hyperoxic group fell was significantly more rapid than that of the air group.

DISCUSSION

VENOUS GAS EMBOLI (VGE) DOPPLER SCORES

All protocols involving simulated submarine escapes promoted large numbers of Doppler detectable VGE. The maximum bubble scores appeared only a short time after surfacing, and in some cases the maximum may have occurred before the first Doppler measurements could be made. It is expected that maximum bubble evolution will occur very shortly after surfacing, since this type of dive profile (rapid ascent) targets the fast tissues (1,7). Therefore, the onset of bubbling may be expected earlier than in saturation dives, as seen in Figure 2, on comparison of the curves for 0.18 MPa saturation and the 2.5 MPa escapes.

There was no discernable difference in the early bubble scores between the groups breathing air or 60% O₂ during submarine escape. This is not surprising, as the total inspired gas load would be similar in both groups, as described below.

As O₂ is metabolized and the more soluble gas CO₂ is produced, the sum of the venous partial pressures of these metabolic gases is less than that on the arterial side, forming the 'oxygen window' (12). Thus a higher oxygen partial pressure will theoretically allow more N₂ to be dissolved and transported in the tissues and venous blood without bubble formation. However, when the PO₂ exceeds the amount of O₂ that the tissues can metabolize, venous PO₂ will start to increase. The excess O₂ will then be able to act as an inert gas and contribute to the formation of bubbles (13), though to a lesser degree than the equivalent amount of N₂ (9). The actual PO₂ when this occurs depends on blood flow and metabolic rate of the tissue in question, but very high O₂ partial pressures during the submarine escapes will undoubtedly exceed the metabolic requirements of even the fastest tissues.

As the amount of gas dissolved in the tissues will therefore be similar in both the hyperoxic and air groups, the initial bubbling will also be similar. However the time to resolution of bubbles was much quicker in the group breathing hyperoxic gas (Figure 2). It is assumed that bubbles formed after air dives mostly contain nitrogen, but in the hyperoxic groups, bubbles appearing immediately after ascents will contain a high ratio of O₂ to N₂. While N₂ in bubbles can only be transported out of tissues via diffusion, O₂ may be consumed in the tissue as time progresses at surface. This will increase the PO₂ gradient between the inside and the outside of the bubbles and accelerate its removal, while also increasing the PN₂ in the bubble. Thus the N₂ diffusion gradient will be increased, and so the combination of these two mechanisms should allow bubbles to resolve more rapidly, hence the swifter time to resolution in the hyperoxic group. A reduction in the overall bubbling period will reduce the risk of DCS (14). Therefore breathing a hyperoxic gas during submarine escape could be of benefit in this respect.

DECOMPRESSION ILLNESS

Pulmonary barotrauma with arterial gas embolisation (AGE) is an ever-present risk during submarine escape. Goats usually exhale spontaneously during the ascents (1), however, on occasion, they succumb to AGE. Clinically it is difficult to differentiate between severe neurological DCS or AGE, even after autopsy. In the present study all sudden deaths or cases with CNS symptoms were considered to be DCS if there were no clear signs of pulmonary barotrauma, i.e. rapid onset of symptoms on surfacing (< 20 min.), oral/nasal bloody froth, and/or post mortem findings. Only one case, occurring after submarine escape from 2.5 MPa in the air group, could be clearly classified as barotrauma / AGE (Table 1).

Two cases of CNS DCS occurred after saturation followed by submarine escape with hyperoxic gas, and another occurred after the same dive profile but using air as the escape gas. Thus, no difference in the incidence of CNS DCS between these groups was seen. As CNS DCS is thought to be linked to the initial bubble load, this was in keeping with the fact that there was no difference in the initial bubble scores between the groups.

The saturation and escape on air profile also produced three cases of limb DCS. The symptoms appeared 60 to 120 min. after the animals had reached surface. However, no limb DCS, or any other symptoms were observed in the hyperoxic group past 20 min. post-surfacing. The probability for such a difference to occur between these two groups was calculated using Fischer's exact test ($p = 0.11$). Although not statistically significant, it does indicate a trend toward reduced occurrence of, or protection against late DCS when breathing hyperoxic gas

during the escape. Concurrently, the limb DCS in the air group appeared during a period when their bubble scores were significantly higher than those of the hyperoxic group.

Late DCS usually manifests as limb pain, which although uncomfortable and possibly debilitating, is not as potentially damaging as the early onset CNS DCS. Therefore, although the administration of a hyperoxic gas during submarine escape will reduce the overall bubble load, importantly, it does not appear to reduce the risk of CNS DCS developing. Further experimental work should be carried out to determine how to reduce the initial bubble load.

OXYGEN TOXICITY

Pure O₂ at increased pressure is a potent convulsive agent, producing tonic-clonic convulsions after a relatively short exposure (15). O₂ convulsions may be fatal if the upper airways are blocked during a submarine escape ascent, while convulsions at the surface increase the risk of drowning. Therefore, it is important that the use of O₂ to decrease the risk of DCI is balanced against the risk of inducing acute O₂ toxicity. In ordinary diving operations the maximum inspired PO₂ is generally limited to between 140 and 200 kPa to avoid O₂ convulsions. However, there is a minimum latency period before the onset of oxygen convulsions, regardless of the oxygen partial pressure (15, 16, 17, 18). Since the minimum latency to O₂ convulsions is four minutes, even at O₂ pressures as high as 30 ata (18), the rapid course of submarine escape would protect against acute O₂ toxicity.

Appositely, the goats in the present study were exposed to a maximum inspired PO₂ of 1500 kPa (15 ata) for 4 s. The inspired PO₂ was above 140 kPa (the lower limit for O₂ convulsions (16)), for less than 100 s. No signs of acute O₂ toxicity, such as increased skittishness, myoclonic jerks or overt convulsions were observed in any of the goats. Therefore, it is hoped that humans may use this hyperoxic gas protocol without risk of O₂ toxicity, although it must be remembered that goats were tested here.

ACKNOWLEDGEMENTS

We thank the chamber staff and animal handlers at the Defence Evaluation Research Agency/QinetiQ. Special thanks to Mark English and Stan Stanley for their technical expertise.

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Annex 4.

Loveman, G.A.M. Jurd K.M. Thacker, J.C. Stansfield, M.R. & Seddon, F.M.

Iso-risk curves for escape from saturation in a distressed submarine.

Proceedings of Humans in Submarines, Editor: H. Ornhagen, Stockholm, 2004

ISO-RISK CURVES FOR ESCAPE FROM SATURATION IN A DISTRESSED SUBMARINE

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BACKGROUND:

Decompression Sickness (DCS) is a major limiting physiological factor to the safety of submarine escape. If a Distressed Submarine (DISSUB) has been subjected to flooding or escape of high-pressure air, the ambient pressure within the submarine will be raised. Thus, in addition to the pressure of the sea that a survivor will be exposed to while attempting an escape, the escapee may already have been subjected to a raised ambient pressure for some time prior to making his escape. The effect of the combination of these pressure exposures and the duration of the exposures must be considered if the survivors are to make a safe escape. Current advice [1] with regard to the combination of DISSUB internal pressure and safe escape depth can be summarised by a curve as shown in Figure 1. This curve is generally referred to as the 'safe to escape curve'. Performing escape from any pressure/depth combination defined by a point within the area of the curve is regarded as safe.

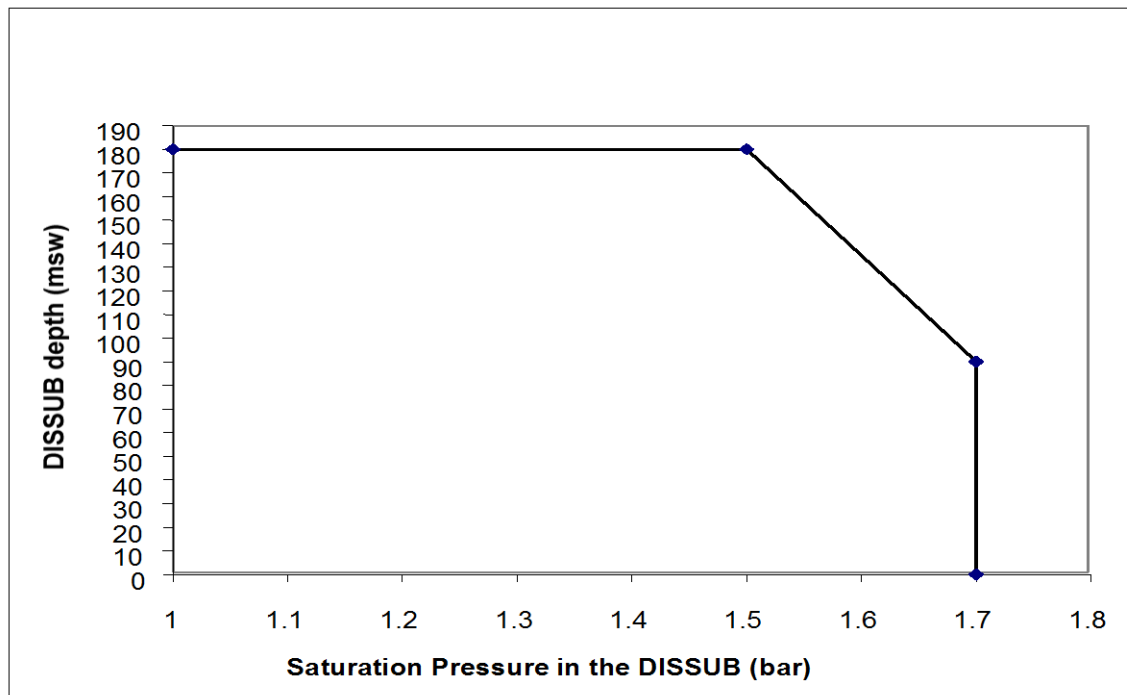


Figure 1. The currently advised safe to escape curve.

The current curve has several limitations. It is based on limited data; the use of the word 'safe' implies no risk of DCS to the escapee; definition of a simple acceptable 'safe' risk level for DCS is unlikely to take into account the wide range of possible symptoms and pathologies and is therefore likely to be misleading; the assumption that safe and unsafe regions can be clearly demarcated by a single curve is not logically justifiable and the

crew are assumed to be saturated at the DISSUB escape compartment internal pressure. The curve is therefore overly conservative in the estimation of safe escape depth for escape where the crew has not been exposed to raised pressure for long enough to become saturated with inert gas.

A model for prediction of risk of DCS has been developed at the Naval Medical Research Centre (NMRC) and calibrated against a dataset of 2383 experimental manned exposures [2]. This semi-empirical model simulates uptake and elimination of inert gas by exponential kinetics in a set of parallel body tissue compartments. Risk of DCS is assumed to accumulate with the existence of an inert gas burden present in any tissues supersaturated above a threshold tension. The gas burden may be due entirely to dissolved gas present above the threshold level, or to dissolved gas and a free gas phase, the existence of which is simulated through the switching of tissue gas elimination from exponential to linear kinetics. This model has been shown to provide useful estimates of DCS probability for a range of exposure data. Models of this type are generally referred to as 'linear-exponential' (LE), a term derived from the manner in which the models describe gas kinetics within the body.

A version of this type of model (named 'USN93'), calibrated against a dataset of 3322 experimental manned exposures, including 58 submarine escape profiles, has already been employed with some success to predict risk of DCS for submarine escape [3].

Thalman *et al.* [2] describe several formulations of LE model, one of which, their 'LE1(base)' model has been reproduced and recalibrated for the purposes of calculating the iso-risk escape curves presented here.

METHODS:

A LE model was coded and its parameters calibrated against the NMRC dataset used to produce the LE1(base) model. The parameters of the LE1(base) model were then recalibrated against a larger data set including both the NMRC dataset and additional data from 290 manned and 568 animal submarine escape exposures simulated in the QinetiQ Submarine Escape Simulator (SES) - both described elsewhere in this symposium. The recalibrated model will be referred to as LE1(ma4). Predictions with the LE1(base) and LE1(ma4) models for direct ascent from saturation exposures were compared with a Hill equation dose-response fit made by Lillo *et al* [4] to a set of combined human, pig and rat data. Figure 2 shows that the slope of the Hill dose-response curve is steeper than that of the LE1(ma4) model. It was decided that inclusion of the Lillo model in the areas of the iso-risk escape curves where it is valid would prevent under-prediction of DCS risk in the final model. LE1(ma4) was therefore combined with the Hill multi-species dose-response curve [4] and the combined model used to produce a set of iso-risk escape curves for submarine escape. The combined model will be referred to as LE1(ma4)H. The 95% confidence regions for the iso-risk escape curves produced with LE1(ma4)H were estimated by the method of propagation of errors.

For prediction of the iso-risk curves, the tower escape pressure profile is assumed to follow the shape of that experienced in an idealised submarine escape tower (pressure doubling every four seconds). The shape of the pressurisation curve is forced to fit the mean required pressurisation time as defined by the Acceptance Curve [5] employed in tower function trials (often referred to as the 'boot curve'). For escape depths less than 10

msw the pressurisation time is taken to be equal to that for 10 msw. For escape depths greater than 220 msw the pressurisation time is taken to be equal to that for 220 msw.

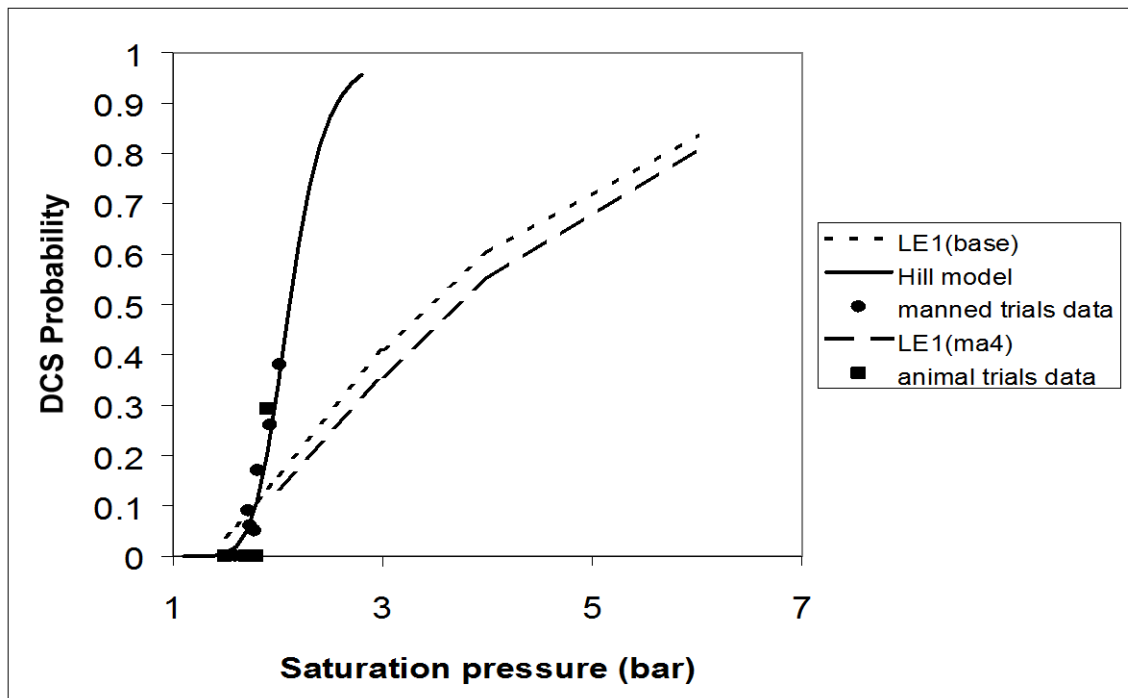


Figure 2. Dose-response curve; decompression risk for saturation exposures.

RESULTS:

In Figure 3, the estimated confidence regions (95%) are shown for the 1%, 5%, 10% and 20% iso-risk escape curves. If the 15 % curve were shown it would mostly lie within the confidence region of the 10% curve, indicating the limits of the accuracy of the model. This does not indicate that the model's prediction of 15% is of no worth, but that the uncertainty in the prediction of the model at this risk level and above is appreciable. Several of the iso-risk escape curves display steps or 'discontinuities'. These steps are due to the structure of the LE model and the method by which risk of DCS is only accumulated above certain thresholds determined in the optimisation of the model parameters. Note that discontinuities in the curves are carried across to the confidence regions. This is due to the manner in which the regions are estimated.

Figure 4 indicates more clearly the predictions of the LE1(ma4)H model in terms of the shape and position of the iso-risk escape curves. The curves are shown at 5% increments in DCS risk (other than the 1% and 5% curves). The smoothed curves in Figure 4 are slightly conservative in some regions with respect to the unsmoothed curves of Figure 3. As figure 4 shows, the model can be used to produce iso-risk escape curves to any required precision, but these curves must be interpreted in the context of the confidence intervals given in Figure 3.

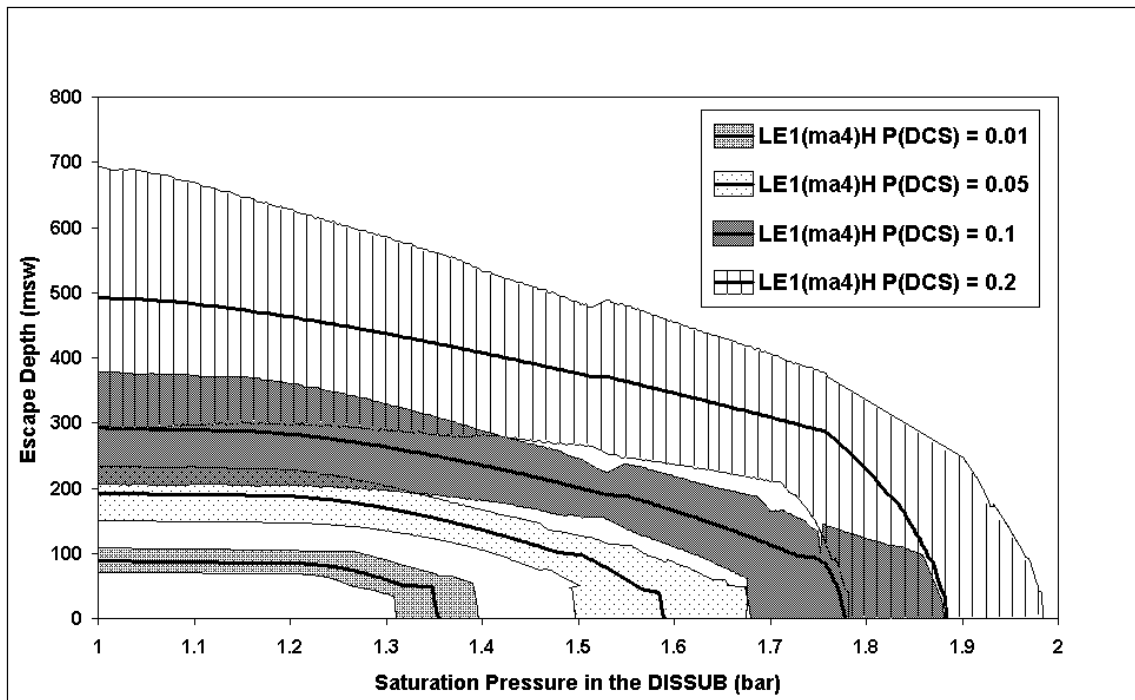


Figure 3: Iso-risk escape curves and 95% confidence regions for LE1(ma4)H

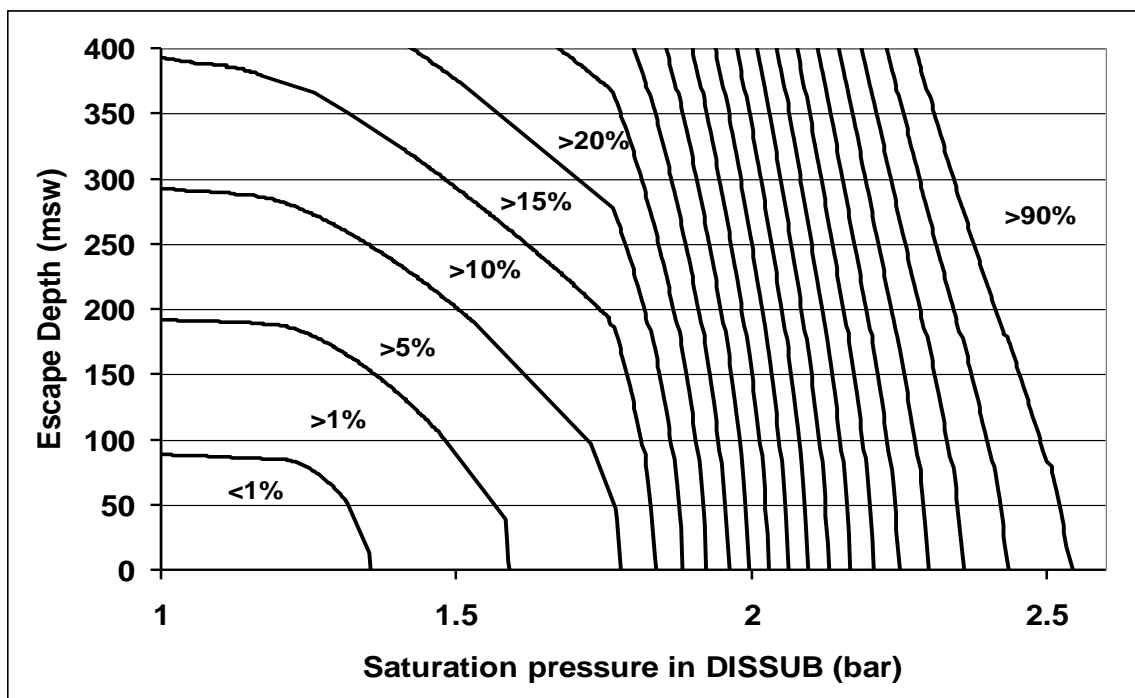


Figure 4. LE1(ma4)H predicts iso-risk escape curves, 5% increments in DCS risk

DISCUSSION:

The models presented here display limitations in terms of their inability to satisfactorily predict the observed level of DCS risk for all trials, their limited accuracy and the likelihood of poor prediction in extrapolation. In spite of these limitations, the curves produced with the LE1(ma4)H model represent the best estimates of DCS risk for submarine escape that can be produced with our current level of knowledge.

For the work presented here, no attempt has been made to apply inter-species scaling between goat and man to the parameters of the model. Including animal data in the calibration of a predictive model for DCS in man without any form of scaling makes the assumption that the animal will respond in the same way as man. That is, the two species have been assumed to have the same pressure-exposure (dose) - response curve.

It is generally thought that DCS events in animal models may be missed, since minor symptoms of DCS will not present as signs noticeable to an observer. For example, acute yet functionally minor symptoms such as slightly altered vision, which may reflect damage to the Central Nervous System (CNS), would not be apparent as signs. This would result in the dose-response curve for a goat being shifted to the right of that for man. However, the limited data for the goat saturation dose-response curve shows good agreement with that for man (see Figure 2). Ball *et al.* [6] have also shown good agreement in DCS risk between a large animal model (sheep) and man.

Although this is evidence for the applicability of animal DCS data to man, it clearly is not proof that animal data can be used in place of data from human trials. However, the inclusion of animal data does increase our assurance in the model for areas where no human data exists.

Addition of the SES manned trials and animal data to the model caused the saturation dose-response curve to be moved slightly to right. However, in LE1(ma4)H, the saturation dose-response is almost entirely predicted by the multi-species Hill model, which is also based on both man and animal data and has employed inter-species scaling [4] to give improved confidence limits on its dose-response curve.

The combined LE1(ma4)H model contains the assumption that the crew are saturated at the ambient DISSUB pressure. Predictions of risk for situations where the crew are not saturated (pressure exposure \ll 24 h) will be overly conservative.

Any iso-risk escape curves in the Figures that give an indication of predicted risk for escapes deeper than 290 msw are extrapolations beyond all trials data. It should be assumed that the model has limited power for extrapolation beyond the calibrating data (\cong 183 msw and 1.9 bar human data.)

This model does not consider risks arising from: high-pressure nervous syndrome (HPNS), toxic effects of oxygen on the CNS, nitrogen narcosis, raised temperature of breathing gas due to adiabatic compression, or impaired lung ventilation due to high density gas will contribute to the limitation of successful escape. It is possible that any one, or a combination, of these factors could become limiting in man at any depth beyond 183 msw. Simulated submarine escape trials at QinetiQ Alverstoke using goats have shown escape to be possible, with limited casualties, from depths as great as 290 msw. Although this cannot be taken as conclusive evidence that men can escape from these depths, it is not unreasonable to assume that successful escape could be made from depths in excess of the current design specification of the UK submarine escape system.

ACKNOWLEDGEMENTS:

The work described in this manuscript was funded under the MOD UK Applied Research Program.

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Annex 5.

Blogg SL, Loveman GA, Seddon FM, Woodger N, Koch A, Reuter M, Gennser M, White MG. Magnetic resonance imaging and neuropathology in the goat nervous system following hyperbaric exposures.

Eur Neurol. 2004; 52(1):18-28

Magnetic Resonance Imaging and Neuropathology Findings in the Goat Nervous System following Hyperbaric Exposures

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Key Words

Decompression sickness · Magnetic resonance imaging · Neuropathology · Hyperbaric exposure

Abstract

Divers may be at risk of long-term CNS damage from non-symptomatic hyperbaric exposure. We investigated the effect of severe, controlled hyperbaric exposure on a group of healthy goats with similar histories. Thirty goats were exposed to various dive profiles over a period of 5 years, with 17 experiencing decompression sickness (DCS). Brains were scanned using magnetic resonance (MR) imaging techniques. The animals were then culled and grossly examined, with the brain and spinal cord sent for neuropathological examination. No significant correlation was found between age, years diving, DCS or exposure to pressure with MR-detectable lesions in the brain, or with neuropathological lesions in the brain or spinal cord. However, spinal scarring was noted in 3 animals that had suffered from spinal DCS.

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Introduction

It is well established that decompression sickness (DCS) is a clinical syndrome that may affect anyone experiencing a rapid reduction in environmental pressure, including aviators, compressed air workers and most commonly, aquatic divers. The syndrome is caused by metabolically inert gases rapidly coming out of solution and expanding within the tissues or the blood to form bubbles [1–4]. DCS may cause peripheral problems, including joint pain (limb ‘bends’) and skin marbling, but more seriously it can affect the central nervous system (CNS). Around three quarters of all CNS decompression incidents are attributed to damage of the spinal cord [5–7], while the remainder affect the cerebrum. The brain is most susceptible to damage from arterial gas embolism, but can also be affected by bubbles passing through a patent foramen ovale (PFO) or a defective lung filter (pulmonary shunt) [8]. In a recent study investigating the relationship of PFO and diving, it was found that regardless of the presence of a PFO, repeated diving was associated with ischaemic brain lesions [9].

In this respect, there is concern that divers who appear to work safely throughout their lives might still be at risk of CNS damage from ‘silent bubbles’. A particular worry

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is that residual damage from several small insults may cause long-term deficits in the aging diver. Pathological studies of brains from divers with no history of DCS and the spinal cords of divers with no recent history of DCS have been cited as cause for concern, as degeneration and vasculopathy of the nervous tissue was observed [10, 11]. It was postulated that recurrent sub-clinical DCS might result in a condition analogous to multi-insult dementia, with gas emboli rather than thromboembolism as the initiator.

However, recent studies [12, 13] have shown no relationship between long-term diving and specific neurological deficits so long as dives are performed safely [14]. It is thought that other factors apart from diving may be responsible for lesion formation. For example, age alone may be an influential factor [15], while lifestyle and health factors may also increase risk. Smoking, use of alcohol, head trauma, age of more than 35 years and cerebrovascular risk factors have all been related to magnetic resonance (MR) imaging (MRI) focal changes in white matter of divers and non-divers [16, 17]. To reveal the true effect of diving on long-term health, a range of factors need to be controlled for, and the subject history needs to be carefully assessed.

Goats have been used as a model for DCS investigation for over 50 years at the Hyperbaric Systems Laboratory, DERA Alverstoke, as they have a similar body mass and a reasonably close approximation to humans in their physiological responses to altered ambient pressures [18, 19]. A database provides full husbandry and case histories for each animal that has been exposed to pressure, including records of each dive profile, any decompression illness and treatments performed. All of the animals have regular health checks and are not subject to alcohol or smoking, cancelling out two factors that may confuse retrospective human studies. As a goat's life expectancy is around 10–14 years (Royal Society for Protection of Cruelty to Animals, UK), an 8- to 10-year-old goat roughly equates to a human of 55–65 years. A large number of these older experimental animals, mostly with extensive dive histories, were due to be culled and so formed an ideal group for investigation on the long-term effects of hyperbaric exposure.

Methods

Thirty-six goats of either sex were used in the present study. Of these, 6 formed a pressure-naïve control group obtained from the usual suppliers. The mean age of the diving group ($n = 30$) was 7.5 ± 2.4 years (table 1), which included 13 animals that had not exhibited

clinical signs of DCS (mean age 7.2 ± 3.0 years) and 17 animals that had experienced some form of DCS (mean age 7.7 ± 2.0 years). These 2 groups (non-DCS and DCS) were well matched regarding age and diving intensity (dives year⁻¹). The precise age of only 2 animals in the control group was known (both 3 years 9 months at the time of culling); however, the dentition and weight of the remaining 4 indicated that they were also 4 years of age.

Individuals in the diving group had been subject to varying numbers of dives (mean number of dives per animal 12.5 ± 6.3) and different types of dives within the period 1993–1998. The DCS group had dived for a longer period (4.0 ± 1.3 vs. 2.3 ± 1.7 years, $p = 0.0059$, Mann-Whitney test), although the number of dives was not significantly different in the 2 groups (table 2). Of the 17 that had experienced DCS, 11 had suffered from limb DCS and 6 had experienced DCS with either cerebral or spinal involvement (table 1).

All of the animals used in the study were fit and healthy and kept in strict regard of the regulations and guidelines laid down by the UK Home Office for experimental animals. The ongoing health of the animals was regularly assured by the exclusion from the herd of goats that had suffered from any chronic debilitating illness, on instruction of the herd veterinary surgeon.

Dives were carried out in the submarine escape simulator at DERA Alverstoke. Pressure profiles were accurately controlled using computer software. The history, type of dives, number of dives, maximum Kisman Masurel (KM) precordial Doppler score [20] experienced throughout their dive history, as well as the incidence and type of DCS, if any, experienced by each animal is described in table 1. Dive types included:

Bounce: A moderately rapid compression (90–120 s) to pressure (0.3–0.42 MPa) followed by 23 min at pressure, then decompression to surface at a rate of 0.3 m of seawater (msw) s⁻¹ (0.003 MPa s⁻¹).

Saturation: This involved a stay (6 or 24 h) at a certain pressure (0.05–0.16 MPa) followed by a relatively slow return to atmospheric pressure over a period of 2.5 min.

Escape: A rapid (28 s) compression to pressure (1.5–2.9 MPa) followed by immediate decompression at a rate of 2.4 msw s⁻¹ (0.024 MPa s⁻¹) to simulate the pressure changes commensurate with a submarine tower escape.

Saturation followed by escape: These dives involved a stay (6 or 24 h) at pressure (between 0.05 and 0.09 MPa), followed by rapid compression and decompression to and from a realistic escape pressure (1.5–2.6 MPa) to simulate escape from a disabled submarine.

The majority of the dives were carried out using air. However, a number of dives involved exposure to increased pressures of oxygen or carbon dioxide during or after a dive, in order to simulate conditions that may be experienced by submariners stranded in a disabled submarine. If decompression illness occurred after a dive, the animal in question was sedated and returned to the chamber for treatment by recompression and hyperbaric oxygen therapy using Royal Navy Treatment Table 61. Following treatment, the animal was assessed by the herd veterinary surgeon over the next few days and only returned to the herd if there were no indications of post-DCS deficit.

MR Imaging

Before culling for neuropathology, all of the animals were scanned using MRI to check for lesions in the brain. A mobile medical MRI unit (Alliance Medical) was employed for this purpose. The mean period between an animal's last dive and MR scanning was 16 ± 21 months. The animals were sedated using Domitor (medetomi-

Table 1. Subject history

Goat ID	Age	First dive	Last dive	Diving years	Dive type	Dives	Limb bend	CNS spinal	CNS cerebral	Highest KM score
88B	11	29/10/1993	08/04/1997	4	SE, E, S	16	0	0	0	4–
91M	8	15/11/1993	16/12/1997	4	SE, E, S	18	0	0	0	4
88A	11	29/10/1993	01/12/1997	4	SE, E, S	17	0	0	0	4
89E	10	19/10/1993	01/05/1997	4	SE, E, S	16	0	0	0	3+
89H	10	26/10/1993	01/05/1997	4	SE, E, S	16	0	0	0	4
F21	6	21/10/1998	21/10/1998	0	E	1	0	0	0	3+
K13	2	20/08/1998	23/11/1998	0	SE, E	3	0	0	0	4
91G	8	12/10/1993	18/03/1997	4	SE, E, S	16	0	0	0	3+
F3	6	18/08/1994	09/12/1996	2	SE, E, S	12	0	0	0	4
F25	6	11/08/1998	29/09/1998	0	SE, E	2	0	0	0	4–
E86	6	04/03/1996	19/03/1997	1	SE, E, S	6	0	0	0	4
91H	8	20/07/1993	12/05/1994	1	S, E	4	0	0	0	3+
K22	2	22/10/1998	27/11/1998	0	SE, E	2	0	0	0	4
F4	6	18/08/1994	23/11/1998	4	SE, E, S	17	1	0	0	4
91U	8	09/08/1993	29/01/1998	5	SE, E, S	16	4	1	0	4
91P	8	14/10/1993	24/11/1998	5	SE, E, S, B	21	1	0	0	4
91F	8	12/10/1993	10/09/1998	5	SE, E, S, B	20	2	0	0	4
91T	8	16/10/1993	28/01/1998	5	SE, E, S	19	1	0	0	3+
E94	6	13/01/1994	19/03/1997	3	SE, E, S	13	1	1	0	4
K23	2	22/10/1998	22/10/1998	0	E	1	0	0	1	4
89C	10	09/09/1993	10/09/1998	5	SE, E, S, B	19	2	0	0	4
F11	6	15/02/1996	27/10/1998	2	SE, E	10	1	1	0	4
91N	8	14/10/1993	28/01/1998	5	SE, E, S	12	4	0	0	4
90A	9	26/10/1993	20/03/1997	4	SE, E, S	16	1	0	0	4
91K	8	07/10/1993	09/09/1998	5	SE, E, S, B	21	2	0	0	4
91V	8	19/08/1993	03/12/1997	4	SE, E, S	9	3	0	0	4
91B	8	10/11/1993	02/12/1997	4	SE, E, S	10	1	0	0	4
E93	8	08/11/1994	03/09/1997	3	SE, E, S	13	1	0	1	4
88C	11	02/11/1993	01/12/1997	4	SE, E, S	14	1	1	0	4
90E	9	19/10/1993	02/12/1997	4	SE, E, S	16	1	0	0	4
F30	4 ^a	control	–	–	–	–	–	–	–	–
F33	4 ^a	control	–	–	–	–	–	–	–	–
F27	4	control	–	–	–	–	–	–	–	–
F26	4	control	–	–	–	–	–	–	–	–
F32	4 ^a	control	–	–	–	–	–	–	–	–
F35	4 ^a	control	–	–	–	–	–	–	–	–

Age is rounded up to nearest full year. B = Bounce; S = saturation; E = escape; SE = saturation + escape.

^a Birth date not known – age derived from dentition.

dine; Pfizer) and Torbugesic (butorphanol; Fort Dodge), administered intra-muscularly, then strapped in a prone position onto an examination stretcher. Scans were performed on a 1.0-Tesla unit (Siemens, Erlangen, Germany). The majority of scans involved fast spin echo (FSE) sequences, acquired in the oblique sagittal plane (TR 1,320 ms, TE 120 ms, slice thickness 10 mm, field of view 240 × 240 mm, matrix 256 × 254), the oblique axial plane (TR 4,179 ms, TE 108 ms, slice thickness 5 mm, field of view 200 × 15 mm, matrix 256 × 256) and the oblique coronal plane (TR 3,000 ms, TE 120 ms, slice thickness 10 mm, field of view 240 × 180 mm, matrix 256 × 128). FSE inversion recovery (FSEIR) sequences in the oblique axial

plane (TR 5,500 ms, TE 20 ms, slice thickness 6 mm, field of view 220 × 160 mm, matrix 256 × 256) were also applied.

The MRIs were sent to the Schiffahrtsmedizinisches Institut der Marine, Kiel, Germany, for evaluation. Previous investigations on the effects of diving using MRI has been carried out at this department [15, 21, 22]. The scans were examined blind, that is, the proportion and identity of the animals exposed to pressure or to have had DCS was undisclosed.

Table 2. Comparison of historical and neuropathological data between groups

	No DCS	DCS	Control	Test	
				Mann-Whitney no DCS/DCS	Kruskal-Wallis all groups
n	13	17	6	30	36
Age, years	7.2 ± 3.0	7.7 ± 2.0	≈4	NS	p < 0.01
Diving years	2.3 ± 1.7	4.0 ± 1.3	0	p = 0.0059	
Dives	9.9 ± 6.9	14.5 ± 5.2	0	NS	
Dives/year diving	4.4 ± 1.1	3.6 ± 0.9	0	NS	
Median WD, LS (IQR)	56 (49)	84 (54)	71 (42)	p = 0.0178 ¹	NS
Median WD, TS (IQR)	12 (25)	15 (25)	6 (3)	p = 0.0409 ¹	NS
Median astrocytosis (IQR)	16 (20)	16 (6)	20 (17)	NS ¹	NS

WD = Wallerian degeneration; LS = longitudinal sections; TS = transverse sections; IQR = interquartile range in parentheses.

¹ Here the DCS group consists of spinal or limb bends only.

Neuropathology

On average, animals were culled 14 ± 12 days following their MR scan. Culling took place at Compton Paddock Laboratories (Berkshire, UK), where tissues including the entire brain and spinal cord, plus selected samples of other tissues including the lungs and heart, were fixed in formaldehyde. Routine checks for PFO were made in every animal. The post-mortem material was then sent to Cambridge University, where it was inspected at the Department of Clinical Veterinary Medicine. Again, examination of the tissues was carried out blind.

Tissue sampling involved the transverse sectioning of each animal's spinal cord at the level of each spinal nerve root entry zone. A block of tissue approximately 3 mm thick was taken from each spinal level to provide a series of transverse blocks. The remaining tissue was sectioned longitudinally along the midline to provide two blocks, which were then embedded. In one of these, the medial surface was sectioned, while the lateral surface of the other was sectioned.

Seven blocks were prepared from the brain of each goat. They included transverse sections from several levels of the cerebrum, one each from the diencephalon, the cerebellum and at the level of obex, while a medial sagittal block was also taken from the right half of the cerebellum.

All tissue blocks were paraffin embedded and 8-μm-thick sections were prepared for staining with haematoxylin and eosin or for glial fibrillary acidic protein (GFAP) immunohistochemistry. Immunohistochemical labelling for GFAP was performed on selected spinal cord blocks using a polyclonal primary antibody (rabbit anti-cow GFAP; Dako) at a dilution of 1:500. Labelling was detected using a diaminobenzidine substrate detection kit (Vector). The sections were then evaluated for any signs of pathological change, including Wallerian degeneration (WD; longitudinal and transverse), astrocytosis using GFAP immunohistochemistry, and perivascular cuffing, using a visual comparison and scoring protocol which was validated by establishing that scores recorded and assessed by 2 independent observers were not significantly different.

Following the initial MRI and neuropathological examination, the results were shared between Cambridge and Kiel. Any lesions

found during MRI evaluation were further investigated by pathological examination of the specific area of the brain where they had been observed.

Spearman rank correlation, Kruskal-Wallis and Mann-Whitney U tests were used for statistical analysis. Statistical significance was defined as $p < 0.05$.

Results

Of the 36 animals in the study, MRI of the brain revealed lesions in only 3 goats. These lesions appeared as T2 hyper-intensities, as shown in figure 1. All 3 animals were from the diving group, but none had ever shown signs or symptoms of DCS. These 3, 91M, 88A and 89H (table 1), had participated in well over the mean number of dives (table 3) and had registered maximum KM Doppler scores following one or more pressure exposures. However, further examination of the areas in which the lesions were located did not identify any evidence of histopathological damage. None of the MR scans of animals in the control group showed any sign of lesions in the brain.

Conversely, post-mortem histological examination of brain tissue revealed that 2 control animals (F33 and F30) had pathological signs of brain damage, exhibiting focal lesions consistent with small areas of cortical infarction (fig. 2). The veterinary pathologist noted that these deficits could be related to head butting. No lesions were found in any of the tissue taken from the brains of the 30 animals in the diving group.

Fig. 1. Arrow marks a T2 hyperintense lesion in the goat (88A) of 2 mm diameter situated in the left deep temporal white matter, between the claustrum and cisterna insulae.

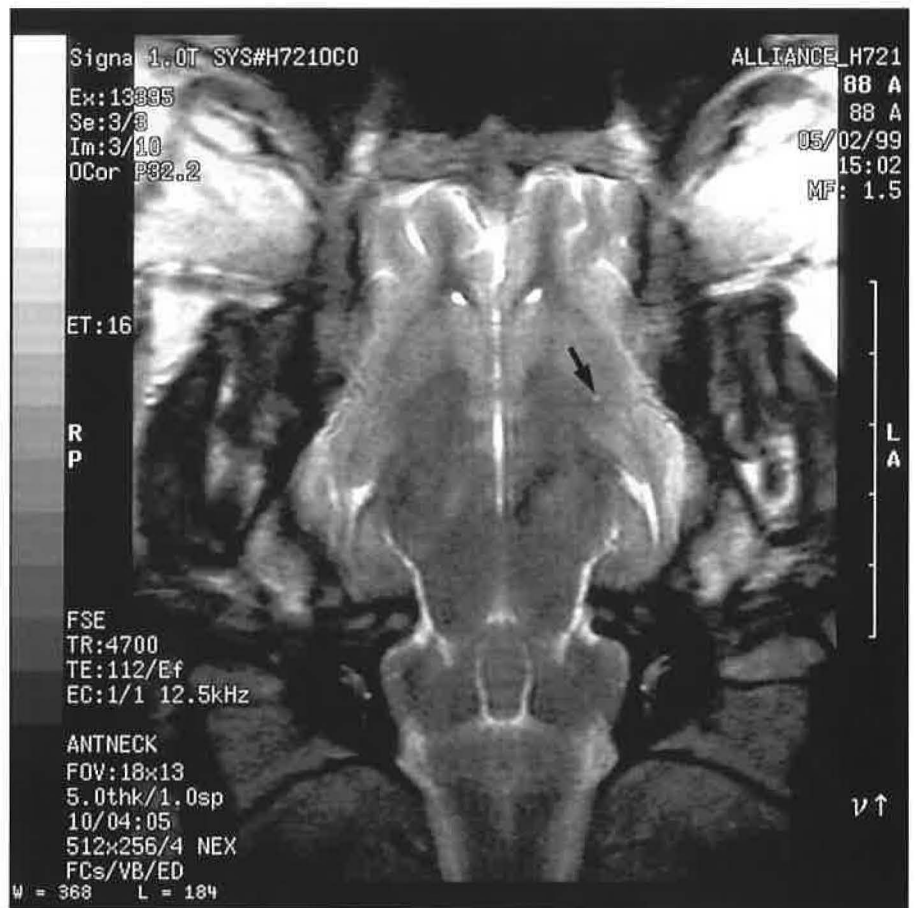


Fig. 2. Example of an incidental lesion found in one of the pressure-naïve control animals (F33). Arrows delineate a distinctly demarcated region of rarefaction of the neuropil of a focal cerebral lesion.

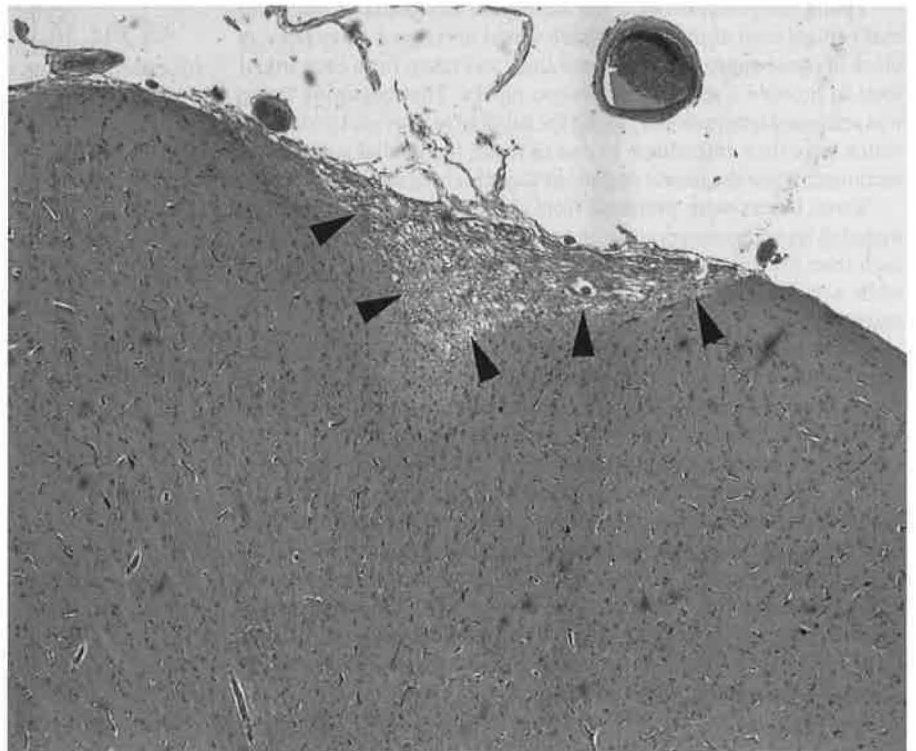


Table 3. Full dive history for those subjects with MR-detectable lesions (91M, 88A and 89H) and neuropathological evidence of spinal cord injury (F4, F11 and E94)

Dive No.	Goat ID											
	91M			88A			89H			F4		
1	S	24 h	S	24 h	S	6 h	SE	24 h	S	6 h	SE	24 h
2	S	6 h	S	24 h	S	24 h	SE	24 h	SE	24 h*	E	
3	S	6 h	E		E		SE	24 h	SE	24 h	SE	24 h
4	E		E		E		S	24 h	S	24 h	E	
5	SE	24 h	SE	24 h	SE	24 h	S	24 h	SE	24 h	E	
6	SE	24 h	SE	24 h	SE	24 h	S	24 h R CO ₂	SE	24 h R CO ₂	SE	24 h R CO ₂ *
7	SE	24 h	SE	24 h	SE	24 h	SE	24 h	S	24 h	SE	24 h PE*
8	SE	24 h	SE	24 h	E		S	24 h	E		SE	24 h PE
9	SE	24 h	S	24 h	SE	24 h R CO ₂	S	24 h	S	24 h	SE	24 h PE
10	S	24 h	SE	24 h	E		SE	24 h	E		SE	24 h
11	S	6 h	E		S	24 h	E		SE	24 h*	—	
12	S	24 h CO ₂	S	24 h R CO ₂	SE	24 h	E		E		—	
13	SE	24 h CO ₂	E		SE	24 h	E		E		—	
14	E		S	24 h	E		E		—		—	
15	S	24 h	E		SE	24 h R CO ₂	SE	24 h PE	—		—	
16	SE	24 h CO ₂	SE	24 h R CO ₂	E	O ₂ PB	E		—		—	
17	SE	24 h PB	E		—		E*		—		—	
18	E		—		—		—		—		—	
	no DCS			no DCS			no DCS			DCS 1 limb		
										DCS 1 spinal DCS 2 limb		
										DCS 1 spinal DCS 2 limb		

S = Saturation; SE = saturation followed by escape; E = escape; PB = post breathe oxygen; PE = oxygen 1 h pre-escape; R = raised.
* Denotes DCS dive.

Table 4. Comparison and correlation of historical and spinal neuropathological parameters for diving subjects

Parameters compared	Correlation coefficient (r) and probability		
	all diving animals (n = 30)	no DCS (n = 13)	DCS (n = 17)
Age vs. number of dives	0.585 (p = 0.0016)	0.773 (p = 0.0074)	0.344 NS
Wallerian degeneration (LS) and age	0.502 (p = 0.0068)	0.605 (p = 0.0360)	0.425 NS
Wallerian degeneration (LS) and number of dives	0.281 NS	0.605 (p = 0.0360)	−0.18 NS
Wallerian degeneration (TS) and age	0.224 NS	0.21 NS	0.244 NS
Wallerian degeneration (TS) and number of dives	0.097 NS	0.389 NS	−0.309 NS
Astrocytosis and age	−0.632 (p = 0.0007)	−0.727 (p = 0.0118)	−0.418 NS
Astrocytosis and number of dives	−0.428 NS	−0.573 (p = 0.0473)	−0.301 NS

LS = Longitudinal sections; TS = transverse sections.

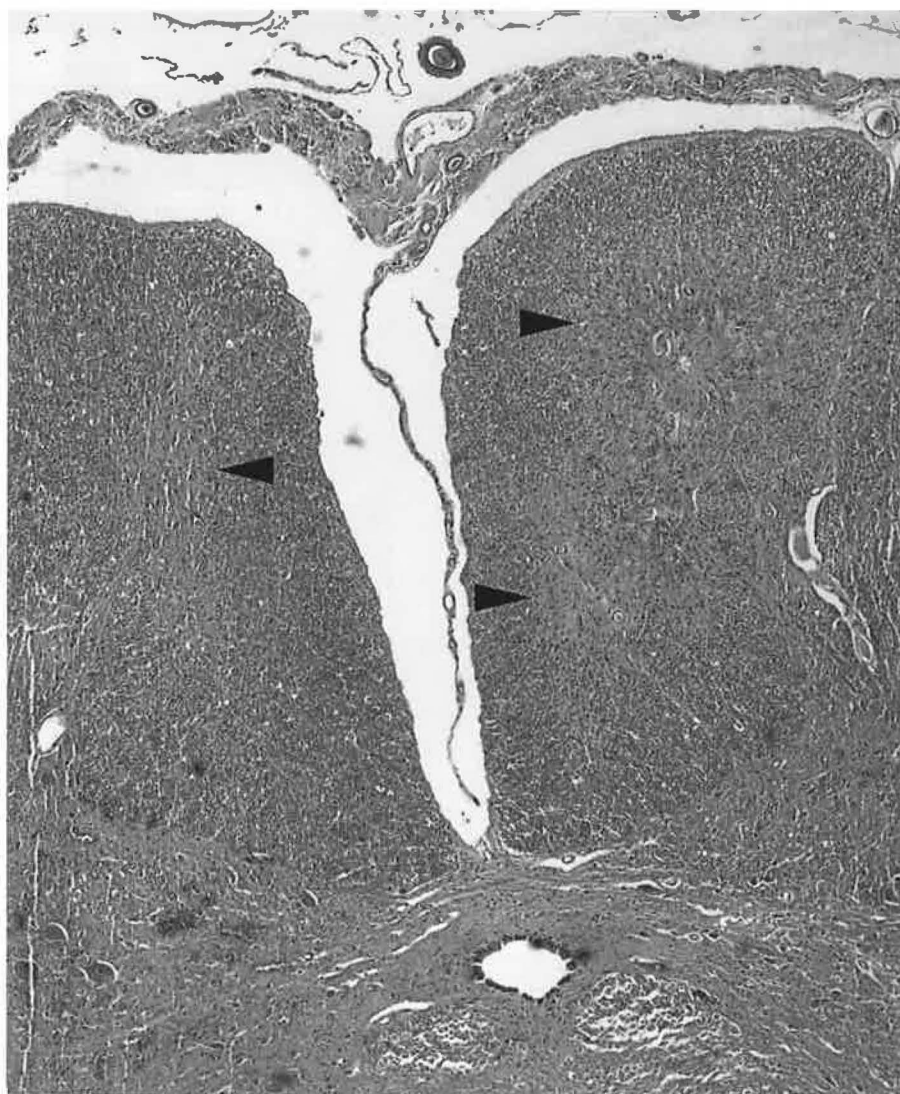


Fig. 3. A low power image of glial scarring (arrows) in the dorsal column of F11.

Spinal cord tissue taken from 3 animals in the diving group (F4, E94 and F11; table 1, 3) that had suffered from DCS showed pathological evidence of spinal cord injury. The lesions were consistent with previous spinal cord white matter infarcts (WD or focal glial scars), at the level of the 5th cervical spinal nerve (F4), the 2nd to 3rd lumbar spinal nerves (F11; fig. 3) and at the 2nd thoracic spinal nerve (E94). The lesions in the first 2 animals occurred bilaterally and involved the dorsal columns, while that in the 3rd animal was unilateral and situated in the ventrolateral area. These sites have been shown to be predilection sites for decompression pathology [23–25].

These 3 animals had all suffered from limb DCS: in F4 following an escape profile; in E94 after saturation followed by escape, and in F11 after saturation and escape

with oxygen post-breathe. Both F11 and E94 had also experienced DCS with spinal involvement (table 3) prior to their limb bends, following saturation with escape, and saturation with escape while breathing raised levels of CO₂, respectively. The spinal cord tissue taken from the control group was normal.

Histological examination of the spinal cord showed there was a significant correlation between the extent of WD in longitudinal sections and the animals' age ($r_s = 0.502$; $p = 0.007$; for all correlations see table 4). The correlation between age and transverse WD was, however, only significant for the non-DCS group. There was no difference in the degree of longitudinal or transverse WD between the DCS group and the non-DCS group ($p = 0.07$ and $p = 0.17$, respectively). However, if only animals with

spinal and limb bends (i.e. excluding cerebral) were counted in the DCS group, then the degree of both longitudinal and transverse WD was larger in the DCS group ($p < 0.05$; table 2). There was no correlation between WD and number of exposures.

With regard to astrocytosis, there was a significant negative correlation between the animals' age ($r_s = -0.651$; $p < 0.001$) and number of dives ($r_s = -0.455$; $p = 0.012$) with the degree of astrocytosis. There was no significant difference between the control and diving groups in regard to spinal histopathology (table 4); however, the small number of control animals and the narrow age range of this group makes this comparison of limited value.

Statistical analysis of the results as a whole showed that there was no correlation between any animal's age and occurrence of any CNS lesions ($r_s = -0.008$) and also no correlation between the number of years an animal had dived and lesion occurrence ($r_s = -0.004$). There was no difference found between the number of lesions noted in the diving and control groups ($p = 0.48$). Similarly, no difference was found between the numbers of lesions noted in animals that had experienced DCS and those that had not ($p = 0.72$).

Discussion

The present study draws longitudinal diving data from an experimental group that is free from human lifestyle influences such as smoking, alcohol, poor diet and poor fitness. The main stressors that these goats had been subject to throughout their lives were due to hyperbaric exposure, namely gas supersaturation and bubble loading, both of which increase the risk of DCS occurring. All of the dives undertaken were severe as far as this risk is concerned. In saturation dives, the time spent at depth is inherently long enough for tissues to supersaturate with gas. Escape dives involve fast ascent rates, and the faster the ascent rate the more likely it is that bubbles will evolve, increasing the risk of DCS [26]. Both of these types of dive and, particularly a combination of the two, carry a much higher risk of DCS than usual sport or commercial dives, which are tailored to minimise DCS incidence.

Subsequently, the effects of repeated, intense, long-term pressure exposure could be examined via MRI and pathology, albeit in a non-human model. The study incorporated the use of MRI techniques that were suitable for both the difficulties intrinsic to scanning a non-human, non-biddable subject (problems with movement artefact

and sedation meant that rapid scanning was necessary) [27], while also providing enough sensitivity to identify any abnormalities in the brain.

Cerebral Findings

The results from this study did not show any significant correlation between the age of the subject, number of years diving, DCS occurrence, or exposure to pressure with MR detectable or pathological lesions in the brain. The number of lesions found was surprisingly low, given the severity of the dives that many of the diving group had been subject to.

A contributing factor to low lesion occurrence could be that a PFO was not found in the hearts of any of the animals in the study; surprisingly, veterinarians at the pathology laboratory used in the present study have never observed a caprine PFO in this herd, although other workers have noted them. This is in contrast to the reported incidence of PFO in over one third of the human population [28]. Although recent findings suggest that within the bounds of uneventful, conservative sports diving, PFO is not linked to the presence of cerebral lesions [29, 30], during a high-risk dive profile or diving accident, PFO with right to left shunt increases the risk of arterial gas embolism, possibly causing cerebral gas embolism and in turn, severe neurological dysfunction [31]. The lack of a common cardiac right to left shunt in the goat may explain the low levels of detectable lesions in the brain of the experimental group and particularly the absence of multiple lesions. For example, Knauth et al. [32], found 34 MR (FLAIR) detectable lesions in 4 divers with PFO, while only 7 lesions were found in 7 divers with no shunt.

The carotid circulation of goats is also slightly different to that of humans. Blood supply to the brain in the goat occurs via an arterial plexus, the carotid rete. The rete is made up of small arterial vessels with a lumen size of around 150 μm in diameter [33]. It is possible that this plexus may be able to act as a filter to bubbles that pass into the arterial circulation. Incidentally, the goats and other *Artiodactyla* share this rete in common with the *Cetacea* and *Sirenia*; this rete might act as a bubble filter in diving mammals.

Given the lack of a common caprine PFO and the presence of this putative filter, it is most likely that any permanent or transient bubble-induced damage to the brain of the goat would come from bubbles forming directly in the cerebral tissue (autochthonous bubbles). The majority of dives performed in the present study were provocative; escape and saturation dives will effectively load the brain with gas, and therefore, upon decompression, will pro-

duce the ideal conditions for autochthonous bubbles to evolve. A theoretical deep escape model has estimated that on surfacing from 280 msw, the nitrogen partial pressure in the brain will be around 6–7 ATA [34], while space-occupying lesions of $>100\text{ }\mu\text{m}$ have been found in the CNS (spinal cord) of dogs following exposure at only 3.6 ATA for 4 h and rapid decompression to 1 ATA (0.1 MPa) [35]. Escapes are also most likely to produce bubbles in fast tissues, which include the brain and spinal cord [34, 36].

If only a small number of these bubbles formed, too few to cause permanent damage (lesions), but enough to cause symptomatic cerebral DCS due to temporarily increased intracranial pressure, then this may explain the cases of K23 and E93 (table 1), where symptoms of cerebral DCS were recorded, but neither pathology nor MRI showed any changes in the cerebral tissue. Human MRIs taken after mild traumatic brain injuries are usually normal [37].

Three animals did have MR-detectable lesions in the brain, but had not suffered from symptomatic DCS. Although no correlation between cerebral lesions and long-term hyperbaric exposure was found, it is interesting to speculate on what may have caused this damage. A possible cause is simply age [15–17], as these 3 animals constituted some of the oldest animals in the diving group (table 1). However, as these lesions were not permanent (tissue damage was not observed in the suspect areas on further pathological examination) and there is no correlation between age and CNS lesions in the present study, this seems unlikely.

It is not possible to conclude what caused the MR-detectable lesions in these 3 goats. However, given the circumstances, including the lack of lesions in similarly high 'silent bubble'-exposed goats, the lack of cerebral DCS-type symptoms, the lack of permanent lesions, not to mention the lack of correlation between diving and cerebral lesions found in the present study, it is not improbable that the cause in this model is damage from head butting. This action could cause transient hyperintensities to appear in the MRIs. As pathological examination is not an option in the living human patient, these findings highlight the value of repeated MRI scanning to qualify initial findings.

Repetitious MR scanning is seldom carried out. For example in studies similar to ours [12, 15, 17, 21, 32, 38], no repeated measurements were made. The present study and others, including those made in the fields of multiple sclerosis [39] and mild traumatic brain injury [40], where the merit of repeated scanning is recognised, show that

MRI-detectable lesions may be transient or change location. A few workers investigating various aspects of DCS have used repeated scanning; Sipinen et al. [41] carried out secondary scanning, ostensibly to increase sensitivity and to verify images. More recently Germonpre et al. [29] scanned subjects 1 year after their initial investigation and stringently assessed their data, only accepting lesions if they appeared hyperintense in both T2 and FLAIR sequences. In future diving studies, it would seem prudent to make further scans in the months following the primary, to validate the permanence of any lesions thought to be associated with hyperbaric exposure, while also thoroughly examining the patient history for any other cause.

Spinal Cord Findings

Similarly to the cerebral study, there was no significant correlation between any of the factors investigated with pathological lesions in the spinal cord; these findings suggest that there is no link between long-term hyperbaric exposure and CNS damage in this model. Accordingly, the small number of spinal lesions found were only observed in animals that had experienced some form of DCS. The spinal cord was not examined with MRI as this technique infrequently reveals changes in the cord following DCS [36]; clinical observations are more useful in these cases.

Only 3 animals in the study presented with lesions in the spinal cord following pathological examination. The lesions were comparable to those previously described in experimental animals exposed to decompression procedures [23–25]. Two of the goats were diagnosed as having DCS with spinal involvement; however, the 3rd (F4) had only shown signs of a limb 'bend' and had not displayed any of the usually overt signs of a caprine spinal DCS event. This incident occurred 3 months before the animal was culled and the lesion detected was consistent with an episode of white matter infarction approximately 3 months prior to death. That this animal did not have clinical signs of spinal damage is interesting; although degeneration of the cord without clinical signs of spinal DCS is possible, it is unlikely and unproven [37]. The mechanisms of limb 'bends' are unknown; it is possible that limb pain may be a manifestation of a minor spinal event. However, the present findings complement previous observations made upon goats and humans [23, 24] that spinal cord infarction can occur in the absence of clinical signs of spinal DCS.

Animals that presented with DCS were treated very swiftly, within 30 min at the most. It is unlikely that a human commercial or sports diver would receive treat-

ment within this period, depending on distance from the nearest hyperbaric therapy unit. It is interesting to speculate on the importance of the rapid turn around to treatment period in aiding the symptomatic restitution that allowed both F11 and E94 (tables 1, 3) to resume successful and DCS-free diving following the spinal DCS incident. However, the goats in the present study were treated once only using Royal Navy Treatment Table 61 (US Navy Table 5). If not fully recovered following the therapy dive, then the animal was euthanised. Humans would probably receive repetitive therapies using longer duration tables until signs and symptoms had resolved. If further hyperbaric treatment had been given, as for human patients, it is possible that spinal lesions may not have formed.

Assessment of the WD and astrocytosis data also showed little evidence to suggest that asymptomatic long-term diving causes degeneration of the CNS. However, some findings did indicate a possible residual effect of spinal DCS; a correlation between age and WD in the whole diving group was found, but when the group was subdivided into DCS and non-DCS, then age and WD correlated only for the non-DCS group (table 4). Added to this, the degree of WD was significantly greater in the animals that had experienced either a spinal or limb bend (table 2), while that of the non-DCS and control groups were smaller and similar (table 2), all of which suggest some degree of chronic damage in those animals that had suffered from spinal DCS.

The correlation between age and number of dives with WD in the non-DCS group was so close (table 4) that it cannot be determined which of these was the determining factor regarding WD in these animals. However, as WD

was of the same magnitude in both the non-DCS group and the control animals, this indicates that diving itself did not cause any major long-term effects in these animals. It is, however, unfortunate that due to economic and humane factors the control group in this study was rather small, and thus this conclusion is only tentative.

Surprisingly, results from GFAP analysis did not show any positive correlation between the severity of astrocytosis and the extent of WD in any of the groups. GFAP expression is a well-established response of CNS tissue to injury and it had been hoped that examination of GFAP-stained sections would provide a sensitive method of evaluating any damage caused by DCS. The group that had experienced DCS revealed a negative correlation with both parameters and similarly, a negative correlation between age, number of dives and astrocytosis was revealed when all of the animals were compared (table 4). It is possible that immunohistochemical detection of GFAP upregulation is a short-lived response in comparison to morphological damage and this could explain these unexpected results.

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Annex 6.

Jurd K, Thacker J, Seddon F, Gennser M, Loveman G.

The effect of pre-dive exercise timing, intensity and mode on post-decompression gas bubbles. *Diving Hyperb Med.* 2011; 41(4):183-8

Original articles

The effect of pre-dive exercise timing, intensity and mode on post-decompression venous gas emboli

Karen M Jurd, Julian C Thacker, Fiona M Seddon, Mikael Gennser and Geoffrey AM Loveman

Abstract

(Jurd KM, Thacker JC, Seddon FM, Gennser M, Loveman GAM. The effect of pre-dive exercise timing, intensity and mode on post-decompression venous gas emboli. *Diving Hyperb Med.* 2011 December;41(4):183-188.)

Introduction: The effect of pre-dive exercise on post-decompression venous gas emboli (VGE) remains contentious. The aim of our study was to investigate the effect of timing, intensity and mode of exercise before diving on post-decompression VGE production.

Methods: Fifteen male volunteers performed three identical 100 min chamber dives to 18 metres' sea water. Two of the three dives were conducted with prior exercise at 24 or 2 h; a dive without prior exercise formed the control. Moderate-intensity impact exercise consisted of jogging on the spot for one minute followed by ten star jumps, repeated for a total of 40 min at 70% of maximum heart rate. Post-dive Doppler monitoring began within 2 min of surfacing and was carried out for at least 180 min. VGE were assessed using the Kisman-Masurel (KM) code and the Kisman Integrated Severity Score (KISS).

Results: The median peak KM grade for each condition following the dives was not significantly different. Pre-dive exercise at 2 h resulted in a significant reduction in the mean KISS compared to the control (11.3 versus 17.2, $P < 0.04$, Wilcoxon sign-ranked test). Moderate-intensity jogging/star jump exercise used in this series of dives resulted in significantly lower mean KISS (11.3 versus 21.8, $P < 0.04$) and median KM grade over 180 min ($P < 0.006$, Mann Whitney U test) compared to high-intensity cycling exercise used in our previous study.

Conclusions: This study suggests that moderate-intensity impact exercise reduces VGE production when conducted 2 h prior to diving.

Key words

Doppler, diving, exercise, bubbles, decompression illness

Introduction

The effect of pre-dive exercise on post-decompression venous gas emboli (VGE) remains contentious. It was thought for many years that exercise before, during, or after diving, was an additional risk factor for decompression sickness (DCS).¹ However, a number of studies conducted by two main groups over the last few years have shown that this may not be the case and that exercise prior to diving may actually help to reduce bubble formation and the incidence of DCS. There are, however, differences in the results of these studies with respect to the timing, intensity and mode of the exercise conducted.²⁻¹⁰

Wisloff et al. demonstrated that a single bout of high-intensity aerobic exercise performed by rats on a treadmill 20 h before a chamber dive reduced VGE formation and gave protection from lethal DCS.² Scheduling appeared to be important, protection occurring only if the interval between exercise and the subsequent dive was 10–20 h. Dujic et al. then demonstrated in man, that a single bout of high-intensity exercise (treadmill running) 24 h before performing a chamber dive to a depth of 18 metres' sea water (msw) significantly reduced the amount of VGE in the pulmonary artery compared to no exercise.³

Further studies in rats found the same high-intensity treadmill exercise starting 2 h before a dive either increased or had no effect on VGE formation and eliminated the protection afforded by exercise 20 h prior to diving.^{4,6} Contrary to this, a study in military divers found that medium-intensity running starting 2 h before a chamber dive to 30 msw decreased VGE formation.⁷ This was repeated using high-intensity running at a controlled heart rate, which resulted in the same outcome.⁸ The same dive profile was then performed in open-water, with medium- or high-intensity cycling 2 h prior to diving; both intensities reduced bubble grades.⁹ Furthermore, Castagna et al. have recently found that 45 min of treadmill exercise starting just one hour before an open-water dive also reduced bubble grades.¹⁰

These apparent contradictions in the effect of pre-dive exercise timing led to our study. Our previous series of dives were preceded by exercise which mimicked the high intensity and duration used by Dujic et al., but substituted treadmill running with low-impact cycling.^{3,11} The exercise was performed at 24 h or 2 h before a chamber dive to 18 msw, but showed no benefit in reducing VGE compared to the no-exercise controls. As a continuation of our study, the present series of dives examined the effect of reducing the intensity and increasing the impact of the exercise on VGE production following identical dive profiles.

Methods

The study was approved by the UK Ministry of Defence Research Ethics Committee and conducted in accordance with the principles of the Declaration of Helsinki.¹²

SUBJECTS

Fifteen male volunteers, aged 22–53 (mean 36.5) years, participated in the study. They comprised Royal Navy (RN) divers and QinetiQ staff with mixed wet- and dry-diving experience, all of whom had passed their dive medical, involving a fitness test. The purpose of, and procedures and risks associated with the study were explained and the volunteers gave their written consent. Each subject's height and weight were measured and their body mass index (BMI) calculated. Their percentage body fat was measured by bioelectrical impedance analysis using a Bodystat 1500™.

HYPERBARIC EXPOSURES

The study was carried out at the QinetiQ Hyperbaric Medicine Unit, Royal Hospital Haslar, Gosport, UK, a Category 1 facility containing an RN Type A recompression chamber. The chamber air dives were to 18 msw with a bottom time of 100 min. Decompression stops were at 6 msw for 5 min and 3 msw for 15 min, with an ascent rate of 15 msw min⁻¹ in accordance with RN Table 11-Mod.¹³ Each subject conducted three dives; two were conducted with exercise bouts at 24 or 2 h pre-dive and a dive with no prior exercise formed the control. The order in which the exercise or control dives were conducted was randomly allocated and each dive commenced at exactly the same time each day (1300 h) to avoid any influence of circadian effects. No flying or diving was permitted for at least seven days before commencing the trial and there were at least seven days between the experimental dives. Alcohol and caffeine were prohibited from the evening of the preceding day, but the subjects were free to eat breakfast and lunch on the day of their chamber dives.

This series of chamber dives formed a continuation of our study examining the effect of pre-dive exercise on VGE formation. The same dive profile, period between dives and timing and duration of pre-dive exercise were used throughout. The only difference was in the mode and intensity of exercise conducted: medium-intensity impact exercise (described below) compared to previous high-intensity cycling.

EXERCISE REGIMEN

The exercise regimen for this series of chamber dives consisted of jogging on the spot for 1 min followed by 10 star jumps, repeated for a total of 40 min. No exercise was permitted for 48 h before a dive or exercise bout. Participants were fitted with a Polar™ heart rate monitor and after a brief

warm-up period they were asked to aim at 70% of their theoretical maximum heart rate (220 - age (in years) beats min⁻¹) for the exercise period.

DOPPLER MONITORING

Pre-cordial Doppler monitoring of VGE was carried out using a continuous-wave Doppler Bubble Monitor (Techno Scientific Inc., TSIDBM 9008) with the subject standing at rest. Pre-dive baseline monitoring was carried out shortly before the dives. Post-dive monitoring began within 2 min of surfacing and was carried out every 5 min for the first 30 min and every 15 min thereafter, up to 180 min. Subjects were asked not to depart before their Doppler VGE score was declining and so, on a few occasions, monitoring was continued beyond 180 min, but only data collected up to 180 min were used in the analysis. Subjects remained at rest for the whole of the monitoring period. VGE were scored using the Kisman-Masurel (KM) code and the Kisman Integrated Severity Score (KISS) was then calculated to give a linearised measure of VGE.^{14,15} Doppler technicians were blinded to the order of the exercise and control dives and were assigned to the monitoring of the same subject for each of their three dives. The Doppler technicians each had several years of experience of audio Doppler monitoring and undertook regular quality assurance assessments. Monitoring sessions were recorded so that they could be re-analysed at a later time if required, using an Archos 605 portable media player, which directly encoded the audio signal to Waveform Audio File Format sampled at 44,100 Hz.

STATISTICAL ANALYSIS

Subject variables are presented as mean and standard deviation (SD). Individual peak Doppler KM grades for

Table 1
Subject demographics

Subject	Age (years)	BMI (kg m ⁻²)	Body fat (%)
1	47	28.7	19.1
2	41	26.3	23.2
3	49	25.4	18.7
4	53	25.1	21.1
5	37	25.1	21.1
6	36	28.1	19.4
7	32	24.8	16.5
8	36	28.1	19.4
9	33	24.7	16.4
10	30	25.0	16.4
11	32	27.5	21.1
12	25	25.3	18.5
13	22	24.7	12.6
14	39	26.2	16.1
15	35	29.3	23.6
Mean (SD)	36.5 (8.5)	26.3 (1.6)	18.8 (3.0)

Table 2
Doppler bubble detection

Doppler bubble detection	Control (no exercise)	Exercise at 24 h	Exercise at 2 h
Median peak KM grade (Range)	3 (0–3–)	2 (0–4–)	2 (0–3+)
Time to median peak KM grade (min)	90	82.5	90
Mean KISS (over 180 min period)	17.2	13.1	11.3

Figure 1

KISS for control dives versus pre-dive exercise at 2 h (bars represent mean value); $P < 0.04$

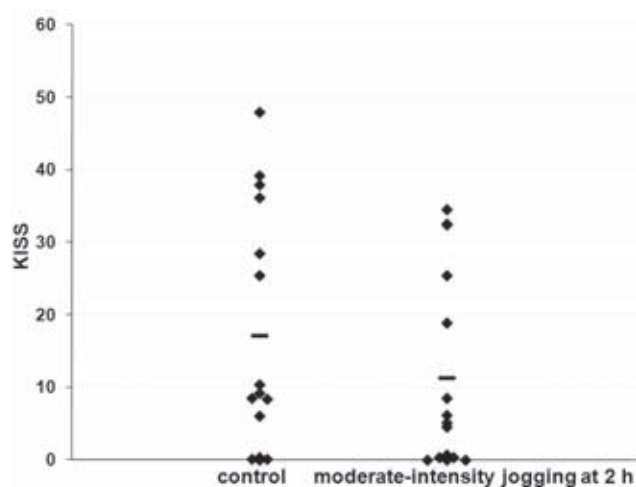
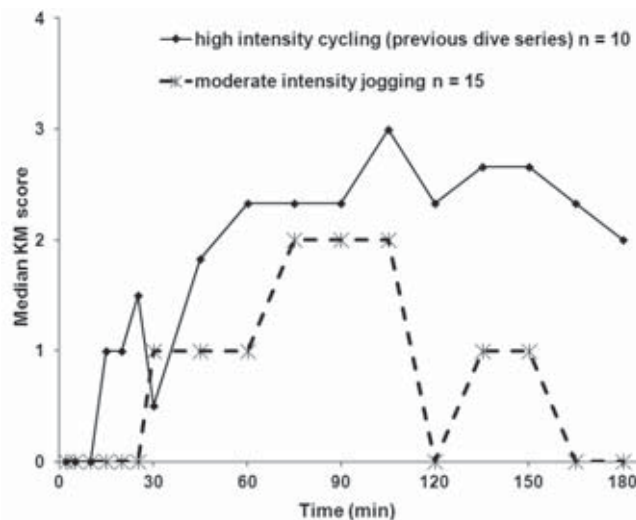


Figure 2

Median KM grades up to 180 min for moderate-intensity jogging versus high-intensity cycling performed 2 h prior to the dive; $P < 0.006$



control and pre-dive exercise dives were compared using the Freidman test. The KISS for pre-dive exercise at 24 or 2 h was compared to the control using the Wilcoxon sign-ranked test. For comparison with our previous series of dives, differences in subject variables were tested using an unpaired t-test. Median KM grades and KISS over the Doppler monitoring period were compared using a Mann Whitney U test. Differences were considered significant if $P < 0.05$.

Results

No DCS occurred in any of the subjects following the dives. Details of individual subject age, BMI and percentage body fat are shown in Table 1.

Details of the Doppler measurement of VGE are shown in Table 2. The median peak KM grade decreased from 3 for the control dives to 2 for those dives with pre-dive exercise at either 2 or 24 h, but this decrease was non-significant. The time to reach the median peak KM grade was similar for all dives. The mean KISS up to 180 min post-dive was lower with pre-dive exercise, but was only significantly different from the control when exercise was conducted at 2 h prior to diving (11.3 versus 17.2, $P < 0.04$, Wilcoxon sign-ranked test). The individual KISS following the control dives and

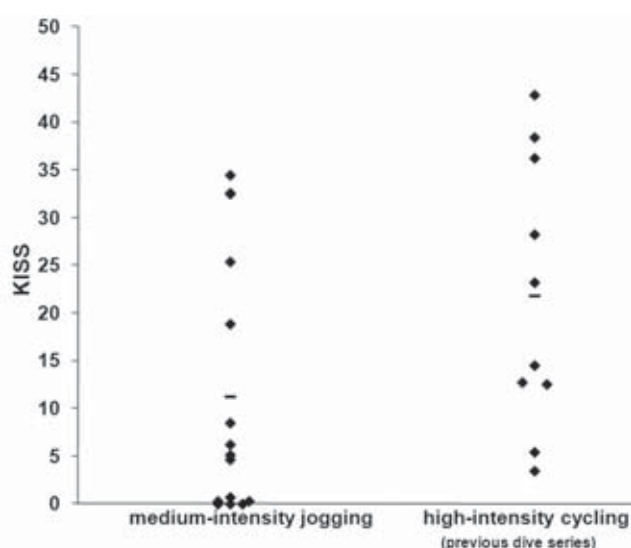
pre-dive exercise at 2 h are shown in Figure 1.

This series of dives was a continuation of our study examining the effect of pre-dive exercise on VGE production. There was no significant difference in the median KM grades over the Doppler monitoring period for this and our previous series of control dives. This allowed the effect of the different mode and intensity of pre-dive exercise to be compared. Changing from the high-intensity, low-impact cycling used previously to moderate-intensity impact exercise resulted in a reduction in median KM bubble grades over the monitoring period when conducted at 2 h ($P < 0.006$, Mann Whitney U Test, Figure 2), but not 24 h, prior to diving. Similarly, the KISS was only different between the exercise conditions when performed 2 h prior to the dive (11.3 versus 21.8, $P < 0.04$, Mann Whitney U Test, Figure 3). There were no significant differences in subject variables.

Discussion

Recent studies have demonstrated that prior exercise can reduce the number of VGE and the incidence of DCS following a pressure exposure.^{2,3,7–10} The peak Doppler bubble grade is often used for comparing the decompression stress between dives. However, some studies have used limited Doppler monitoring, with measurements at four time

Figure 3
KISS for moderate-intensity jogging versus high-intensity cycling performed 2 h prior to the dive
 (bars represent mean value); $P < 0.04$



points in some and as few as only two in others, making it difficult (or impossible) to know whether a peak had been reached. Furthermore, the duration of the monitoring has been as short as 60 min, which may have missed VGE produced in those with a long latency of bubble evolution. Indeed, following our present dives the maximum latency to VGE detection was 120 min.

We monitored VGE for at least 180 min, from first appearance until a peak was reached and then until bubbles either declined or disappeared, totalling a minimum of 17 measurements for each subject for each dive. No significant difference was demonstrated between the peak KM grades for the control dives and those with prior exercise at either 24 or 2 h. However, a single peak Doppler grade gives no information as to the grades over the whole of the monitoring period. The KISS integrates VGE over time, providing a more complete picture of bubble activity and gas load than a single peak KM grade.¹⁵ We found no significant difference between the KISS for control dives and those with pre-dive exercise at 24 h. However, the KISS was significantly reduced when exercise was conducted 2 h prior to the dive.

The benefit of this pre-dive exercise at 2 h, but not at 24 h, led us to question whether the results of our previous series of dives could be explained in terms of the intensity/mode of exercise. The only difference we found was a significant reduction in bubbles in changing from the previous high-intensity cycling to moderate-intensity jogging when conducted 2 h prior to a pressure exposure. This suggests that exercise mode/intensity does indeed have an effect if conducted this close to a dive.

The majority of published results on the effect of pre-dive exercise on post-decompression VGE have come from two main groups, showing benefit at either 24 h or 2 h before diving. It is important that independent studies are conducted so that confidence in the results of such studies is robust. Moreover, if there is a common mechanism involved it will not be influenced by factors that may be peculiar to a particular research group. Our previous dive series used the same exercise intensity and duration as that used by Dujic et al. 24 h before diving, but changed the exercise mode from running to cycling and examined its effect at 24 h or 2 h prior to diving.^{3,11} This did not result in a reduction in VGE and in our present dive series there was no benefit from medium-intensity jogging on the spot (which can be considered as similar in impact to treadmill running) when conducted 24 h prior to diving. Thus, it may be that only the combination of high-intensity and running (impact) exercise is effective in reducing VGE when conducted 24 h prior to a dive, as reported by Dujic et al.³

For pre-dive exercise conducted at 2 h, both medium- and high-intensity running and cycling have been reported to reduce VGE.⁷⁻⁹ However, in contrast, our previous dive series showed that high-intensity cycling at this time did not reduce VGE formation and others have found no benefit from high-intensity running this close to a dive.²⁻⁶ The results of our present dive series confirm the earlier results of Blatteau et al. by demonstrating that moderate-intensity jogging on the spot 2 h prior to diving reduces VGE formation.⁷ An interesting recent finding is that a period of whole-body vibration 1 h before diving decreased VGE formation.¹⁶ Vibration may have a similar action to impact exercise and this may account for the beneficial effect we observed with higher-impact exercise such as jogging and jumping, while we observed no such benefit for low-impact cycling.

When conducting a series of investigations it is desirable to have a level of confidence in the reproducibility of VGE production following control dives. In our study, there was no significant difference in the level of VGE between our present and previous series of control dives. However, reproducibility has been highlighted by others as being problematical. Studies in rats weighing less than 300 g produced few bubbles on some occasions, but many on others (median Doppler grade 0 versus grade 4).^{4,5,17} Similarly in man, control dive profiles which had been chosen to reproducibly produce significant Doppler grades resulted in very low bubble grades (median peak grade 0) in a study which had previously resulted in a median peak grade of 3.^{3,18} This lack of reproducibility in VGE following control dives leads to the suspicion that dives with prior exercise may also produce differing results on different occasions. Thus, variability in VGE in studies with relatively small subject numbers may be responsible for some of the differences between studies.

Gas bubbles produced following a pressure exposure are thought to grow from micronuclei present in tissues and crevices on blood vessel walls. Muscle activity can induce micronuclei, and microbubbles have recently been demonstrated in the leg muscles of human subjects after exercise on a cycle ergometer, which decayed over time following cessation of exercise.¹⁹ The half-life of intravascular exercise-induced micronuclei was in the order of one hour in another study.²⁰ Some forms of exercise may act to dislodge micronuclei from the vessel surface and increased blood flow during exercise may cause 'wash-out' of bubble micronuclei from the endothelial cell surface. Removal of such micronuclei before a pressure exposure would have obvious benefits in terms of VGE production, but the net effect will be the difference between their formation and elimination. For exercise close to a dive, the effect may be different depending on the duration of the dive.

If there is a simple common mechanism for the effect of exercise before diving per se it would seem reasonable that studies would agree on timing and exercise mode and intensity. The exact mechanism(s) of any protection afforded by exercise is unknown at present, but is likely to be multifactorial.^{2,21–23} To have a major impact on diving 'safety', reductions in Doppler grades that represent a substantial reduction in gas load must be demonstrated, as high numbers of VGE are associated with an increased risk of DCS.^{24,25} The protective effect may be too small or too variable to allow more stressful dives to be carried out with improved safety. Some apparent disparities between studies in the timing and intensity/mode of exercise can be explained, but others remain unresolved. Perhaps commonality should be sought in developing an approach for larger scale trials using consistent dive profiles and full Doppler monitoring, which may then lead to a consensus on the benefit of exercise before diving.

Conclusion

This study suggests that moderate-intensity impact exercise reduces VGE production when conducted 2 h prior to diving.

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Conflict of interest: none

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Annex 7.

Loveman, GAM.

Optimising submarine tower escape.

Proceedings of the 11th International Naval Engineering Conference, Edinburgh 2012

Optimising submarine tower escape

G A M Loveman, BSc (Hons)

QinetiQ, UK

SYNOPSIS

Escape from a distressed submarine (DISSUB) involves the rapid pressurisation of the escaper in a small airlock (the escape tower) which is flooded until reaching ambient sea pressure, followed by ascent to the surface. Current escape towers of UK RN submarines may be operated in one of two modes referred to as 'inboard-vented' or 'non-vented.' Traditionally, the system has been optimised for use in the inboard-vented mode. QinetiQ originated a concept to optimise an escape tower for use with the non-vented method simply by increasing the diameter of the flood orifice and associated flood pipe work, thus decreasing pressurisation time and reducing the likelihood of decompression sickness (DCS). QinetiQ was tasked by the MoD to investigate this more fully using a mathematical model developed in-house to simulate submarine tower escape. Using the optimised non-vented escape method is predicted to have several benefits, including lower Hood Inflation system (HIS) air usage, lower rates of DCS and, in contrast to inboard-vented escape, the safety of the method is not compromised if the DISSUB is at a significant angle of heel or pitch. In addition, it is suggested that, for shallow scenarios, a tower optimised for non-vented runs may still be successfully used in the inboard-vented mode, avoiding the large air-water interchange that occurs for shallow non-vented escape. Ongoing studies will help inform the MoD decision as to whether to optimise escape towers for non-vented escape.

INTRODUCTION

To discharge its duty of care to submariners, the MoD has fitted submarines with submarine escape systems. The MoD requires ongoing advice on the hazards and mitigation measures that could be implemented in order to meet its single statement of user need for submarine escape, rescue, abandonment and survival (SMERAS): "The user shall be able to maximise the survivors from a submarine that has sunk or must be abandoned on the surface, whenever and wherever a Royal Navy submarine is operating."¹ The procedures and methods described here apply to the in-service escape equipment as fitted to current UK RN submarines.

Author's Biography

Geoff Loveman has been an employee of QinetiQ since 1993. His roles include technical direction of QinetiQ SMERAS research programmes and advising on the physical and physiological issues pertinent to different escape, rescue and abandonment systems. Geoff has authored mathematical models for the prediction of safety of escape from a DISSUB, involving optimization of non-linear models of DCS simulating gas bubble growth within the body. Geoff has authored reports on many aspects of submarine escape including defining the acceptable envelope of escape tower operation based on physical and physiological considerations. He has also designed mathematical models for simulating conditions within a distressed submarine, allowing prediction of the use of resources and atmosphere control equipment.

BACKGROUND

Submarine tower escape

An escape tower is an airlock onboard a submarine, allowing rapid equalisation of pressure between the airlock and the sea. (Pressure increases by approximately 1.0 bar for each 10 m of descent below the surface of the sea.)

In tower escape, one or two personnel escape at a time. The escapers climb into the tower from the DISSUB compartment via a lower hatch which is then closed. The tower is flooded with seawater from outside the submarine, via a flood system. The rate of flooding depends on the square root of the pressure differential between sea and tower and on the diameter of the flood pipe. The desired flooding rate is achieved through the use of a fixed diameter orifice plate mounted on the end of the flood pipe.

During the escape procedure, the air inside the tower is compressed, increasing tower pressure until equalisation is achieved between tower pressure and the ambient sea pressure. The upper hatch of the tower, being spring-loaded, then opens and the escapers exit and ascend to the surface.

The hood inflation system

The hood inflation system (HIS) supplies air to the escaper(s) during DISSUB tower escape. The escaper(s) wear submarine escape immersion equipment (SEIE), part of which comprises a suit with a built-in inflatable stole, similar to a life-jacket. This provides buoyancy for the ascent to the surface. The HIS is designed to keep the stole inflated to a pressure slightly above the ambient tower pressure, excess air passes from the stole to the hood via two relief valves, providing breathing air for the escaper, air in the hood can pass to the tower via an opening at the base of the hood. The HIS air is stored in dedicated cylinders. There is a finite mass of air available. Due to this, air usage per escaper is important, as there must be enough air stored at each end of the submarine to allow the entire crew to escape.

Some physiological constraints on tower escape

Decompression Sickness

Breathing air at raised pressure causes an accumulation of dissolved gases (mainly nitrogen) in the body's tissues. Subsequent rapid return to surface pressure allows these gases to come out of solution, forming bubbles in the body. These bubbles can directly disrupt tissue function, or indirectly affect function by blocking the blood supply to cells, or by disturbing blood biochemistry. The range of signs and symptoms that may result from these processes are referred to specifically as decompression sickness (DCS). DCS can lead to permanent paralysis or other neurological disability and in extreme cases, death. DCS may be avoided by limiting the time spent breathing gases at raised pressure and by controlled or staged decompression.

Barotrauma

The body is mostly comprised of fluid filled structures. Since fluids are highly incompressible, these structures are largely unaffected by exposure to raised ambient pressure. However, the air filled structures of the body, namely the lungs, ears and sinuses may be subject to damage during changes in ambient pressure. Of primary concern in tower escape are injury to the middle ear (barotrauma auris mediae) and injury to the lung (pulmonary barotrauma). In other circumstances, pulmonary barotrauma would not necessarily be life threatening. However, given the likely scenarios in which tower escape would be attempted, pulmonary barotrauma would almost certainly lead to death of the escaper.

Maximum rates of pressurisation

The introduction of sea water into the escape tower reduces the volume of the air space. Once the vent is closed the continued flooding increases the pressure at a geometric rate, the pressure doubling in constant time. This doubling time can be selected through control of variables such as the height of the vent and the flood inlet orifice diameter.

If pressurisation is too rapid (pressure doubling time too short), the escaper may suffer barotrauma of descent such as eardrum rupture or lung damage (“lung-squeeze”) which may lead to serious injury or death during the ascent to the surface².

A previous review of injuries occurring in escape trials due to the pressurisation phase of escape recommended that, in order to avoid barotrauma, a pressurisation rate based on pressure doubling every 4 s should be regarded as the maximum acceptable². The review also recommended that allowing longer pressure doubling times at the start of the pressurisation phase may reduce stress on the escaper with negligible increase in the risk of DCS.

The flood orifice diameter of current RN escape systems is fixed to give a peak pressure doubling rate of doubling every 4 s, the initial pressurisation being slower and gradually accelerating. This pattern of pressure doubling may be desirable since the escaper has a short time to adapt to the rapid pressurisation.

Inboard-vented and non-vented tower configuration

The escape tower is fitted with a vent pipe which, when open, allows air to pass from the tower into the DISSUB compartment, where the rest of the crew are awaiting their turn to escape. The tower may be setup in either of two configurations which are referred to as ‘inboard-vented’ and ‘non-vented.’

Inboard-vented escape and the effect of the height of the vent

In an inboard-vented escape, the vent pipe is initially open. A valve in the flood system (the ‘flood valve’) is opened, allowing seawater to flood the tower. While the vent pipe remains open, the tower pressure does not noticeably increase because air passes from the small volume of the tower into the larger volume of the DISSUB compartment below (this increases the pressure in the DISSUB slightly for each escape cycle). This part of the procedure is commonly referred to as the ‘flood phase’ or simply ‘the flood.’ When water reaches the level of the mouth of the vent pipe (the ‘vent height’), the vent is shut. The remaining air in the tower, which occupies the volume of the tower above the level of the mouth of the vent pipe, is commonly referred to as ‘the bubble.’ Water continues to fill the tower via the flood pipe and the pressure in the tower now increases as the bubble is compressed. This part of the escape procedure is commonly referred to as the ‘compression phase,’ the ‘pressurisation phase’ or simply, ‘the press.’

According to Boyle’s law (and ignoring thermal effects for simplicity), when a sufficient volume of water has entered the tower to halve the volume of the bubble, the pressure in the bubble will have doubled. Understanding this relationship is key to understanding the dynamics of tower pressurisation and the importance of the vent height. During the flood and until water reaches the vent, the pressure differential between the sea and the tower remains constant (ignoring the relatively small head of water within the tower) and thus, the rate at which water enters the tower via the flood pipe also remains constant. If the vent height (as measured from the lower hatch) were to be increased such that the initial bubble volume was halved, then the initial rate of pressure increase from the moment the vent was shut would be doubled.

Since the water flow rate is proportional to the square root of the differential between sea and tower pressure, the reduction in differential due to the pressure doubling has only a small effect on the rate of water ingress for most of the pressurisation. As the bubble volume is further compressed, the volume of water required to halve the bubble volume again is itself halved. Or put another way, the volume of water required to double the tower pressure halves with each succeeding pressure doubling. This process leads to an exponentially accelerating rate of pressurisation. In the final seconds of the pressurisation, the reduction in differential pressure between sea and tower begins to have a significant effect on the rate of water ingress and pressurisation slows rapidly to equalisation.

Inboard-vented versus non-vented escape

If a DISSUB were grounded in relatively shallow water, with, for example, an escape tower depth of 30 m, then the initial pressure differential driving the flood of the tower would be at most 3.0 bar. If the vent was left open, there would be a long, slow flood phase, during which any HIS air used would be wasted and pass to the DISSUB compartment below. This effect causes an increasing use (and wastage)

of HIS air if the inboard-vented method is employed at progressively shallower depths. Non-vented runs do not suffer this effect because the HIS air used is not vented to the DISSUB but instead increases the tower pressure, an effect referred to as 'air-aiding,' this leads to the tower reaching equalisation sooner, resulting in less air used in total.

If the escape tower depth is sufficiently great, then air-aiding has less effect in reducing the total differential pressure and the inboard-vented method becomes more efficient in terms of air usage. The shortening of the inboard-vented flood phase due to the increased pressure differential, combined with the rapid pressurisation phase afforded by a smaller bubble, allows a reduction in total air usage. Thus there is a cross-over depth at which the inboard-vented and non-vented methods use the same amount of air. In the past it has therefore been common to recommend the use of the inboard-vented method for escapes deeper than this cross-over depth and the non-vented method for shallow escapes. However, at very shallow escape depths, use of the non-vented method will result in a large bubble and therefore a large air-water interchange upon tower equalisation which could be injurious to the escaper(s). The inrush of water may also create many small air bubbles in the water in the tower which reduces visibility and buoyancy.

Inboard-vented escape and the effect of DISSUB angle on maximum pressurisation rates

Inboard-vented escape can be compromised by the pitch and/or roll angle of the submarine. If the DISSUB is lying on the sea bed with some angle of pitch/roll, the bubble of air above the vent will be altered in volume for inboard-vented runs (Fig 1). For scenarios where the bubble volume is reduced, this effect could lead to breaching of the pressure doubling limit.

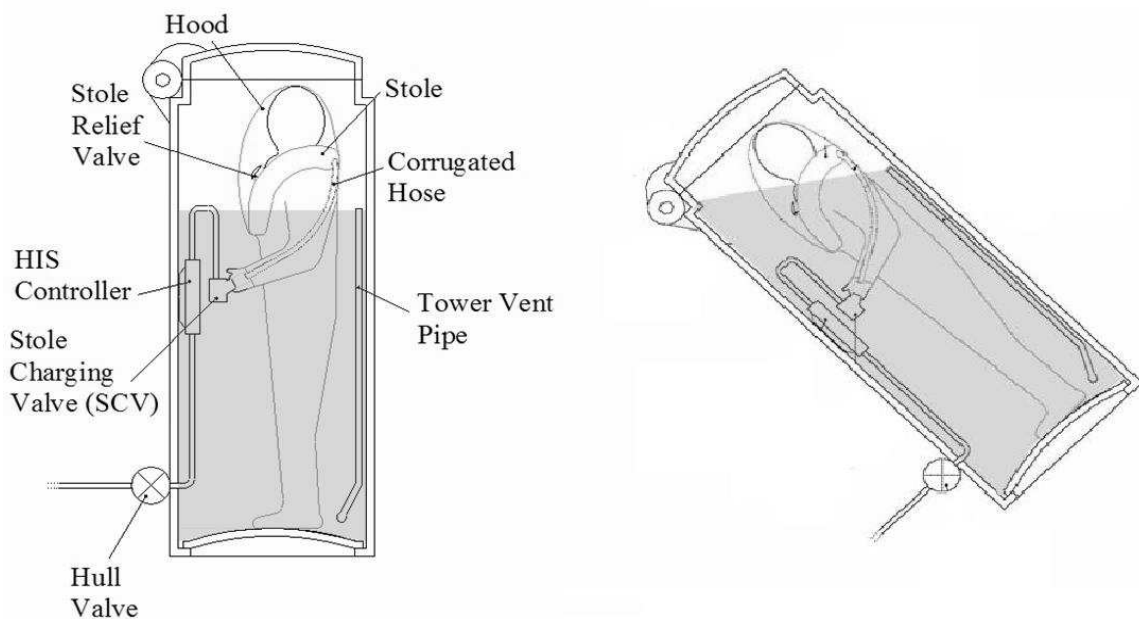


Fig 1 Effect of DISSUB pitch angle on air bubble volume for inboard-vented escape

Non-vented escape and the effect of an increased flood orifice diameter

In a non-vented escape, the vent pipe is shut prior to opening the flood valve so, in effect, the bubble has the same volume as the escape tower (minus the volume of the escapers). The entire process consists of a pressurisation phase only and no air passes into the DISSUB compartment below. Since the bubble is relatively large, the pressurisation in a non-vented escape is slower than in inboard-vented escape for similar towers with the same diameter flood orifice and risk of DCS to the escaper is therefore increased. However, this slowing of pressurisation may be overcome by increasing the diameter of the flood pipe and orifice sufficiently, in which case, the tower may be said to be optimised for non-vented escape, eliminating any difference in risk of DCS for the escaper when compared with inboard-vented escapes.

AMESim based model for escape tower simulation

A model for simulating the escape tower and functioning of the HIS was previously developed by QinetiQ (at that time, the Defence Research Agency) and the Fluid Power Centre at University of Bath³. The model has subsequently been enhanced to reflect updates to the escape system components and to run within LMS Imagine.labs Adaptive Modelling Environment for Simulation (Imagine.Lab AMESim), a dynamic simulation package for fluid systems engineering. A number of submodels exist for simulation of different tower types and configurations, however, for simplicity, the group of models is referred to here as the QinetiQ HIS model.

OBJECTIVES

In order to determine whether an optimised non-vented method could be adopted safely it is necessary to show that:

- a diameter (increased over the current value) can be established for the flood orifice and associated flood pipe work, that will allow each tower type to be flooded non-vented at such a rate as to provide pressure doubling not more rapidly than every 4 s;
- any non-vented pressure profile proposed for use does not result in a marked increase in predicted risk of DCS when compared with the current inboard-vented escape profile for the same depth;
- any non-vented pressure profile proposed for use does not result in an increase in HIS air usage when compared with the current inboard-vented escape profile for the same depth or still allows sufficient air for the full crew to escape.

METHOD

The QinetiQ HIS model was used to generate pressure/time profiles and air usage predictions for escape depths from 30 to 180 m; this was carried out for simulated inboard-vented and non-vented escapes for the current TRAFALGAR class submarine tower configuration, a one-man, or single escape tower (SET) with a 19 mm diameter flood orifice. Simulations were also carried out for non-vented escapes with the flood orifice parameter in the model increased to allow rapid non-vented pressurisation of the SET, but at a rate no greater than pressure doubling every four seconds for an escape at 180 m. A small number of trial runs in Imagine.Lab AMESim showed this to be possible with the flood pipe orifice diameter set to 32.5 mm. Plots were made showing predicted pressurisation times and pressure doubling rates for a selection of escape depths for the system fitted with a 32.5 mm flood orifice.

RESULTS

Fig 2 shows a plot of predicted pressure doubling times for escape depths of 30 and 180 m for inboard-vented escape with the escape system fitted with a 19 mm flood orifice and for non-vented escape with the escape system fitted with 32.5 mm flood orifice and pipe work.

Fig 3 shows a plot allowing comparison of predicted pressurisation times for 30 and 180 m inboard-vented escapes with a 19 mm flood orifice and for non-vented escapes with 32.5 mm flood pipe work.

Note that in Fig 2 and Fig 3, the flood phase of the inboard-vented profiles has been removed to allow comparison of the pressurisation phases of the inboard-vented with the non-vented escape profiles.

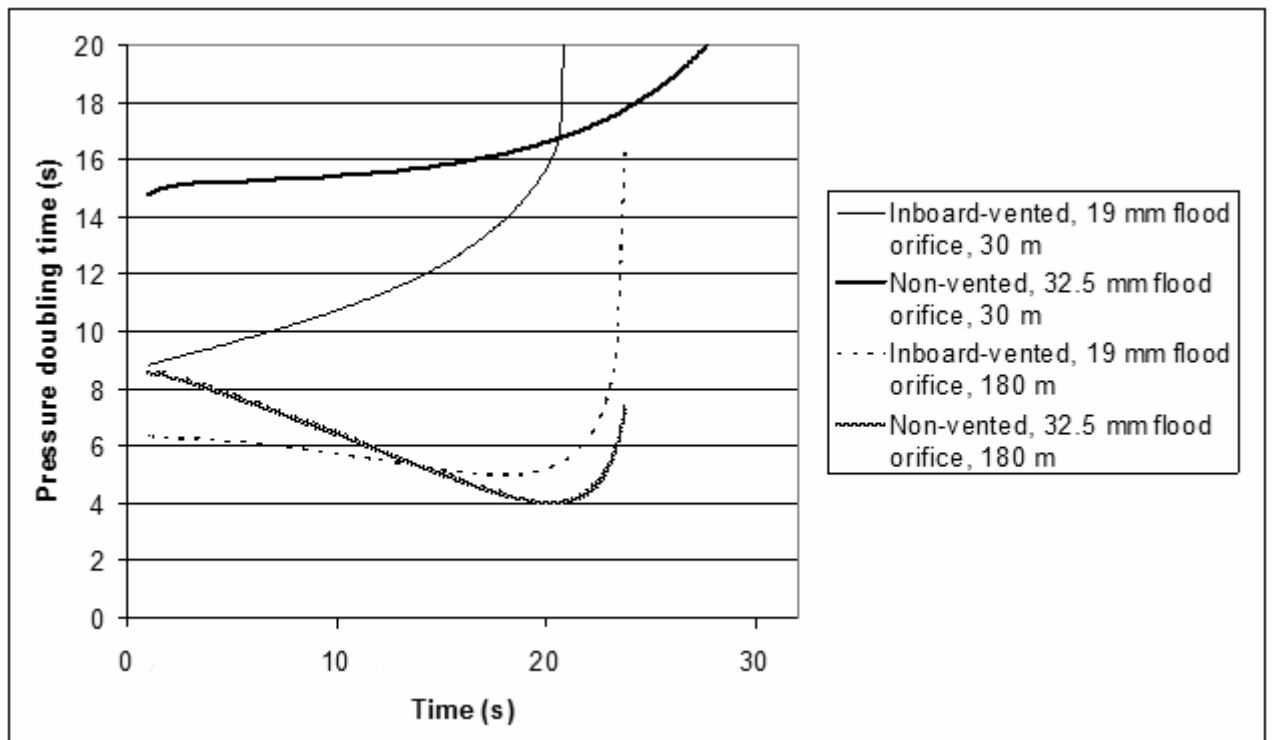


Fig 2 Predicted tower pressure doubling times for inboard-vented escapes with a 19 mm flood orifice and for non-vented escapes with a 32.5 mm flood orifice

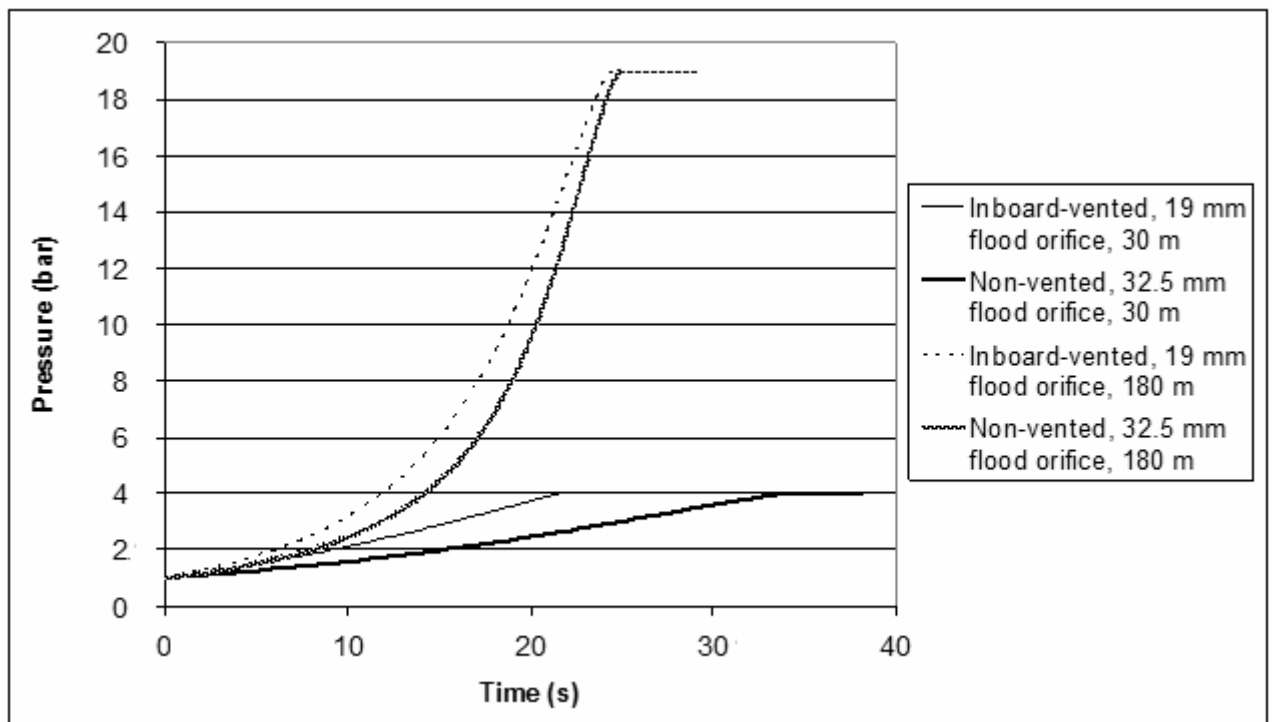


Fig 3 Predicted tower pressurisation curves for inboard-vented escapes with a 19 mm flood orifice and for non-vented escapes with a 32.5 mm flood orifice

DISCUSSION

Fig 2 and Fig 3 show predicted pressure doubling times and escape profiles for a SET with the flood orifice increased to 32.5 mm. It can be seen from Fig 2 that this flood orifice diameter is predicted to give the desired pressure doubling every 4 s for an escape at 180 m tower depth².

Fig 3 shows predicted escape profiles for 30 and 180 m for inboard-vented escape using a flood orifice of 19 mm diameter and for non-vented escape with a 32.5 mm diameter orifice. It can be seen that, in terms of pressurisation time, the profiles are fairly similar, with the 30 m non-vented run with 32.5 mm orifice being slightly longer in duration. If the flood phase of the inboard-vented runs is taken into account, the inboard-vented runs will be appreciably longer (up to approximately a minute longer for shallow escapes). Thus the escape cycle time for each escaper to leave the submarine may be reduced for optimised non-vented runs, allowing the entire crew to escape in perhaps three-quarters of the time required for inboard-vented escape. In inboard-vented escape, a large proportion of the HIS air requirement is used during the flood phase. This air is essentially wasted and is also detrimental to the survival of the crew since it raises the pressure in the escape compartment, exacerbating the risk of DCS. Since non-vented escapes do not cause any increase in compartment pressure, the method does not increase DCS to the crew waiting to escape. Therefore, optimised non-vented escapes will allow a net reduction in the rate of DCS for all scenarios.

It should be noted that increasing the flood orifice diameter will have a negligible effect on the velocity of the incoming water jet during the non-vented escape. It is only the volume of water entering the tower per unit time that is substantially increased. This causes an increase in the rate of water rise in the tower. The main danger in this case would be that the escaper might be caught by surprise by the rate of water rise in the tower and fail to steady themselves against the buoyancy of their SEIE. The likelihood of this occurrence could be reduced through appropriate training.

Thus, the use of a flood orifice, optimised in diameter for the non-vented method, has many benefits to recommend its adoption with few disadvantages.

A question which therefore arises is why the current system was designed primarily for inboard-vented escape. Referring to historical documentation reveals that one main reason for this may have been that the original intent was to have a One Man Escape Chamber (OMEC) that would be flooded with seawater to the level of a vent pipe as with the current inboard-venting method, but that once water reached the level of the vent pipe, the flood pipe would be closed and the escaper would be pressurised to the escape depth using compressed air from a high pressure supply⁴. The reasons for the pressurisation on air are obvious: the SEIE did not exist at this time and the use of the Davis Submerged Escape Apparatus (DSEA) was known to have problems due to oxygen toxicity at high pressures⁵. Without SEIE or breathing apparatus to supply clean air, pressurisation to the escape depth using seawater would result in the escaper breathing poisonous levels of carbon dioxide and possibly other toxic gases, oil fumes *etc.*

Testing of this system showed problems that could not be resolved,⁶ requiring the introduction of an escape suit and HIS. Since the inboard-vented method was ingrained in the design and as alteration of the vent height is certainly easier than altering the flood pipe work diameter, there must have been little incentive at this time to consider the benefits of switching to an entirely non-vented system.

It should be noted that the difficulty of altering the flood pipe work once installed must be considered – any flood pipe work must be installed with a diameter sufficiently large that only the flood orifice itself has a significant effect on the flooding rate. For TRAFALGAR class submarines this is not anticipated to present an engineering problem and only minor alteration to the existing pipe work and flood valve would be necessary.

Adoption of a single escape method across all scenarios would allow instructions to the crew to be made substantially simpler and reduce training requirements in this area.

As stated earlier, at very shallow escape depths, use of the non-vented method will result in a large air-water interchange upon tower equalisation which could be disorientating or injurious to the escaper(s). Use of the inboard-vented method for shallow escapes avoids this problem, but in current systems has been shown to result in excessive use of HIS air due to prolonged flood and pressurisation times. Inboard-vented shallow escapes in a system optimised for non-vented escape would not suffer the

problem of prolonged flood and pressurisation times to the same extent. However, a suitable depth must be determined for switching between non-vented and inboard-vented escapes. Also, flood orifice diameters and vent heights must be determined for each type of escape tower that will allow safe escape for each mode of escape when used across the appropriate range of depths. These considerations form part of ongoing studies to help inform the MoD decision as to whether to optimise escape towers for non-vented escape.

CONCLUSIONS

The QinetiQ HIS model predicts that a modified flood orifice optimised for the non-vented escape method can be safely used in TRAFALGAR class submarines, however, the possible use of inboard-vented escape for very shallow depths remains to be investigated.

The optimised-non-vented escape method has several beneficial aspects, including that rates of DCS will be lower for all escape scenarios, HIS air usage will be reduced, escape cycle time will be reduced and the method is not compromised if the DISSUB is at a significant pitch angle.

ACKNOWLEDGEMENTS

This work was funded through the Maritime Strategic Capability Agreement, a contract awarded to QinetiQ by the UK MoD, Defence Equipment and Support.

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Annex 8.

Loveman, GAM.

Optimising submarine tower escape, effects of submarine angle and shallow depth.

Proceedings of PACIFIC 2013 International Maritime Conference, Sydney, October 2013

Corrigendum

A commonly made assumption amongst those working underwater is that a depth change of 10 metres of sea water is associated with a pressure change of 1 bar (100 kPa).

This assumption implies a fixed value for the density of sea water, ρ , which may be derived from the formula for the pressure, P , acting at depth D , in a column of water:

$$P = \rho g D \quad \text{Equation (i)}$$

Where g is the acceleration due to gravity, 9.80665 m.s^{-2}

The change of pressure with depth is therefore:

$$\frac{\partial P}{\partial D} = \rho g \quad \text{Equation (ii)}$$

For the pressure-depth relationship as stated above, we see that $\frac{\partial P}{\partial D} = 0.1 \text{ bar} \cdot \text{m}^{-1}$, substituting this value into **Equation (ii)**, the sea water density may be calculated as:

$$\rho = \frac{1}{10g} \text{ bar} \cdot \text{s}^2 \cdot \text{m}^{-2}$$

This value for the density of sea water has been substituted into **Equation (1)** and consequently **Equations (4)** and **(7)** in this paper; however, this has not been made clear in the text.

The author is indebted to Dr William Lee, Reader in Industrial Mathematics of the University of Portsmouth for pointing out this omission.

Replacement of the substituted value with ρ leads to the following, more generally applicable formulae (note that in these formulae, SI units may be used throughout):

$$\frac{\partial V(t)}{\partial t} = -CA \sqrt{\frac{2 \left(P_E - P_0 \left(\frac{B}{V(t)} \right)^n \right)}{\rho}} \quad \text{Equation (1)}$$

$$t = \frac{k - \frac{V(t)}{\sqrt{P_E}} \cdot {}_2F_1 \left(\frac{1}{2}, -\frac{1}{n}; 1 - \frac{1}{n}; \frac{P_0 \left(\frac{B}{V(t)} \right)^n}{P_E} \right)}{\sqrt{\frac{2}{\rho}} \cdot AC} \quad \text{Equation (4)}$$

$$t = \frac{k - \frac{B}{\sqrt{P_E}} \cdot \left(\frac{P_E}{P_0} \right)^{-\frac{1}{n}} \cdot {}_2F_1 \left(\frac{1}{2}, -\frac{1}{n}; 1 - \frac{1}{n}; \frac{P_0 \left(\frac{B}{V(t)} \right)^n}{P_E} \right)}{\sqrt{\frac{2}{\rho}} \cdot AC} \quad \text{Equation (7)}$$

Optimising Submarine Tower Escape, Effects of Submarine Angle and Shallow Depth

Geoff Loveman

QinetiQ, UK

ABSTRACT

Escape from a distressed submarine (DISSUB) involves the rapid pressurisation of the escaper in a small airlock (the escape tower) which is flooded until reaching ambient sea pressure, followed by ascent to the surface. Current escape towers of UK Royal Navy (RN) submarines may be operated in one of two modes referred to as 'inboard-vented' or 'non-vented.' Traditionally, the system has been optimised for use in the inboard-vented mode. QinetiQ originated a concept to optimise an escape tower for use with the non-vented method simply by increasing the diameter of the flood orifice and associated flood pipe work, thus decreasing pressurisation time and reducing the likelihood of decompression sickness (DCS). QinetiQ was tasked by the MoD to investigate this more fully using a mathematical model developed in-house to simulate submarine tower escape. Using the optimised non-vented escape method is predicted to have several benefits, including lower hood inflation system (HIS) air usage, lower rates of DCS and, in contrast to inboard-vented escape, the safety of the method is not compromised if the DISSUB is at a significant angle of heel or pitch. In addition, for scenarios shallower than 30 m a tower optimised for non-vented escape may still be successfully used in the inboard-vented mode, avoiding the large air-water interchange that occurs for shallow non-vented escape.

BACKGROUND

Submarine Tower Escape

An escape tower is an airlock on board a submarine, allowing rapid equalisation of pressure between the airlock and the sea. (Pressure increases by approximately 1.0 bar for each 10 m of descent below the surface of the sea.) All UK RN submarines are fitted with an escape tower at each end. Each tower is either a Forward or Single Escape Tower (FET or SET), from which one person escapes at a time or a Logistics and Escape Trunk (LET), from which one or two people may escape at a time. The escapers climb into the tower from the DISSUB compartment via a lower hatch which is then closed. The tower is flooded with seawater from outside the submarine. The desired flooding rate is achieved through the use of a fixed diameter orifice plate mounted on the end of the flood pipe. During the escape procedure, the air inside the tower is compressed, increasing tower pressure until equalisation is achieved with the ambient sea pressure. The upper hatch of the tower, being spring-loaded, then opens and the escaper(s) exit and ascend to the surface.

The Hood Inflation System

The HIS supplies air to the escaper(s) during DISSUB tower escape. The escaper(s) wear submarine escape immersion equipment (SEIE), part of which comprises a suit with a built-in inflatable stole, similar to a life-jacket. This provides buoyancy for the ascent to the surface.

The HIS is designed to keep the stole inflated to a pressure slightly above the ambient tower pressure. Excess air passes from the stole to the hood via two relief valves, providing breathing air for the escaper. Air in the hood can also pass to the tower via an opening at the base of the hood. The HIS air is stored in dedicated cylinders and there is a finite mass of air available. Air usage per escaper is an important factor, as there must be enough air stored at each end of the submarine to allow the entire crew to escape.

Some Physiological Constraints on Tower Escape

Decompression sickness - Breathing air at raised pressure causes an accumulation of dissolved gases (mainly nitrogen) in the body's tissues. Subsequent rapid return to surface pressure allows these gases to come out of solution, forming bubbles in the body. The range of signs and symptoms that may result are referred to specifically as decompression sickness (DCS). DCS can lead to permanent paralysis, neurological disability or death. DCS may be avoided by limiting the time spent breathing gases at raised pressure and by controlled or staged decompression.

Barotrauma - The body is mostly comprised of fluid filled structures. Since fluids are highly incompressible, these structures are largely unaffected by exposure to raised ambient pressure. However, the air filled structures of the body, namely the lungs, ears and sinuses may be subject to damage during changes in ambient pressure. Of primary concern in tower escape are injury to the middle ear (barotrauma auris mediae) and injury to the lung (pulmonary barotrauma). In other circumstances, pulmonary barotrauma would not necessarily be life threatening. However, given the likely scenarios in which tower escape would be attempted, pulmonary barotrauma would almost certainly lead to serious injury or death of the escaper.

Maximum rates of pressurisation - A previous review of injuries occurring in escape trials due to the pressurisation phase of escape recommended that, in order to avoid barotrauma, a pressurisation rate based on pressure doubling every 4 s should be regarded as the maximum acceptable [1]. The review also recommended that allowing longer pressure doubling times at the start of the pressurisation phase may reduce stress on the escaper with negligible increase in the risk of DCS. The flood orifice diameter of current RN escape systems is set to give a peak pressure doubling rate of doubling every 4 s, the initial pressurisation being slower and gradually accelerating. This pattern of pressure doubling may be desirable since the escaper has a short time to adapt to the rapid pressurisation.

Inboard-Vented and Non-Vented Tower Configuration

The escape tower is fitted with a vent pipe which, when open, allows air to pass from the tower into the DISSUB compartment, where the rest of the crew are awaiting their turn to escape. The tower may be setup in either of two configurations which are referred to as 'inboard-vented' and 'non-vented.'

Inboard-vented escape - In an inboard-vented escape, the vent pipe is initially open. During flooding of the tower, while the vent pipe remains open, the tower pressure does not noticeably increase because air passes from the small volume of the tower into the larger volume of the DISSUB compartment below (this increases the pressure in the DISSUB slightly for each escape cycle). This part of the procedure is commonly referred to as the 'flood phase' or simply 'the flood.' When water reaches the level of the mouth of the vent pipe (the 'vent height'), the vent is shut. The remaining air in the tower, which occupies the

volume of the tower above the level of the mouth of the vent pipe, is commonly referred to as 'the bubble.' Water continues to fill the tower via the flood pipe and the pressure in the tower now increases as the bubble is compressed. This part of the escape procedure is commonly referred to as the 'compression phase,' the 'pressurisation phase' or simply, 'the press.'

Non-vented escape - In a non-vented escape, the vent pipe is shut prior to opening the flood valve so, in effect, the bubble has the same volume as the escape tower (minus the volume of the escapers). The entire process consists of a pressurisation phase only and no air passes into the DISSUB compartment below (this reduces risk of DCS for the remaining crew waiting their turn to escape). Since the bubble is relatively large, the pressurisation in a non-vented escape is slower than in inboard-vented escape for similar towers with the same diameter flood orifice and risk of DCS to the escaper is therefore increased.

Inboard-vented versus non-vented escape - If a DISSUB were grounded in relatively shallow water, with, for example, an escape tower depth of 30 m, then the initial pressure differential driving the flood of the tower would be at most 3.0 bar. If the vent was left open, there would be a long, slow flood phase, during which any HIS air used would be wasted and pass to the DISSUB compartment below. This effect causes an increasing use (and wastage) of HIS air if the inboard-vented method is employed at progressively shallower depths. Non-vented runs do not suffer this effect because the HIS air used is not vented to the DISSUB but instead increases the tower pressure, an effect referred to as 'air-aiding,' this leads to the tower reaching equalisation sooner, resulting in less air used in total.

Inboard-vented escape and the effect of DISSUB angle on maximum pressurisation rates - Inboard-vented escape can be compromised by the pitch and/or roll angle of the submarine. If the DISSUB is lying on the sea bed with some angle of pitch/roll, the bubble of air above the vent will be altered in volume for inboard-vented runs (Fig 1). For scenarios where the bubble volume is reduced, this effect could lead to breaching of the pressure doubling limit.

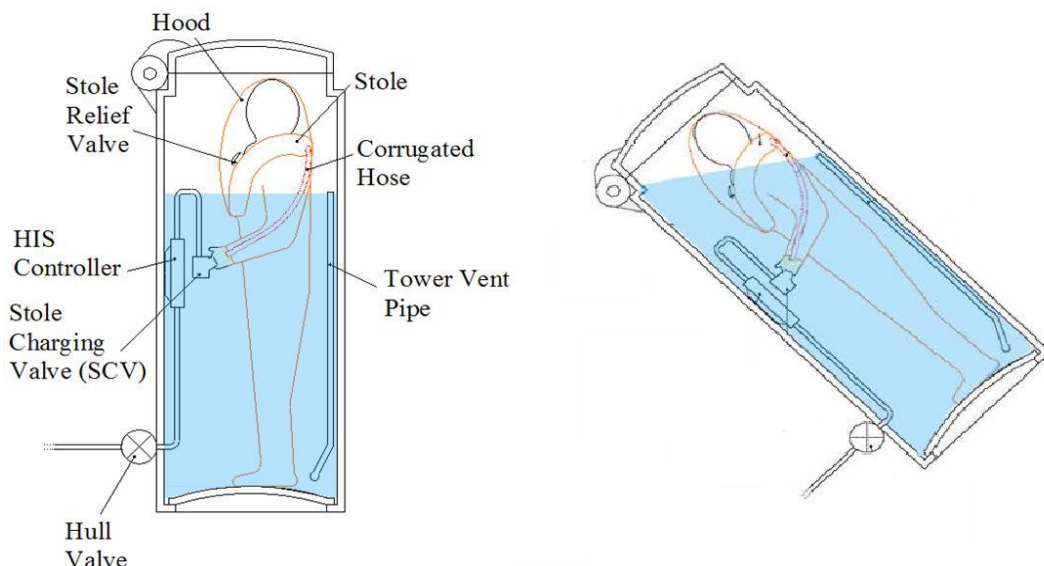


Fig 1. Effect of DISSUB pitch angle on air bubble volume for inboard-vented escape

Optimised non-vented escape, the effect of increasing flood orifice diameter – The slower pressurisation of non-vented escape may be overcome by increasing the diameter of the flood pipe and orifice sufficiently. In which case, the tower may be said to be optimised for non-

vented escape, eliminating any difference in risk of DCS for the escaper when compared with inboard-vented escapes.

Shallow escape and air/water interchange - The optimised-non-vented escape method has been shown to have several beneficial aspects, including that:

- that rates of DCS will be lower for all escape scenarios;
- HIS air usage will be reduced;
- escape cycle time will be reduced;
- the method is not compromised if the DISSUB is at a significant pitch angle [2].

However, at very shallow escape depths, use of the non-vented method will result in a large bubble, and therefore a large air-water interchange at tower equalisation, which could possibly be injurious to the escaper(s). The inrush of water may also create many small air bubbles in the water in the tower which reduces visibility and buoyancy. The incoming water may also push air out of the hood, further reducing buoyancy.

The extent to which any of these effects will actually affect the escaper is currently unknown. In order to avoid the large air/water interchange in shallow escapes it would be necessary to use the inboard-vented method. Shallow inboard-vented escapes waste a large amount of HIS air due to prolonged duration of the flood phase. However, optimising for non-vented escape by increasing the flood orifice diameter would substantially shorten the flood phase for shallow inboard-vented escape, possibly saving enough air to make this method viable.

Prediction of duration of tower pressurisation

Equation (1) was derived from the formula for measurement of fluid flow using an orifice plate [3] and is a first order ordinary differential equation for the rate of change of the tower bubble volume $V(t)$, during pressurisation of the escape tower without the use of the HIS.

$$\frac{\partial V(t)}{\partial t} = -C \left(A \sqrt{2g} \sqrt{10 \left(P_E - P_0 \left(\frac{B}{V(t)} \right)^n \right)} \right) \quad \text{Equation (1)}$$

Where:

P_0 is the initial tower pressure, equal to the submarine compartment pressure (bar)

P_E is the ambient sea pressure (equalisation pressure) at the tower depth (bar)

n is the polytropic index for the pressurisation

g is the acceleration due to gravity, 9.81 m.s^{-2}

A is the cross sectional area of the orifice in the flood orifice plate (m^2)

B is the volume of the bubble above the vent at the start of the press (m^3)

C is the meter coefficient which is defined as

$$C = \frac{C_d}{\sqrt{1 - \beta^4}}$$

Where:

C_d is the coefficient of discharge and

$$\beta = d_2/d_1$$

d_1 = diameter of the flood pipe (m)

d_2 = diameter of the orifice hole (m)

Pressure in the bubble at time t is given by:

$$P(t) = P_0 \left(\frac{B}{V(t)} \right)^n \quad \text{Equation (2)}$$

Temperature in the bubble may be derived from the following formula for a polytropic process (based on trials data, the value of the polytropic index, n , is approximately 1.1 for this process [4]):

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \quad \text{Equation (3)}$$

Equation (1) has an analytic solution, shown below as Equation (4). The solution contains the Gaussian hypergeometric function denoted as ${}_2F_1$. Evaluation of this function is not always straightforward but MATLAB, MathCAD and the R statistical package all contain prewritten functions to evaluate ${}_2F_1$.

$$t = \left(k - \frac{V(t)}{\sqrt{P_E}} \cdot {}_2F_1 \left(\frac{1}{2}, -\frac{1}{n}; 1 - \frac{1}{n}; \frac{P_0 \left(\frac{B}{V(t)} \right)^n}{P_E} \right) \right) \quad \text{Equation (4)}$$

$$2\sqrt{5} \, A C \sqrt{g}$$

The value of the constant of integration, k , in Equation (4) can be calculated by setting $t = 0$ and $V(t) = B$ to give:

$$k = \frac{B}{\sqrt{P_E}} \cdot {}_2F_1 \left(\frac{1}{2}, -\frac{1}{n}; 1 - \frac{1}{n}; \frac{P_0}{P_E} \right) \quad \text{Equation (5)}$$

The value of k must be recalculated for different escape depths.

The volume of the bubble at equalisation (V_E) is given by:

$$V_E = B \left(\frac{P_E}{P_0} \right)^{-\frac{1}{n}} \quad \text{Equation (6)}$$

Substituting for k and V_E from Equations (5) and (6) in Equation (4), the predicted time for pressurisation from vent shut to equalisation at a given depth can then be calculated from:

$$t = \frac{\left(k - \frac{B}{\sqrt{P_E}} \left(\frac{P_E}{P_0} \right)^{-\frac{1}{n}} \cdot {}_2F_1 \left(\frac{1}{2}, -\frac{1}{n}; 1 - \frac{1}{n}; 1 \right) \right)}{2\sqrt{5} AC \sqrt{g}} \quad \text{Equation (7)}$$

Note that the entire pressurisation profile can also be predicted using Equation (4) with a range of values of $V(t)$ from B to V_E .

AMESim Based Model for Escape Tower Simulation

A model for simulating the escape tower and functioning of the HIS was developed by QinetiQ (at that time, the Defence Research Agency) and the Fluid Power Centre at University of Bath [5]. The model was subsequently enhanced to reflect updates to the escape system components and to run within LMS Imagine.labs Adaptive Modelling Environment for Simulation (Imagine.Lab AMESim), a dynamic simulation package for fluid systems engineering. A number of submodels exist for simulation of different tower types and configurations. However, for simplicity, the group of models is referred to here as the QinetiQ HIS model.

OBJECTIVE

To determine, in a system optimised for non-vented escape, a depth shallower than that which inboard-vented escape can be safely made with respect to rates of pressure doubling and HIS air usage, including effects of DISSUB angle.

METHOD

For each tower type, flooding and pressurisation were modelled for both inboard-vented and non-vented escape across the range of depths 10 to 180 m in 10 m increments. In all cases, the flood system orifice diameter was selected to optimise the escape system for non-vented escape at 180 m. For inboard-vented escape, each of these scenarios was also considered for the respective tower tilted at 45° in the plane which maximises variation in tower bubble volume when the water reaches the vent during inboard-vented escape. Following analysis of the results, the method was repeated for the LET at a reduced angle of 30°.

For situations where the angle of pitch/roll is such that the water level in the tower reaches the upper hatch prior to reaching the vent, the formula for calculation of the volume of a cylindrical wedge was required to calculate the bubble volume at the start of the pressurisation phase, see Fig 2 and Equation 8.

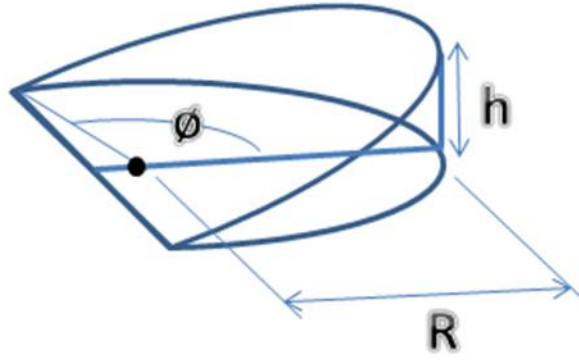


Fig 2. A cylindrical wedge

$$Volume = \frac{hR^2}{3} \frac{3\sin\phi - 3\phi\cos\phi - \sin^3\phi}{1 - \cos\phi} \quad \text{Equation (8)}$$

RESULTS

Effect of pitch/roll on bubble volume at start of pressurisation for inboard-vented escape

Fig 3 shows the calculated volume of the air bubble in the tower at the start of pressurisation for DISSUB pitch/roll in the plane which results in maximal variation in the bubble volume. The Figure shows the marked effect of altered pitch/roll angle on bubble volume for the LET, which, being a two-man tower, has a larger internal volume than the one-man SET or FET.

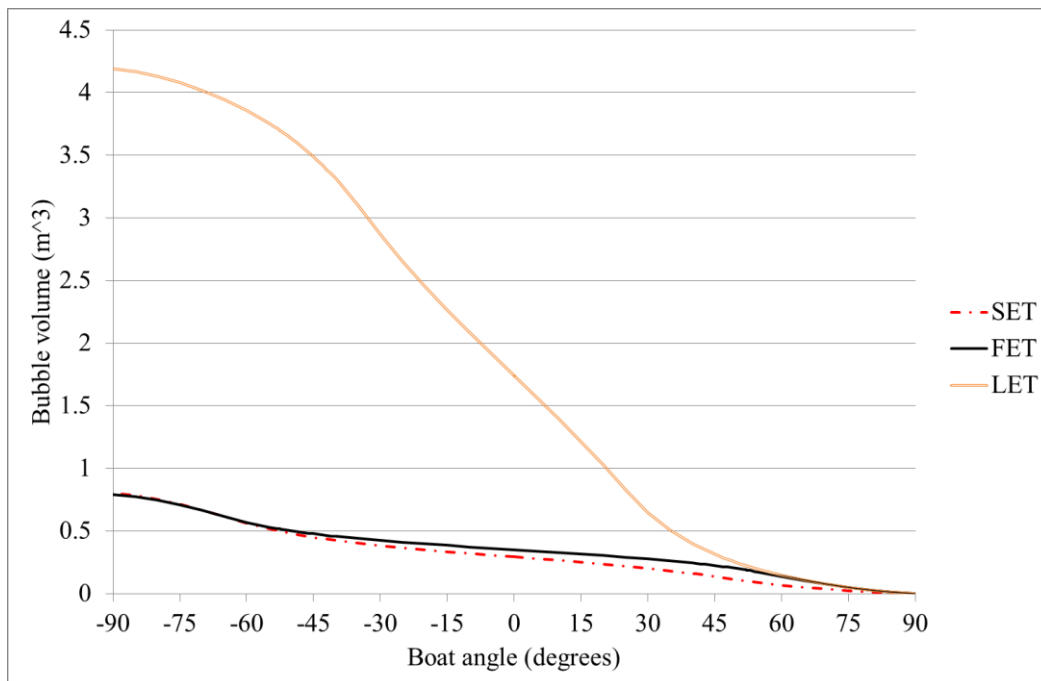


Fig 3. Volume of bubble at start of pressurisation for DISSUB pitch/roll in the plane which results in maximal variation in bubble volume during inboard-vented escape

Crossover depth for shallow inboard-vented escape based on pressure doubling

Table 1 shows the maximum depth (to the nearest 10 m) at which inboard-vented escape could be achieved while limiting the predicted minimum pressure doubling times to > 4 s for towers either upright or at a 45° angle. For escape from depths > 10 m using the LET at an angle of 45° , the pressurisation was predicted to be too rapid using the inboard-vented method. However, by reducing the modelled tower angle to 30° , the pressurisation in the LET was predicted to be acceptable for depths < 30 m.

		Maximum depth for inboard-vented escape based on pressure doubling time (m)		
Tower	Flood orifice diameter (mm)	Tower upright	Tower 45° angle minimising bubble volume	Tower 45° angle maximising bubble volume
SET	28	60	30	100
FET	28	80	40	100
LET	64	80	10	150

Table 1. Maximum depth for inboard-vented escape based on pressure doubling time

Air usage during shallow inboard-vented escape

As shown in Table 2, optimising the system for non-vented escape by increasing the flood orifice diameter and then running the system in inboard-vented mode for escapes from 10 m was predicted to reduce HIS air usage by approximately 50% for both the LET and SET, whether upright or at a tower angle of 45° in the plane minimising bubble volume. Predictions for the FET were similar to the SET.

	SET, Tower upright	LET, Tower upright	SET, Tower 45° angle minimising bubble volume	LET, Tower 45° angle minimising bubble volume
Optimised for inboard- vented	2.8	3.1	3.1	3.9
Optimised for non- vented	1.3	1.4	1.5	1.7

Table 2. Air usage per man (kg) for inboard-vented tower escape from 10 m in towers with flood orifice diameters optimised for either inboard-vented or non-vented escape

Tower bubble volume at equalisation

For escape at 30 m, the volume of the air/water interchange for inboard-vented escape is predicted to be ~ 30% to 50% of that for non-vented escape. The volume of the interchange for the LET is reduced from 1.65 to 0.67 m³ by switching from non-vented to inboard-vented escape, the mass of water entering the tower on equalisation being reduced by approximately one tonne.

Air/water interchange volumes are predicted to be as large as 2.86 m³ for non-vented escape from 10 m in the LET. However, it is not clear whether this would be noticeably different or more severe than the 2.37 m³ interchange volume that is predicted for inboard-vented escape at the same depth in the LET when the tower is tilted at an angle of 45°, an effect which cannot occur for non-vented escape.

DISCUSSION

Non-vented escape at depths shallower than 30 m, in a system optimised for non-vented escape, will have the largest air/water interchange volumes on upper hatch opening. Therefore, to make switching to the inboard-vented escape method for shallow escape worthwhile, inboard-vented escape needs to be achievable at depths from surface to 30 m. Based on the predictions from mathematical modelling of the escape system, shallow inboard-vented escape could be made from the SET and FET, for depths < 30 m and tower angles of up to 45°. For the LET, shallow inboard-vented escape could be made for depths < 30 m and tower angles of up to 30°.

It is not known whether the reduction in volume of incoming water achieved by switching from non-vented to inboard-vented escape will appreciably increase chances of successful escape. This must be established, since the requirement for inboard-vented escapes when shallow would necessitate more complicated instructions and training for submariners than using non-vented escape at all depths.

CONCLUSIONS

The optimised-non-vented escape method has several beneficial aspects, including that rates of DCS will be lower for all escape scenarios, HIS air usage will be reduced, escape cycle time will be reduced and the method is not compromised if the DISSUB is at a significant pitch angle. The use of the inboard-vented method for very shallow depths, in a tower optimised for non-vented escape, has been shown to be feasible. However, the necessity for this will depend on whether there are marked negative effects on the escaper due to the volume of incoming water when the tower upper hatch opens. QinetiQ is working with the MoD to determine the likely forces involved during large volume air/water interchange and how these may affect the escaper.

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Annex 9.

Geoff AM Loveman, Fiona M Seddon, Julian C Thacker, M Graham White and Karen M Jurd.

Physiological effects of rapid reduction in carbon dioxide partial pressure in submarine tower escape.

Diving and Hyperbaric Medicine. 2014 June; 44(2):86-90

Physiological effects of rapid reduction in carbon dioxide partial pressure in submarine tower escape

Geoffrey AM Loveman, Fiona M Seddon, Julian C Thacker, M Graham White and Karen M Jurd

Abstract

(Loveman GAM, Seddon FM, Thacker JC, White MG, Jurd KM. Physiological effects of rapid reduction in carbon dioxide partial pressure in submarine tower escape. *Diving and Hyperbaric Medicine*. 2014 June;44(2):86-90.)

Introduction: The objective of this study was to determine whether adverse effects from a rapid drop in inspired carbon dioxide partial pressure ($P_i\text{CO}_2$) in the breathing gas could hinder or prevent submarine tower escape.

Methods: A total of 34 male volunteers, mean (SD) age 33.8 (7.5) years, completed the trial. They breathed air for five minutes then 5% CO_2 /16% O_2 , 79% N_2 (5 CO_2 /16 O_2) for 60 minutes before switching to breathing 100% O_2 for 15 minutes and then returned to air breathing. Breathing gases were supplied from cylinders via scuba regulators and mouthpieces. Blood pressure, cerebral blood flow velocity, electrocardiogram and end-tidal CO_2 and end-tidal O_2 were monitored throughout. Subjects were asked at intervals to indicate symptom type and severity.

Results: Symptoms whilst breathing 5 CO_2 /16 O_2 included breathlessness and headache. Following the switch to 100% O_2 seven subjects reported mild to moderate faintness, which was associated with a significant drop in cerebral blood flow compared to those who did not feel faint ($P < 0.02$). No subject vomited or fainted following this breathing-gas switch.

Conclusions: This study shows that the risk of fainting, sudden collapse or vomiting on switching to 100% O_2 following acute exposures to hypercapnia at a $P_i\text{CO}_2$ of up to 5.0 kPa is less than 8%.

Key words

Hypercapnia, oxygen, cerebral blood flow, Doppler, physiology, submarine

Introduction

In a scenario where the crew of a UK Royal Navy (RN) submarine is unable to surface their vessel, they may attempt escape. The escape tower is an air-lock supplied with diving quality air. The submarine crew member will switch from breathing a possibly hypercapnic and hypoxic atmosphere in the distressed submarine (DISSUB) to a normocapnic (approximately 0.0395 kPa inspired carbon dioxide partial pressure, $P_i\text{CO}_2$) and normoxic atmosphere in the escape tower. Subsequent pressurisation during tower escape means that the escaper will also be exposed to a hyperoxic atmosphere, with the inspired oxygen partial pressure ($P_i\text{O}_2$) reaching as high as 380 kPa at the maximum permitted escape depth (180 metres' sea water, msw).

An early study reported that switching from breathing a hypercapnic gas (6% CO_2) to 100 kPa O_2 resulted in nausea and vomiting in three of six subjects.¹ The authors indicated that the work could have been better controlled. To our knowledge only one other study has examined the effect of this gas switch; using 7 kPa $P_i\text{CO}_2$, it was found that two of 12 subjects vomited shortly after the switch to oxygen breathing.² Cerebral hypoperfusion has been associated with nausea.³ The reduction in cerebral blood flow associated with a rapid reduction in $P_i\text{CO}_2$ combined with a rapid elevation in $P_i\text{O}_2$ could induce nausea and vomiting, in addition to the risk of fainting. Vomiting during the pressurisation or ascent phase of submarine escape would likely result in pulmonary injury and possibly death. The term 'carbon dioxide-off' effect refers to any symptoms that might be experienced by an individual who has been

exposed to a high level of CO_2 (a hypercapnic atmosphere) and then switches to breathing a normal (normocapnic) or reduced (hypocapnic) level.

Fainting can be provoked by anything that endangers cerebral perfusion.⁴ The switch from breathing a hypercapnic gas in the DISSUB to a hyperoxic gas whilst stood in the submarine escape tower might lead to cerebral hypoperfusion, which could in turn result in fainting. A crew member who faints in the escape tower presents an additional obstacle for fellow crew members to negotiate and furthermore his airway could be compromised.

The purpose of the present study was to determine the risk to escapers with $P_i\text{CO}_2$ of approximately 5.0 kPa and $P_i\text{O}_2$ of approximately 16.0 kPa that might exist in the DISSUB when a switch is made to breathing 100 kPa O_2 (the maximum $P_i\text{O}_2$ that can be delivered under normobaric conditions and equivalent to that experienced in tower escape breathing air at approximately 40 msw tower depth).

Methods

The study was carried out at the QinetiQ Hyperbaric Medical Unit, St. Richard's Hospital, Chichester, UK and was conducted in accordance with the principles of the declaration of Helsinki.⁵ An ethical protocol for the study was reviewed and approved by the QinetiQ Research Ethics Committee (approval number: SP774v2.3).

A power calculation (single-sample binomial test, two-tailed, power = 0.8 and $P = 0.05$) showed that 34 subjects would

need to complete a switch from a hypercapnic and hypoxic breathing gas to 100% O₂, without vomiting or fainting, to demonstrate the underlying risk to be less than 8%.

SUBJECTS

Volunteer subjects were requested to fast from 2000 h and to refrain from alcohol for 24 h prior to the morning of the test. They were asked to drink only clear liquids other than taking their usual caffeinated drink in the morning and not to consume any liquids for two hours prior to the test.

PROCEDURE

All tests were carried out at normobaric ambient pressure. A nose clip was worn throughout the test. Each subject sat at rest breathing air from a scuba mouthpiece for 5 min while baseline measurements were taken. The subject then breathed room air for a short period. The subject then commenced breathing a hypercapnic, hypoxic mixture for 60 min. The composition of the mixture was 5% CO₂, 16% O₂, 79% N₂, referred to here as 5CO₂/16O₂.

A subjective symptoms questionnaire was administered each minute for the first 5 min of breathing 5CO₂/16O₂, then after a further 5 min and then at 10 min intervals. The subject was required to rate their level of discomfort on a five-point scale – as none, mild, moderate, severe or intolerable – for four symptoms – nausea, breathlessness, faintness and headache.

At 50 min the subject was asked to stand. At 60 min the breathing gas was switched to 100% O₂ and the subjective symptoms questionnaire administered at 1 min intervals for 5 min, then at 2 min intervals. At 75 min the breathing gas was switched to air and the subject asked to sit. At 80 min the test was ended.

INSTRUMENTATION AND MEASUREMENTS

PCO₂ and PO₂ were measured continuously at the centre of the scuba mouthpiece (AMIS 2000 respiratory mass spectrometer, Innovision Denmark). Mean blood flow velocity in the middle cerebral artery (MCA_{v_{mean}}) was measured continuously using transcranial Doppler (TCD) (TC-Pioneer EME/Nicolet Vascular), the probe being located at the temporal region above the zygomatic arch. Insonation of the MCA was adjusted to the angle resulting in the highest recorded blood velocity and best-quality Doppler signal.

At 1 min intervals for 5 min after changing breathing gas and 5 min intervals thereafter, mean arterial pressure (MAP) was measured with an automated sphygmomanometer (DINAMAP® Pro 1000, General Electric) at the brachial artery of the right arm. Electrocardiogram (ECG) was continuously displayed on two ECG monitors. The 3-lead monitor of the DINAMAP® Pro 1000 was used to allow display of the lead I signal and a 5-lead monitor (LifePulse10, HME Ltd.) was used to display the lead II signal.

TEST TERMINATION CRITERIA

The test would be terminated:

- at the subject's request;
- on a subjective questionnaire response of 'intolerable' to any aspect;
- on failure of any equipment used to monitor withdrawal variables;
- on recording end-tidal carbon dioxide (ETCO₂) > 8.5 kPa for more than five consecutive breaths;
- if the subject began to vomit;
- if the subject requested assistance as feeling severely faint or the subject fainted;
- on subjective signs of impending panic or
- if BP, measured by DINAMAP was greater than either a systolic of 180 or a diastolic of 110 mmHg, sustained for over 1 min.

STATISTICS

The relative percentage changes in respiratory rate, heart rate, MAP, ETCO₂ and MCA_{v_{mean}} were calculated for the minute pre-switch to the minute post-switch to 100% O₂. A boxplot was used to determine whether any of these data warranted further statistical analysis. Where this was the case, subject data were grouped according to symptoms and differences between groups tested using the unpaired, unequal variance *t*-test. Differences were considered significant if *P* ≤ 0.05.

Results

SUBJECT DETAILS

A total of 39 male volunteers participated in the trial. The procedure was stopped in six subjects; three because they exceeded the upper BP limits, two whilst breathing 5CO₂/16O₂ and one on 100% O₂ (the last subject's data were included in the analysis, however); two for increasing ventricular ectopics (not present on their pre-trial ECGs) whilst breathing 5CO₂/16O₂ and one who was entraining room air around the mouthpiece during the test. The mean (SD) age of the 34 volunteers whose data were used was 33.8 (7.5) years; height 180.7 (5.7) cm; body mass 82.8 (9.1) kg.

SYMPTOMS

No subject vomited, fainted or was incapacitated on the switch to 100% O₂ breathing. Six subjects reported no symptoms throughout the test. Eleven subjects reported mild to moderate headache. Only three subjects reported a headache that developed after the switch to 100% O₂, as opposed to eight whose headache developed whilst breathing 5CO₂/16O₂; three of these eight found their symptoms of headache resolved following the switch to 100% O₂.

Seven subjects reported mild to moderate faintness occurring only after the switch to breathing 100% O₂, while six reported

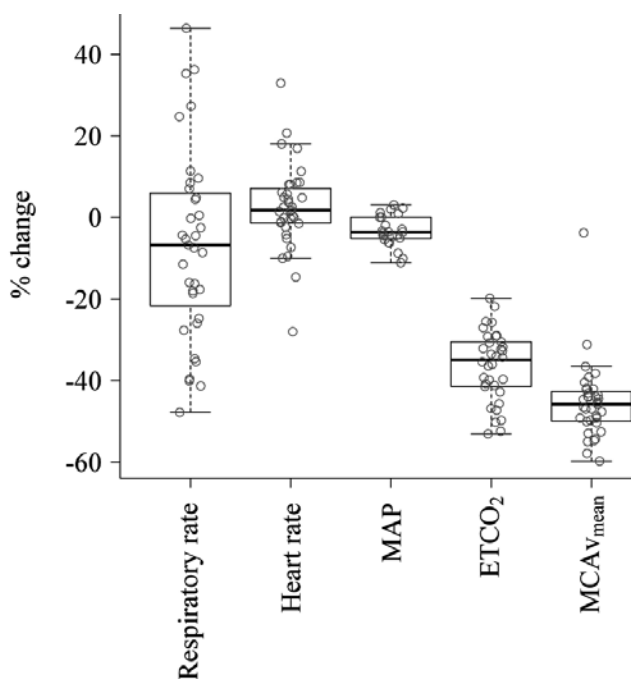
Table 1

95% confidence intervals on absolute values of physiological variables ($n = 34$); MAP—brachial BP was measured once per min, other signals were recorded continuously; * value taken over 1 min; † value taken over 5 min; $\text{MCAv}_{\text{mean}}$ —mean middle cerebral artery blood flow velocity

	Air baseline*	First min* 5CO ₂ /16O ₂	First 5 min† 5CO ₂ /16O ₂	After 30 min* 5CO ₂ /16O ₂	Final min* 5CO ₂ /16O ₂	First min* 100% O ₂	First 5 min† 100% O ₂	Final min* 100 % O ₂	Final min air*
Respiratory rate (breaths·min ⁻¹)	8 ± 1.2	8.9 ± 1.2	9.1 ± 1.2	10.2 ± 1	12.7 ± 1.2	11.6 ± 1.4	9.8 ± 1.4	9.5 ± 2	8.5 ± 1
MAP (mmHg)	94 ± 2	99 ± 4	100 ± 4	97 ± 4	106 ± 4	102 ± 2	99 ± 2	98 ± 4	95 ± 2
Heart rate (beats·min ⁻¹)	66 ± 4	67 ± 4	67 ± 4	69 ± 4	82 ± 4	84 ± 6	82 ± 6	76 ± 4	65 ± 4
$\text{MCAv}_{\text{mean}}$ (cm·s ⁻¹)	52 ± 4	73 ± 6	77 ± 6	71 ± 6	72 ± 8	39 ± 4	38 ± 4	43 ± 6	45 ± 6
ETCO ₂ (kPa)	5.2 ± 0.2	6.6 ± 0.2	6.9 ± 0.2	6.9 ± 0.2	6.8 ± 0.2	4.3 ± 0.2	4.1 ± 0.2	4.1 ± 0.4	4.4 ± 0.4

Figure 1

Percentage change in physiological variables taken over 1 min before and after switching to 100% O₂ ($n = 34$); heavy lines denote median values; box extents show interquartile range; whiskers denote data values within 1.5 times the interquartile range from upper/lower quartiles



mild faintness whilst breathing 5CO₂/16O₂. Faintness was the only symptom which developed in an appreciable number of subjects following the switch to 100% O₂. One subject reported mild nausea after the switch to 100% O₂ and one reported mild nausea whilst breathing 5CO₂/16O₂. Eighteen subjects reported mild to severe breathlessness whilst breathing 5CO₂/16O₂. Three of these continued to experience breathlessness on the switch to 100% O₂, one of whom rated it as moderate.

CHANGE IN PHYSIOLOGICAL VARIABLES ON SWITCH TO 100% OXYGEN

The values of physiological variables are summarised in Table 1. Figure 1 shows a boxplot of the percentage changes in respiratory rate, heart rate, MAP, ETCO₂ and $\text{MCAv}_{\text{mean}}$ taken from 1 min pre-switch to 1 min post-switch to 100% O₂. There was a significant difference in the percentage drop in $\text{MCAv}_{\text{mean}}$ on the switch between subjects experiencing faintness following the switch ($n = 7$, mean reduction in $\text{MCAv}_{\text{mean}}$ 51%) compared to those who did not ($n = 27$, mean reduction in $\text{MCAv}_{\text{mean}}$ 44%) ($P < 0.02$, unpaired, unequal variance t -test). The boxplot demonstrates no significant change in the mean respiratory rate, heart rate or MAP.

Discussion

SYMPTOMS WHILST BREATHING 5CO₂/16O₂

Increased cerebral blood flow and headache and possible nausea related to increased intracranial pressure were anticipated in subjects whilst breathing 5CO₂/16O₂, the symptoms of headache in eight subjects and one reported case of mild nausea were in accord with the findings of an earlier study.¹ Cerebral blood flow increases in the order of 50% when breathing 5% CO₂.⁶ At 2.5% CO₂, there is no effect; at 3.5% a significant effect has been reported and at 7% the effect is far greater than at 5%.^{6,7} After 5 min of breathing 5CO₂/16O₂ in the present study, the $\text{MCAv}_{\text{mean}}$ increased by 49%, in agreement with these previous studies.

Moderate hypertension was recorded in all subjects whilst breathing 5CO₂/16O₂, which has also been reported by others investigating the effect of an increased P_iCO_2 .⁸

EFFECTS OF THE SWITCH TO 100% OXYGEN

Nausea and vomiting

No subjects vomited. One reported mild nausea which

developed after the switch to 100% O₂. Since one subject reported mild nausea whilst breathing 5CO₂/16O₂, there is little or no evidence of a difference in the apparent effects of breathing 5CO₂/16O₂ and the switch to 100% O₂ in terms of inducing nausea.

Some studies have not shown any evidence of incapacitation when switching from breathing a hypercapnic gas to air. Exposure to CO₂ at a concentration of 7% has been used as a tool to investigate panic and fear.⁹ Neither sudden collapse nor vomiting was reported, although headache was, on return to air breathing. In another study, subjects were exposed inside a chamber to a PCO₂ of 1.3–5.6 kPa for 5 days, coming out of the chamber once each day to breathe air for 30 min. The study did not report any adverse effects on the subjects of switching between hypercapnia and air.¹⁰ In the studies where adverse effects were reported, the P_iCO₂ was higher.^{1,2} It appears that a CO₂-off effect that causes vomiting when switching to 100% O₂ following acute (~1 h) exposures to hypercapnia may only become apparent when switching from a P_iCO₂ above 5.0 kPa and that the severity may rapidly increase with only slight further increases in P_iCO₂.

Headache

In the current study, only three subjects reported headache that developed after the switch to 100% O₂, with the majority of subjects that experienced headache (8 of 11) having symptoms developing whilst breathing 5CO₂/16O₂. Thus the exposure to 5CO₂/16O₂ was more likely to induce headache than the switch to 100% O₂. The resolution of symptoms in three subjects following this switch suggests that it was at least as likely to reduce as to provoke headache.

Faintness

Faintness (mostly mild) was the most frequent symptom reported following the switch from hypercapnia to breathing 100% O₂. This occurred in seven subjects where faintness was not reported prior to the switch. There is some controversy over whether administration of 100% O₂ can maintain cerebral oxygenation in spite of hypoperfusion. It has been argued that hyperoxic hyperventilation and hypocapnia could decrease cerebral blood flow in excess of the effect of the increased O₂ content of breathing gas and paradoxically diminish O₂ delivery to the brain.¹¹ However, other authors have presented evidence that any likely effect of hypoperfusion (such as inducing fainting) caused by breathing 100% O₂ would be offset by the increased blood O₂ tension.¹² A clear independent cerebral vasoconstrictive effect of hyperoxia across a wide range of arterial PCO₂ has been demonstrated in at least one study.¹³ Therefore, the decrease in cerebral blood flow observed in the present study when subjects switched to breathing 100% O₂ is likely to have been caused by cerebral vasoconstriction due to hyperoxia and the associated hypocapnia.

Several studies using TCD to measure MCAv_{mean} have demonstrated a drop in values in association with pre-syncope and syncope. Passive head-up tilt in healthy

subjects reduces MCAv_{mean} and cerebral O₂ saturation and pre-syncope symptoms appear when there is a reduction of about 50% in MCAv_{mean}.^{14–16} Similar percentage drops in MCAv_{mean} associated with symptoms of faintness have been observed in the present study.

Signs of imminent syncope have been associated with reductions in MCAv_{mean} of 62% and 68% induced by sudden cold water immersion.¹⁷ MCAv_{mean} has also been measured in one study after acute hypercapnia reversal.¹⁸ Subjects rebreathed from a bag containing 5% carbon dioxide in O₂ up to an ET_{CO}₂ of 10% or to the limit of tolerance. When rebreathing ceased, there was a rapid decline in MCAv_{mean} within 42 s, followed by a further rapid decline to below baseline, MCAv_{mean} falling by 31% in total.¹⁸

Another study found reductions in MCAv_{mean} of 44% and 69% respectively and concluded this decrease to be more important as a predictive factor of syncope than the MAP.¹⁹ This is in agreement with the present study where a mean percentage decrease in MCAv_{mean} of 51% was associated with pre-syncope symptoms (sensation of mild or moderate faintness) while decrease in MAP was not associated with the group of subjects who experienced faintness developing following the switch.

LIMITATIONS OF THE STUDY

Use of a demand valve (DV) regulator for the mouthpiece

Subjects who were inexperienced in the use of a DV made comment on the difficulty of breathing. It is known that breathing systems have an effect on the depth, flow and pattern of breathing.^{20,21} The use of a DV regulator could be avoided in future trials by supplying the subjects' breathing gases from pre-filled Douglas bags.

Duration of the test and effects of raised pressure

It should be noted that survivors waiting in the DISSUB may be exposed to raised ambient pressure and wait for up to seven days before rescue or escape. Investigation of prolonged (chronic) exposure to hypercapnic gas at raised pressure and the effects that acid-base balance, buffering and compensation may have on the response to a switch from hypercapnia to hypocapnia and/or hyperoxia was outside the scope of the current study. Effects of a switch to air or 100% O₂ following prolonged exposure to raised PCO₂ and/or hyperbaric exposure remain as possible topics for future investigation.

Possible additional effect of Valsalva

The Valsalva manoeuvre is carried out during the compression phase of escape in order to equalise pressure across the tympanic membrane, preventing otic barotrauma. During Valsalva, the MCAv_{mean} can drop by about 35% when supine, and by around 50% when standing.²² Thus, Valsalva may partially compromise cerebral perfusion and this may be compounded by any CO₂-off effect during escape. This issue is currently under investigation.

Conclusions

On undergoing a switch from breathing 5CO₂/16O₂ to breathing 100% O₂, a significant difference was observed in percentage drop in MCAv_{mean} between subjects who had symptoms of faintness that developed after this switch and those who did not, suggesting that feeling faint is linked to the drop in cerebral perfusion. The risk of incapacitation owing to fainting, sudden collapse or vomiting on switching to 100% O₂ following acute exposures to hypercapnia at a P_iCO₂ of up to 5.0 kPa is less than 8%. The relative mildness of symptoms observed does not indicate that a change to current procedures is necessary. However, the limitations of the current study suggest that the possibility of worse symptoms in some DISSUB scenarios cannot be ruled out. Evidence from other studies suggests that the severity of symptoms will increase if P_iCO₂ rises above 5.0 kPa.^{1,2}

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Conflicts of interest: nil

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Annex 10.

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Decompression illness in goats following simulated submarine escape: 1993-2006.

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Decompression illness in goats following simulated submarine escape: 1993–2006

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ABSTRACT

The United Kingdom Ministry of Defence commissioned work to define the relationship between the internal pressure of a distressed submarine (DISSUB), the depth from which escape is made and the risk of decompression illness (DCI). The program of work used an animal model (goat) to define these risks and this paper reports the incidence and type of DCI observed. A total of 748 pressure exposures comprising saturation only, escape only or saturation followed by escape were conducted in the submarine escape simulator between 1993 and 2006. The DCI following saturation exposures was predominantly

limb pain, whereas following escape exposures the DCI predominantly involved the central nervous system and was fast in onset. There was no strong relationship between the risk of DCI and the range of escape depths investigated. The risk of DCI incurred from escape following saturation was greater than that obtained by combining the risks for the independent saturation only, and escape only, exposures. The output from this program of work has led to improved advice on the safety of submarine escape.

INTRODUCTION

In the event of a United Kingdom Royal Navy (RN) submarine being unable to surface, the crew may elect to abandon the distressed submarine (DISSUB) via an escape tower, an airlock specifically designed for emergency evacuation. Escape towers of most modern submarines allow for one or two men at a time to escape. The process involves pressurization of the tower by flooding with sea water, which leads to equalization with the external sea pressure, allowing the outer hatch of the escape tower to open. This is followed by buoyant ascent to the surface. As this procedure involves exposure to raised pressure, it carries a risk of decompression illness (DCI), a limiting physiological factor to the safety of submarine escape.

The duration of the exposure to raised pressure is reduced through rapid pressurization and ascent. Following World War II, considerable work was carried out in order to determine pressurization and ascent rates that might be safely achievable [1]. Through refinement of process and equipment, tower escape has been accomplished from an RN submarine at a depth of 180 meters [2], a depth sufficient to allow escape from most areas of the continental shelf around the British Isles.

The internal pressure of an operational submarine is usually normobaric, approximately 1.0 bar absolute (a) (100 kPa). However, the pressure in the compartments of a DISSUB may rise due to flooding or internal release of air from damaged high-pressure air systems. Thus, the crew may be exposed to raised pressure within the DISSUB for some time prior to effecting tower escape. None of the preceding work examined the effect of exposure to raised pressure within the DISSUB before escape from the submarine. In the worst credible case, the crew will be exposed for sufficient time to fully saturate their body tissues with gases at the partial pressures present in the DISSUB.

The UK Ministry of Defence had a requirement to define the relationship between the DISSUB internal pressure (the saturation pressure), the DISSUB depth from which escape is made (the escape depth) and the risk of DCI. The program of work used an animal model (goat) to help define these risks, and this paper reports the incidence and type of DCI observed. The risks were adequately defined at the end of 2006, and experimental work using animals ceased.

METHODS

The program of trials was carried out at various intervals between 1993 and 2006.

Animals

A total of 748 pressure exposures were conducted under Home Office Licence according to the letter and spirit of the Animals (Scientific Procedures) Act 1986. The program of work was also reviewed internally by an Ethics Review Committee. Female and male adult goats weighing 30.0 to 83.0 kg (mean 55 ± 10 kg) underwent a period of specific training and familiarization with the procedures and chamber environment before use. Typically, two or three animals were exposed concurrently. Each animal had an interval of at least four weeks between consecutive pressure exposures and was certified in good health by a veterinary surgeon prior to each use.

Pressure exposures

Pressure exposures took place inside the purpose-built Submarine Escape Simulator (SES). The facility comprised two interconnecting spherical pressure vessels, one with a 3-meter internal diameter (14.1 m³ volume) and the other with a 2-meter internal diameter (4.2 m³ volume), with an interconnecting pressure-tight door and access doors at either end.

Three categories of pressure exposure were carried out: saturation only, escape only and saturation followed by escape.

Saturation only

The specified saturation pressure was maintained in the vessel to ± 0.005 bar by the addition of air. Oxygen concentration was measured with a pressure-compensated paramagnetic oxygen analyzer (Servomex) and maintained at $21\% \pm 0.3\%$ by an automatic oxygen inject system (Analox). Carbon dioxide partial pressure was measured by infrared spectroscopy (ADC) and kept below 0.005 bar (a). Organic gases and excess humidity were scrubbed by an environment conditioning system containing activated charcoal, silica gel and soda lime. The relative humidity in the chamber was maintained between 60% and 70%, and temperature was in the range 18–24°C depending on ambient conditions.

An initial pilot study was conducted to investigate whether six hours was an adequate time for saturation in the goat. A total of 60 exposures using goats weighing 30.0–76.0 kg (mean 58.1 kg), was carried out using

a six-hour duration to pressures ranging from 1.60 to 2.67 bar (a). Subsequently, 142 exposures of 24 hours' duration were conducted using goats weighing 35.5–81.0 kg (mean 52.6 kg) at pressures ranging from 1.50 to 2.35 bar (a). These exposures were carried out using compression and decompression times ranging from one to three minutes depending on the saturation depth and comfort of the animals, which was negligible when compared to the duration of the whole exposure. Animals were allowed to roam in the 3-meter sphere of the SES with free access to water and pelleted food; fresh grass was withheld for the preceding 24 hours.

Escape only

The animals undertook the simulated escape exposures in the 2-meter sphere of the SES. The interconnecting door between the spheres was closed and the 3-meter sphere charged with air to the pressure that was pre-calculated to result in the desired escape depth on the pressure equalization of the spheres, while the 2-meter sphere containing the animals remained at normobaric pressure. A computer-controlled valve system then allowed air to transfer from the 3-meter to the 2-meter sphere pressurizing it at the rate which would be experienced while making an escape from an RN submarine. Since the process was one of equalization, the required maximum pressure (escape depth) achieved in the 2-meter sphere could not be exceeded.

It should be noted that the profile of the pressurization phase experienced while making an escape from an RN submarine depends on the type of escape tower and the nature of the escape method, which can be varied by configuring the tower according to the particular scenario. Some of the escape exposures simulated these different tower configurations, and for this reason had a different duration of the pressurization phase; typically this pressurization phase lasted less than 30 seconds.

Following the rapid pressurization, there was a four-second hold at "depth" in order to simulate the time required for the tower upper hatch to open and the escaper to exit the tower, which is standard UK RN procedure. This was followed by a linear decompression to the surface at a rate of $2.75 \text{ m} \cdot \text{s}^{-1}$. The total time under pressure for an escape-only profile would not exceed 180 seconds.

A total of 284 escape-only pressure exposures were carried out using goats weighing 35.0 – 83.0 kg (mean 55.2 kg) simulating escape depths of 150–290

meters. Food was withheld at least 90 minutes prior to escape, to reduce the risk of bloat from expansion of intestinal gases during the fast decompression.

Saturation followed by escape

A total of 262 saturation exposures followed by escape were carried out using goats weighing 35.0-81.0 kg (mean 53.6 kg). Animals were compressed to the required saturation pressure in the 3-meter sphere of the SES, where they remained under the same conditions as for a saturation exposure with free access to water and pelleted food. Prior to the end of the saturation period, two attendants entered the pressure vessel and transferred the animals to the 2-meter sphere in readiness for the escape procedure. The pressure was then maintained in the 2-meter sphere until the escape profile described above commenced.

Decompression illness

Following the pressure exposures, animals were observed in an open pen next to the chamber while monitoring procedures were carried out. Diagnosis of DCI was carried out by personnel experienced in the signs of DCI in goats.

The following diagnostic criteria were used for the different types of DCI:

- Limb (L): Limb lifted off the ground, pawing or stamping, walking with limp.
- Central nervous system (CNS): Unsteadiness, swaying, collapse, arching of back.
- Respiratory (R): Fast shallow breathing, increased heart rate, raspy breathing.
- Pulmonary barotrauma (PBT): Rapid onset collapse within two minutes, loss of consciousness.
- Marginal (M): Transient and usually minor signs of DCI which rapidly resolve without treatment.

Note that the definition of decompression sickness (DCS) includes all of the above types except PBT.

Statistical analysis

Weights are expressed as means \pm standard deviations. Confidence intervals on percentage rates of observed DCS are the exact Clopper Pearson 95% confidence intervals for samples from the binomial distribution computed independently for each pressure profile.

RESULTS

Data presented in the following tables have differing sample sizes for each pressure profile. Therefore it is important to consider the confidence intervals for the percentage DCS observed.

Saturation-only exposures

Six-hour exposures

Table 1 shows the number exposed to each pressure, together with the incidence and type of DCS experienced at that pressure.

Table 1

Pressure [bar (a)]	DCS/Total exposed (n)	% DCS (95% C.I.)	DCS type
1.6	0/2	0.0 (0 – 84)	
1.9	2/24	8.3 (1 – 27)	2 L
2.0	3/24	12.5 (3 – 32)	3 L, 1 M
2.2	4/4	100 (40 – 100)	4 L
2.52	3/4	75 (19 – 99)	3 L
2.67	2/2	100 (16 – 100)	2 L

Details of six-hour pressure exposures and incidence of DCS

The overall incidence of DCS for the six-hour exposures was 23.3% [13-36 (95% C.I.)]. All signs were limb pain only, with one marginal case. Onset times for the DCS observed ranged from 13 to 61 minutes, with most occurring between 15 and 30 minutes.

24-hour exposures

Table 2 shows the number exposed to each pressure for 24 hours, together with the incidence and type of DCS experienced at that pressure.

Table 2

Pressure [bar (a)]	DCS/Total exposed (n)	% DCS (95% C.I.)	DCS type
1.5	0/24	0.0 (0 – 14)	
1.7	0/24	0.0 (0 – 14)	
1.8	0/24	0.0 (0 – 14)	
1.9	7/24	29.2 (12 – 51)	7 L
2.02	1/3	33.3 (1 – 91)	1 L
2.1	0/3	0.0 (0 – 71)	
2.2	0/4	0.0 (0 – 60)	
2.23	2/3	66.7 (9 – 99)	2 L
2.25	3/3	100 (29 – 100)	3 L
2.28	5/9	55.6 (21 – 86)	4 L, 1 CNS + L
2.295	0/3	0.0 (0 – 71)	
2.3	2/6	33.3 (4 – 78)	2 L
2.31	3/3	100 (29 – 100)	2 L, 1 L + R
2.32	5/6	83.3 (36 – 100)	5 L
2.35	3/3	100 (29 – 100)	2 L, 1 L + R

Details of 24-hour pressure exposures and incidence of DCS

The overall incidence of DCS after the 24-hour exposures was 21.8% [15-30 (95% C.I.)]. Exposures shallower than 1.9 bar (a) did not elicit DCS. All DCS observed involved limb pain. Cases observed following exposures between 1.9 bar (a) and 2.25 bar (a) were limb pain only. A single case of CNS DCS occurred following exposure to 2.28 bar (a); this animal also displayed limb signs. There were two cases of respiratory DCS following saturation pressures above 2.31 bar (a), again in conjunction with limb pain. Onset times for DCS ranged from seven to 300 minutes, with most occurring by 60 minutes.

Escape-only exposures

Simulated submarine escape profiles from normobaric conditions were performed from 150 meters down to and including 290 meters. Table 3 shows the number exposed to each escape depth together with the incidence and type of DCS experienced at that pressure.

Table 3

Depth (m)	DCS/Total exposed (n)	% DCS (95% C.I.)	DCS type	PBT
150	0/3	0.0 (0 – 71)		1
200	1/21	4.8 (0 – 24)	1 CNS	0
220	2/32	6.2 (1 – 21)	2 CNS	0
240	3/68	4.4 (1 – 12)	3 CNS	3
250	0/21	0.0 (0 – 18)	1 M	2
260	2/42	4.7 (1 – 16)	2 CNS	0
270	4/44	9.1 (3 – 22)	3 CNS, 1 L	0
280	2/10	20.0 (3 – 56)	2 CNS	0
290	3/43	7.0 (1 – 19)	3 CNS	6

Details of escape-only exposures and incidence of DCS

The overall incidence of DCS after all escape-only exposures was 6.2% [4-10 (95% C.I.)]. All except one of the cases of DCS following escape were diagnosed as rapid onset CNS. The onset times for DCS ranged from two to 22 minutes, with most occurring within 15 minutes. The single exception was a case of limb pain DCS. PBT was diagnosed in 4.2% [2-7 (95% C.I.)] of the exposures. More cases of PBT were diagnosed after escapes from 290 meters than for all lesser escape depths, with 14% [5-28 (95% C.I.)] of exposures resulting in PBT compared with 2.5% [1-5 (95% C.I.)] after escapes in the range 150 to 280 meters.

Saturation followed by escape

These exposures simulated a DISSUB scenario where the crew effect escape after exposure to raised ambient pressure for sufficiently long that the body tissues are saturated with respect to the partial pressure of nitrogen in the DISSUB. Table 4 shows the number exposed to each saturation pressure and the subsequent escape depth, together with the incidence and type of DCS experienced following this combination.

The overall incidence of DCS after saturation followed by escape was 15.8% [12-21 (95% C.I.)]. There was also a 1% [0-3 (95% C.I.)] incidence of PBT. The predominant types of DCS observed were limb pain and CNS. Respiratory DCS was diagnosed only after saturation exposures greater than 2.1 bar (a) followed by escape. DCS onset times ranged from four to 189 minutes, with most occurring by 60 minutes.

DISCUSSION

Decompression research using goats has been carried out since J.S. Haldane's work in the first part of the 20th century [3] and formed the basis of submarine escape studies by Donald in 1944 [1], which was continued by the Admiralty Experimental Diving Unit. In 1962 it was recommended that manned submarine escapes should be conducted by the RN in open water, eventually leading to successful escape from a submarine at a depth of 180 meters [2]. The work reported here made use of well-established animal facilities and expertise. Goats display a similar range of DCI signs to man [3], are relatively easy to handle and their response to decompression from saturation has been shown by other researchers to be scalable to that of man (and other species), using body mass as a scaling factor [4].

A pilot study conducted to investigate the time to saturation in the goat was a necessary starting point given previous discrepancies by researchers over the years, starting with Haldane in the early 1900s [3], who stated that three hours was sufficient time for the tissues of the goat to reach saturation. Davidson, *et al.* [5] found that there was no increase in the severity of DCI after 4, 6, 12, and 24 hours and suggested that "goat tissues that take longer than 4 hours to saturate fully, if there are such tissues, play no part in the production of bends." Eaton and Hempleman [6] reported that six hours represents the time for saturation in goats. Our pilot study tested 24 hours in comparison to six hours. Taking into account increased

Table 4

Saturation pressure bar (a)	Escape depth (m)	DCS/Total exposed (n)	% DCS (95%C.I.)	DCS type	PBT
1.5	200	1/20	5.0 (0 – 25)	1 CNS	0
1.5	240	1/20	5.0 (0 – 25)	1 CNS	0
1.5	250	1/20	5.0 (0 – 25)	1 CNS	1
1.5	260	2/20	10.0 (1 – 32)	2 L	0
1.7	220	1/20	5.0 (0 – 25)	1 CNS	0
1.7	240	0/20	0.0 (0 – 17)		0
1.7	260	1/20	5.0 (0 – 25)	1 CNS	0
1.8	150	3/20	15.0 (3 – 38)	3 L	0
1.8	200	2/20	10.0 (1 – 32)	2 L	0
1.8	240	5/20	25.0 (9 – 49)	4 L, 1 CNS	0
1.9	150	4/20	20.0 (6 – 44)	4 L	0
2.05	200	1/3	33.3 (1 – 91)	1 L	0
2.07	200	0/3	0.0 (0 – 71)		0
2.1	200	0/3	0.0 (0 – 71)		0
2.12	200	2/3	66.7 (9 – 99)	2 L	0
2.13	200	1/3	33.3 (1 – 91)	1 CNS	0
2.14	200	3/9	33.3 (7 – 70)	3 L	0
2.15	200	2/3	66.7 (9 – 99)	1 L, 1 CNS + R + L	1
2.155	200	2/3	66.7 (9 – 99)	1 L, 1 CNS	0
2.175	200	2/3	66.7 (9 – 99)	2 L	0
2.183	200	3/3	100 (29 – 100)	1 L, 1 L + CNS, 1 CNS	0
2.20	200	4/6	66.7 (22 – 96)	3 L, 1 L + R	0

Details of saturation pressures/escape depths and incidence of DCS

gas load, determined by Doppler ultrasound, following decompression for 24-hour exposures compared with six-hour exposures, it was decided that for practical purposes, 24 hours should be taken as the time to “saturation” in the goat for subsequent trials.

DCI was diagnosed according to the criteria outlined in the methods by the same key staff throughout the program and included symptoms of PBT. However, in the following discussion DCS is used to mean all symptoms apart from PBT. Cases of PBT are discussed separately. In general, cases of DCS observed with later onset times appeared less severe than those with early onset. CNS DCS presented with shorter onset times and limb DCS presented over a much longer duration. In man, DCS can be reported many hours and even days after a pressure exposure, whereas the latest onset time recorded during the present trials

was five hours and most were less than one hour. It is possible that mild symptoms reported by humans will be missed in an animal, which may account for some of the later DCS reports in man.

The signs of DCS following the six-hour and 24-hour saturation exposures were predominantly limb pain, with most of the onset times between 15 and 60 minutes, whereas following escapes the DCS was predominantly CNS with a much faster onset time, nearly all presenting within 15 minutes. These results are consistent with the finding of Lanphier and Lehner that short/deep dives produced a higher incidence of CNS DCS than long/shallow dives [7]. The signs of DCS observed during the present trials are in agreement with decompression theory, which suggests that the risk of DCS following submarine escape is dependent on gas elimination from tissues with rapid gas exchange, *e.g.*, CNS, whereas after saturation exposures the risk is determined by tissues with slow gas exchange. Thus, a deep, fast submarine escape profile is more likely to affect the tissues with the fastest gas exchange and result in CNS symptoms. Escapes following saturation resulted in both limb and CNS DCS, in agreement with the saturation and escape components of these profiles affecting the slow and fast tissues respectively.

Most escapes were uneventful, but CNS DCS occurred over almost the full range of depths tested, and the data do not suggest a strong relationship between the risk of DCS and escape depth. It should be noted that when CNS DCS did occur it was fast in onset, which, in a DISSUB scenario could result in the escaper being severely incapacitated such that he is unable to get into his life raft, thus jeopardizing survival. The consequence of different DCS symptoms can vary enormously in a DISSUB scenario: For example, limb pain DCS would be unlikely to impact on the survival of a well-motivated escaper.

Our data suggest that the risk of DCS incurred from escape following saturation is greater than that obtained by combining the risks for the independent saturation-only, and escape-only, exposures. For example, a

saturation exposure at 1.8 bar (a) resulted in 0% DCS [0-14 (95% C.I.)], an escape exposure from 240 meters resulted in 4.4% DCS [1-12 (95% C.I.)] and the equivalent escape following saturation exposure resulted in 25% DCS [9-49 (95% C.I.)]. Mathematical modeling of the data [8] showed that the pressure required to provoke 50% DCS [40-60 (95% C.I.)] in the goat after 24 hours was 2.24 bar (a). When a 200-meter escape was added to a 24-hour saturation, then the saturation pressure required to provoke 50% DCS [35-65 (95% C.I.)] was reduced to 2.14 bar (a).

PBT was diagnosed only following exposures involving escape, with the majority of cases after escapes from 290 meters. Compression and subsequent expansion of the air in the SES during the escape simulation caused increasing temperature swings and noise levels with increasing escape depth; this may have increased the likelihood of breath-holding, leading to the higher numbers of PBT following the 290-meter escapes. It is worth noting that the temperature swings in the SES may be greater than those that would be experienced by submariners in DISSUB tower escape, where incoming sea water and breathing air should both have a cooling effect. The animals were not forced to maintain an open

airway throughout the decompression. Submariners trained to maintain an open airway should have a lower risk of PBT. It is possible that cases of PBT could have masked DCS occurrences. Due to this possibility, cases of PBT were removed from the calculation of the 95% binomial confidence limits on the rates of DCS.

The data from this program of work illustrate the relationship between the saturation pressure and the escape depth in DISSUB scenarios using an animal model. This enabled the mapping out of areas of higher risk of DCS before testing of lower-risk areas by man [9]. These and other data contributed to the calibration of mathematical models for estimation of DCS risk in DISSUB scenarios, which has led to improved advice on the safety of escape [8].

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Conflict of interest

The authors have declared that no conflict of interest exists with this submission.



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Annex 11.

Jurd KM, Seddon FM, Thacker JC, Blogg SL, Stansfield MR, White MG, Loveman GAM.

Submarine “safe to escape” studies in man.

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Submarine ‘safe to escape’ studies in man

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ABSTRACT

The Royal Navy requires reliable advice on the safe limits of escape from a distressed submarine (DISSUB). Flooding in a DISSUB may cause a rise in ambient pressure, increasing the risk of decompression sickness (DCS) and decreasing the maximum depth from which it is safe to escape. The aim of this study was to investigate the pressure/depth limits to escape following saturation at raised ambient pressure. Exposure to saturation pressures up to 1.6 bar (a) (160 kPa) ($n = 38$); escapes from depths down to 120 meters of sea water (msw) ($n = 254$) and a combination of saturation followed by escape ($n = 90$)

was carried out in the QinetiQ Submarine Escape Simulator, Alverstoke, United Kingdom. Doppler ultrasound monitoring was used to judge the severity of decompression stress. The trials confirmed the previously untested advice, in the Guardbook, that if a DISSUB was lying at a depth of 90 msw, then it was safe to escape when the pressure in the DISSUB was 1.5 bar (a), but also indicated that this advice may be overly conservative. This study demonstrated that the upper DISSUB saturation pressure limit to safe escape from 90 msw was 1.6 bar (a), resulting in two cases of DCS.

INTRODUCTION

Escapes have been conducted at sea from submarines with mixed success for over 100 years. Submarine escape procedures and equipment for Royal Navy (RN) submarines have evolved over this time using an incremental approach. An intense research effort by the RN and Royal Naval Physiological Laboratory at the start of the 1960s testing rapid pressurization led to a number of submarine escapes at sea [1]. A deeper escape capability was then investigated through animal testing of various depth/time profiles followed by manned testing in hyperbaric chambers, eventually leading to successful escapes from a submarine at a depth of 180 meters of sea water (msw) in 1970 [2]. Further refinement of procedures and equipment to demonstrate the tower escape system with hooded ascent from the maximum designed depth culminated in Deep Escapex 1987 [3]. These escapes were made from submarines at 1 bar (a) (100 kPa) internal pressure. The Navy Board subsequently endorsed the requirement for more research on escape from pressurized submarines in order for the UK Ministry of Defence (MoD) to fulfil its duty of care for submariners with respect to escape and rescue and extend, if practicable, the pressure/depth limits on escape from RN submarines.

In a distressed submarine (DISSUB), the crew can either await rescue by a submersible or they can escape. Rescue by submersible is the preferred option. However, this involves a delay while waiting for the arrival of rescue forces. Advice to aid the decision as to whether to escape or await rescue from a DISSUB is contained on the Submarine Escape and Rescue Instructions Cards (the Guardbook). In some DISSUB scenarios escape may be the only viable option. RN submarines are fitted with escape compartments forward and aft. Each escape compartment contains sufficient Submarine Escape Immersion Equipment (SEIE) for the entire crew and is fitted with an escape tower through which the survivors of a DISSUB may escape. The escape procedure involves a rapid pressurization of the submariner in the escape tower to that of the ambient sea pressure, followed by buoyant ascent to the surface wearing SEIE.

Various factors can contribute to the decision to escape, but the limiting physiological factor to the safety of submarine escape is decompression sickness (DCS). Flooding of a DISSUB may cause a rise in ambient pressure inside the escape compartments. Any increase in pressure of the escape compartment will increase the amount of gas taken up by the survivors’

body tissues, increasing the risk of DCS, and decreasing the maximum depth from which it is safe to escape.

The relationship between the pressure in a DISSUB prior to escape and the safe escape depth is known as the “safe to escape curve.” The approach to defining the safe to escape curve has involved a combination of animal trials, manned trials and mathematical modeling. Animal work mapped out the high-risk areas to be avoided in manned trials and also provided evidence that there may be greater scope for successful escape than the advice originally given in the Guardbook [4]. This study describes manned trials aimed at defining the safe decompression limits to escape from a pressurized DISSUB.

METHODS

Ethical approval for the study was granted by the UK MoD Research Ethics Committee and conducted in accordance with the principles enunciated in the Declaration of Helsinki [5]. The trials were conducted at DERA and QinetiQ Alverstoke between 1995 and 2003 and were designed to minimize the risk of DCS through incremental progression from the safest pressure/depth combinations.

Subjects

Male volunteers ($n = 43$) who were instructors from the Submarine Escape Training Tank (SETT) at Fort Blockhouse, Gosport, UK, participated in the trials. The purpose, procedures and associated risks were explained, and the volunteers gave their informed written consent. They were familiarized with the layout inside the Submarine Escape Simulator (SES), and all volunteer subjects, chamber and medical staff were thoroughly rehearsed in emergency procedures.

Chamber and pressure profiles

Dry pressure exposures were carried out using the SES. This comprised two spherical pressure vessels, one 3 meters in diameter (14 m³ volume) and the other 2 meters in diameter (4 m³ volume), with an inter-connecting pressure-tight door and access doors at either end. The SES was purpose-built, with a computer-controlled gas transfer system, to accurately reproduce the pressure profile that a man would experience while making an escape from an RN submarine. It was fitted with a hood inflation system (HIS) that supplies air to the escaper during escape in order to imitate a submarine escape tower. The installation of a low-light camera in the 2-meter sphere

allowed visual monitoring of the subjects throughout the escape procedure. Abort buttons were installed in the 2-meter sphere, which were available for subjects to activate in the event of any problem during escape procedures. Once activated, the chamber would stop and hold at the depth at which the abort was activated and planned abort procedures and algorithms would be followed by the chamber supervisors, according to depth.

The trials were conducted in phases, aimed at testing saturation exposures, escapes and the combination of saturation and escape exposures. For saturation, subjects were exposed in groups of three to 1.5 bar (a) ($n=15$) or 1.6 bar (a) ($n=23$) for 24 hours, with a compression and decompression rate of 1 bar.min⁻¹. The specified pressure was maintained in the vessel to ± 0.005 bar by the addition of air. Oxygen concentration was measured with a pressure-compensated paramagnetic oxygen analyzer (Servomex) and maintained at $21\% \pm 0.3\%$ by an automatic oxygen inject system (Analox). Carbon dioxide partial pressure was measured by infrared spectroscopy (ADC) and maintained below 0.005 bar. Organic gases and humidity were scrubbed by an environmental conditioning system containing activated charcoal, silica gel and soda lime. The temperature was adjusted for subject comfort.

The series started with “work-up” escapes ($n=254$) from 30 msw (the depth that the SETT instructors are familiar with in their day-to-day work) and progressing in increments to depths down to 120 msw. These were conducted in order to familiarize the subjects with the experimental procedures, and also to establish the safety of these profiles before progressing to saturation, followed by escape from these depths. An incremental design was then developed which increased the saturation pressure in 0.05 bar steps, progressing from 1.5 bar (a) while keeping the escape depth constant at 90 msw, until DCS was observed (the experimental protocol stipulated that a trial series was halted if a second case of DCS was observed). This was followed by a return to 1.5 bar (a) saturation, increasing the escape depth in 15-msw increments to 120 msw; then increasing the saturation pressure to 1.55 bar, with escape from 90 msw and 105 msw.

For each subject there was an interval of at least 24 hours between each work-up pressure exposure and at least one week between saturation and escape and the next pressure exposure. For escapes, and saturation followed by escape, subjects were exposed in pairs. The aim was to expose 14 different subjects to each

saturation pressure/escape depth profile or until a second case of DCS occurred. The available subject pool meant that some subjects undertook more than one series. Three subjects participated in all six series of escape from saturation (over a period of five years), with others to a lesser extent.

For the simulated escape procedure, the subjects wore submarine escape immersion suits (SEIS) on top of lightweight clothing. On verbal instruction, the subjects zipped-up their SEIS hoods and connected their SEIS hand-held push-fit connector to the HIS. A 10-second countdown was given before pressurization commenced. The escape procedure involved a rapid pressurization, a nominal four-second hold at depth to simulate the escape hatch opening in a single-man escape tower, followed by a linear decompression to the surface at a rate of $2.75 \text{ m}\cdot\text{s}^{-1}$. The subjects wore a nose clip to aid equalization of middle-ear pressure during pressurization. On reaching the equalization pressure the subjects were informed that they had reached “depth” through chamber communications and a “bottom light” indicator. They then released the push-fit connector and breathed “normally” during the decompression.

For the saturation/escape profiles, the subjects were assessed by the Independent Medical Officer (IMO) immediately prior to the end of the saturation period and then transferred to the 2-meter sphere in readiness for the escape procedure. The pressure was maintained in the 2-meter sphere until the escape profile commenced. On reaching the “surface” the subjects transferred to the 3-meter sphere where the IMO monitored them during a four-minute “line-stand.” Following their exit from the chamber they removed their SEIS (usually worn for no more than 45 minutes) and underwent a medical examination by the IMO.

Medical cover and subject monitoring

Independent medical cover was provided throughout the exposures by the Institute of Naval Medicine (INM), Alverstoke, UK. Full resuscitation equipment was available and during the escapes, two medical officers who were qualified and in-date for cardio-pulmonary resuscitation were present.

Each subject underwent physical and neurological examination before and after each pressure exposure. Three-lead electrocardiogram (ECG) monitoring was carried out during the escapes for real time medical monitoring. The subjects underwent a “bend watch” of

one hour following simulated escapes and five-hour following saturation or escapes from saturation.

Precordial audio Doppler monitoring of venous gas emboli (VGE) was carried out using a TSI DBM9 with subjects standing at rest and also after movement (deep knee bend and returning to standing). Subjects were monitored at 0.25, 0.5 and one hour following escapes only, and after saturation and saturation/escapes at hourly intervals thereafter until VGE disappeared or until a maximum of eight hours after decompression had elapsed. VGE were scored according to the Kisman-Masurel (KM) code [6] and the Kisman Integrated Severity Scores (KISS) [7] calculated for the eight hours monitoring period (saturation and saturation/escape exposures).

Statistical analysis

Statistical analysis was carried out using SPSS 12.0.1. Median peak KM grades and KISS over the Doppler monitoring period were compared using the Kruskal Wallis test for three or more comparisons and Mann-Whitney U test for two comparisons. Differences were considered significant if $p < 0.05$. The Kruskal-Wallis and Mann-Whitney U tests assume independence of samples, and it is recognized that repeated use of subjects violates this assumption. However, only a small minority of subjects undertook every saturation/escape series. For multiple comparisons, the level of significance was adjusted using the Bonferroni correction, *i.e.*, for two comparisons significance was $p < 0.025$ and for three comparisons $p < 0.017$.

RESULTS

Details of the numbers of all pressure exposures (including work-ups) are shown in Table 1. There were a total of 38 saturation exposures, 254 escapes (excluding aborted escapes), plus 90 escapes from saturation.

Exposure to 1.5 or 1.6 bar (a) air saturation for 24 hours did not result in DCS. No cases of DCS presented following any of the escapes from 1 bar (a). The escape profiles did, however, result in seven cases of middle ear barotrauma, causing these escapes to be aborted at depths between 54 and 117 msw (during 3 x 90-msw, 1 x 105-msw and 3 x 120-msw profiles). All subjects who suffered middle ear barotrauma returned to normal diving duty after one month.

Exposures that increased the saturation pressure in 0.05 bar (a) steps, progressing from 1.5 bar (a), followed by escape from 90 msw were halted at

Table 1. Number and outcome of pressure exposures

saturation pressure (bar (a))	escape depth (msw)	exposures (n)	DCS (n)
1.00	30	78	0
1.00	45	16	0
1.00	60	54	0
1.00	90	72	0
1.00	105	16	0
1.00	120	18	0
1.50	0	15	0
1.60	0	23	0
1.50	30	2	0
1.50	45	2	0
1.50	60	4	0
1.50	75	4	0
1.50	90	14	0
1.50	105	14	0
1.50	120	14	0
1.55	90	14	0
1.55	105	12	0
1.60	90	10	2

1.6 bar (a)/90 msw when a second case of DCS occurred. The first was a case of cutis marmorata DCS (upper right abdomen) at 182 minutes post-decompression; the second was neurological DCS (generalized weakness in both legs) at 153 minutes post-decompression. Both subjects were treated using RN Treatment Table 62 in the hyperbaric chamber at the Royal Hospital Haslar and made a full recovery. A total of 10 subjects completed this exposure (out of an intended 14), which gave an incidence of DCS of 20% (95% confidence interval 2.52-55.6%) for this profile.

Having reached the saturation pressure where DCS was encountered, subsequent trials returned to saturation at 1.5 bar (a) and increased the escape depth in 15-msw increments to 120 msw. The next series then increased the saturation pressure to 1.55 bar (a) and tested escape from depths of 90 msw and 105 msw. Only 12 subjects completed the latter profile because of lack of subject availability due to operational requirements. No signs or symptoms of DCS were evident in any of the subjects following these exposures.

VGE were detected following saturation and saturation/escape profiles, but not following escapes from

between 30 and 120 msw. The KM grades and KISS were greater following movement, but only the resting results are reported here in order to negate the inter-individual difference in technique and effort exerted in deep knee bends.

Details of subjects and Doppler monitoring of VGE are shown in Table 2. Saturation at 1.5 bar (a) resulted in low-grade VGE in 33% of subjects. However, saturation at 1.6 bar (a) resulted in VGE detection in 78% of subjects, of whom more than half were KM grade 3 or above, demonstrating the effect on decompression stress of the addition of 0.1 bar (a) (1 msw) to the saturation pressure. The addition of a 90-msw escape after prior saturation at 1.5 bar (a) doubled the percentage of subjects with VGE, but again these were low-grade. Increasing the escape depth to 105 or 120 msw demonstrated a further increase in subjects with VGE and increased the peak KM grade and the KISS. Increasing the saturation pressure further to 1.55 bar (a) with escape from 90 or 105 msw demonstrated an increase in median KISS from prior saturation at 1.5 bar (a), and also increased the percentage of subjects with peak KM grade 3 or above. The addition of a 90-msw escape to prior saturation at 1.6 bar (a) resulted in 100% of subjects with Doppler-detectable VGE, of whom 60% had KM grade 3 or above.

The pressure profile and associated KISS for each subject over the eight-hour monitoring period are shown in Figure 1. It should be noted that for the 1.6-bar (a) saturation/90-msw escape profile, the scores from only eight of the 10 subjects are shown. This is due to the recompression treatment of the two subjects suffering DCS before Doppler monitoring was completed.

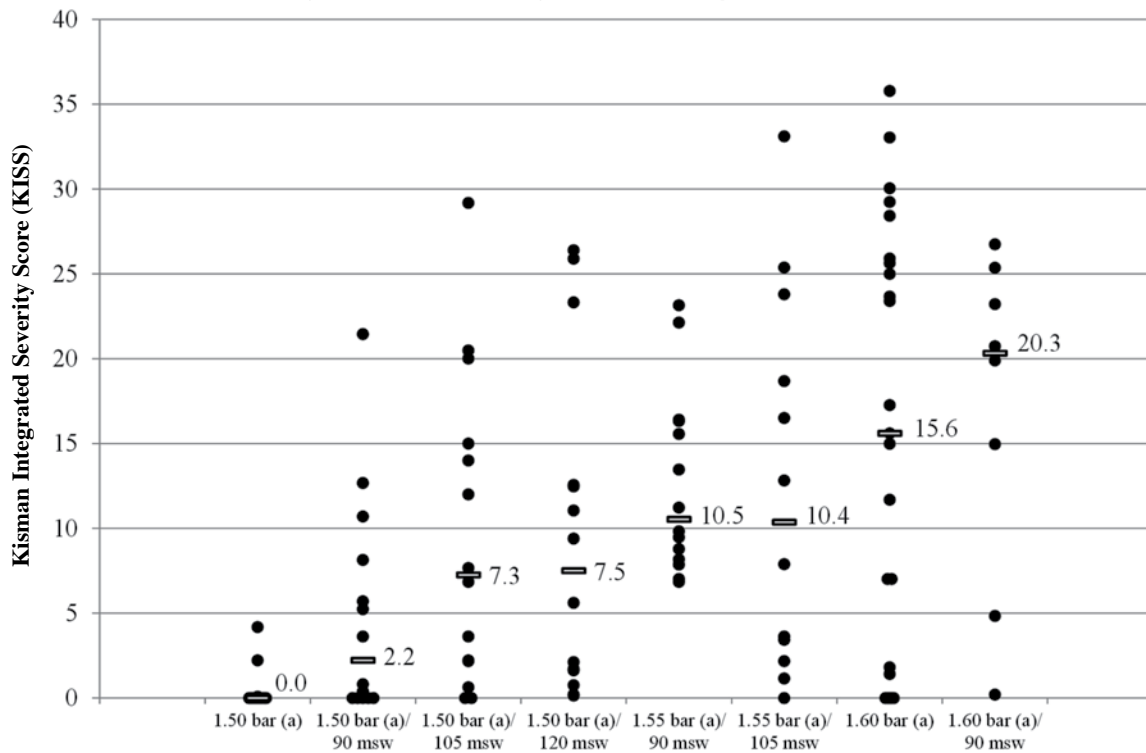
The lowest median KISS was zero for the 1.5 bar (a) saturation pressure profile. The highest median KISS of 20.3 was attained following the pressure exposure where DCS occurred: 1.6 bar (a)/90 msw. The median KISS for the saturation element alone was 15.6, escape only from 90 msw did not result in VGE. However, the addition of this escape profile clearly has an effect on VGE when combined with prior saturation.

The median peak KM grades for 90-msw escapes preceded by saturation at 1.5, 1.55 or 1.6 bar (a) are shown in Figure 2. Statistical testing showed a significant difference for both the median KISS and median peak KM grades between the three exposures ($p < 0.002$ and $p < 0.009$ respectively, Kruskal Wallis). *Post-hoc*

Table 2. Details of subjects and Doppler monitoring

Saturation pressure [bar (a)]	1.5	1.5	1.5	1.5	1.55	1.55	1.6	1.6
Escape depth (msw)	0	90	105	120	90	105	0	90
Subjects (n)	15	14	14	14	14	12	23	10
Mean age (SD) (years)	37.3 (1.38)	38.3 (5.62)	40.1 (3.98)	40.4 (3.43)	39.6 (3.84)	40.4 (2.27)	38.5 (2.78)	41.4 (4.84)
VGE present (%)	33%	64%	86%	100%	100%	92%	78%	100%
Peak KM grade (median)	0	1.50	2.33	2.66	2.66	2.33	2.66	3.00
Subjects with a peak KM grade ≥ 3 (%)	0%	14%	36%	21%	36%	42%	48%	60%
KISS (median)	0	2.2	7.3	7.5	10.5	10.4	15.6	20.3*

* based on eight subjects as two subjects treated for DCS

Figure 1. KISS following simulated escape from saturation

KISS following simulated escape from saturation; bars represent the median value, which is displayed adjacent to the bar.

testing showed this difference to be between the 1.5-bar (a)/90-msw exposure and both the 1.55-bar (a)/90-msw and 1.6-bar (a)/90-msw exposures for the KISS ($p<0.002$ and $p<0.02$ respectively, Mann-Whitney U) and for the median peak KM grade ($p<0.007$ and $p<0.017$ respectively, Mann-Whitney U). There was no significant difference between 1.55 bar (a)/90 msw and 1.6 bar (a)/90 msw.

The median peak KM grades for 1.6-bar (a) saturation and 1.6-bar (a)/90 msw are shown in Figure 3. There was no significant difference between the median KISS or median peak KM grades for 1.6-bar (a)/90-msw (profile where DCS occurred) and 1.6-bar (a) saturation-only. The main distinction between the two pressure profiles was the shorter latency and higher initial KM grades of VGE for the

Figure 2. Median peak KM grades for simulated 90-msw escape from increasing saturation pressures

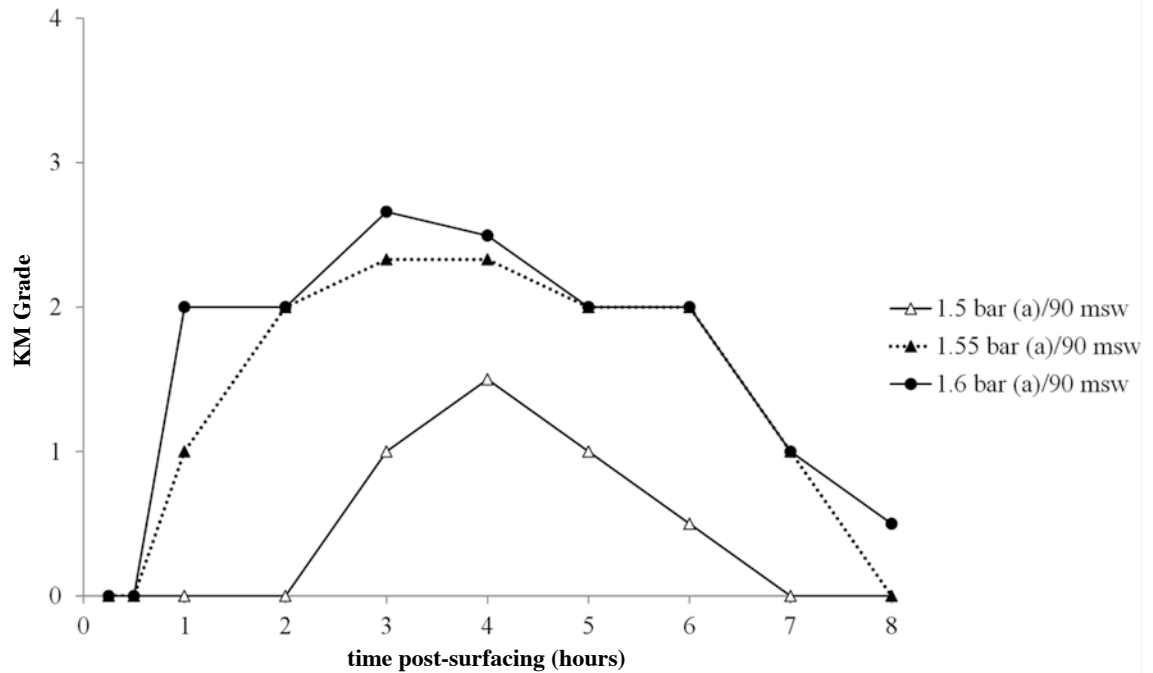
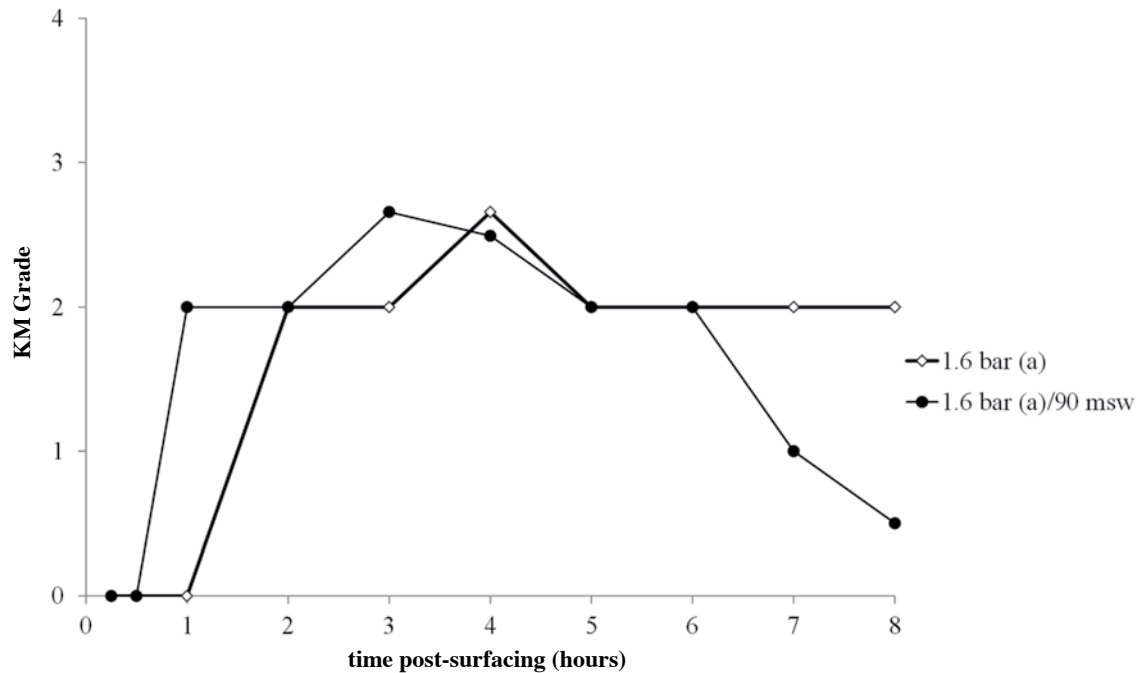


Figure 3. Median peak KM grades for 1.6-bar (a) saturation-only and for 1.6-bar (a)/90-msw escape



1.6-bar (a)/90-msw profile. The subject with cutis marmorata had the highest KM grade (3+) of all the subjects for that profile. However, the subject with neurological DCS had a resting KM grade of only 2.

DISCUSSION

This study reports the first simulated submarine escapes from raised pressure – a world first. The risk of DCS associated with the pressure exposures in this study was generally low. However, it demonstrated that even small increases in saturation pressure in a DISSUB can have a great effect on the safety of ensuing escape. No DCS was observed following escapes from 90 msw with prior saturation at 1.5 bar (a), which was significant, as it confirmed the untested Guardbook advice at that time. Further testing went on to demonstrate the limit to safe escape with respect to DCS as 1.6-bar (a) saturation followed by 90-msw escape.

The approach to defining the “safe to escape curve” has involved a combination of animal trials, manned trials and mathematical modeling. When plotting a safe to escape curve, the submariners’ tissues are assumed to be saturated with the inert gases at the ambient partial pressures in the DISSUB. A number of previous studies aimed at determining the maximum pressure for direct ascent to the surface have demonstrated a very low incidence of DCS below 1.7 bar (a), with increasing incidence of DCS above this saturation pressure [8-13], thus defining the upper DISSUB pressure limit of the safe to escape curve. Van Liew and Flynn suggest a saturation pressure of 1.62 bar (a) as the threshold for limb pain DCS [14]. The present study showed no DCS following direct ascent from saturation at 1.5 or 1.6 bar (a), in accordance with these previous studies.

Many hundreds of manned escapes have been performed, both at sea during exercises and in dry chambers, to depths down to 90 msw with no reported cases of DCS; and to 150 msw and deeper with a low incidence of DCS [1,2,3,15,16]. In the present study no DCS resulted from simulated escapes down to 120 msw, in agreement with these previous chamber and sea trials. Escapes deeper than 120 msw were not carried out for a number of reasons, primarily safety, as some previous escapes from 150 msw resulted in DCS [1,3].

The rapid pressurization during submarine escapes can cause middle ear barotrauma, which has been demonstrated in previous sea and chamber trials and is considered an acceptable risk in the context of escape from a DISSUB. There were seven cases of middle

ear barotrauma in the present study resulting in aborted escapes, all affected made a complete recovery. However, 254 escapes and a further 90 escapes from saturation were completed successfully.

Decompression can induce the formation of VGE without overt DCS. Doppler ultrasound has been used for many years to detect VGE both during and after decompression and has provided much useful information regarding the relative decompression stress of different decompression procedures [17,18]. Higher VGE scores have been associated with exposures that carry a high risk of DCS [19,20] and were used as a guide to decompression stress in the present study.

Analysis of Doppler data collected during our study shows that above a certain threshold the saturation element of the pressure exposures is responsible for the majority of decompression stress, as may be expected. The addition of 0.1 bar (a) (1 msw) to the starting saturation pressure was associated with more decompression stress than the addition of 90-msw escape to the end of the saturation exposure – 1.5 bar (a) to 1.6 bar (a) vs. 1.5 bar (a) to 1.5 bar (a)/90 msw. No VGE were detected following simulated escapes down to 120 msw. However, escape after saturation resulted in higher observed KM grades than saturation alone. Some variance in results may be expected due to particular subjects participating in different series of pressure exposures, as some tended to be “non-bubblers,” consistently producing no VGE, while others tended to produce many, and others were more variable. The median peak KM grades in Figures 2 and 3 show that the most striking aspect of the profile where DCS occurred was the shorter latency and higher initial KM grade of VGE. Shorter latency times for VGE onset have been associated with increased DCS risk reported by others [21].

The present study has informed the advice on limits to escape from shallow saturation. The progress described here contributes to the understanding of the relationship between the pressure in a DISSUB prior to escape and the safe escape depth, *i.e.*, the safe to escape curve. These data have contributed to the calibration of a mathematical model predicting the likelihood of DCS following submarine escape [22].

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Conflict of interest

The authors have declared that no conflict of interest exists with this submission. ■

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Annex 12.

Loveman GAM, Seddon FM, Thacker JC, Stansfield MR, Jurd KM.

Submarine tower escape decompression sickness risk estimation.

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Submarine tower escape decompression sickness risk estimation

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ABSTRACT

Actions to enhance survival in a distressed submarine (DISSUB) scenario may be guided in part by knowledge of the likely risk of decompression sickness (DCS) should the crew attempt tower escape. A mathematical model for DCS risk estimation has been calibrated against DCS outcome data from 3,738 exposures of either men or goats to raised pressure. Body mass was used to scale DCS risk. The calibration data included more than 1,000 actual or simulated submarine escape exposures and no exposures with substantial staged decompression. Cases of pulmonary barotrauma were removed from the cali-

bration data. The calibrated model was used to estimate the likelihood of DCS occurrence following submarine escape from the United Kingdom Royal Navy tower escape system. Where internal DISSUB pressure remains at ~ 0.1 MPa, escape from DISSUB depths < 200 meters is estimated to have DCS risk $< 6\%$. Saturation at raised DISSUB pressure markedly increases risk, with $> 60\%$ DCS risk predicted for a 200-meter escape from saturation at 0.21 MPa. Using the calibrated model to predict DCS for direct ascent from saturation gives similar risk estimates to other published models.

INTRODUCTION

Evacuation of a United Kingdom Royal Navy submarine is possible via a small airlock, the escape tower. During the escape procedure, one or two personnel enter the escape tower, which is then rapidly flooded with sea water. This process allows rapid equalization between the pressure within the escape tower and the external sea pressure. Upon equalization, an outer hatch opens and the buoyancy of the suits worn by the escapers carries the submariners to the surface. Prior to escape, the crew may be exposed to raised pressure within the distressed submarine (DISSUB) due to flooding or release of air from high-pressure systems. The exposure to raised pressure within the submarine and subsequently in the escape tower, followed by rapid return to normal atmospheric pressure, puts the crew at risk of suffering decompression sickness (DCS).

The UK Ministry of Defence (MoD) had a requirement to define the relationship between the DISSUB internal pressure, the depth from which escape is made and the risk of DCS. This paper describes the calibration of mathematical models for the prediction of DCS risk following submarine tower escape. The base model used was the linear-exponential (LE) model developed by Thalmann, *et al.* [1]. The model is briefly described here to allow reference to the parameter names. For

a full description of that model, the reader is referred to the original paper [1]. Note that throughout this paper, ambient pressure at sea level is taken to be 0.1 MPa and is assumed to increase by 0.01 MPa for each 1 meter increase in depth.

The LE model

The LE model is a statistical formulation that allows the prediction of decompression risk. The model uses “lumped” physical/physiological parameters such that the value of a single parameter might, for example, contain information on the relative solubility of a gas in a combination of tissues and the averaged rate of blood perfusion of those tissues. For the work presented here, nitrogen is the only inert gas considered. The body is represented by n independent compartments. During exposure to raised pressure, the rate of change of nitrogen tension in each compartment follows exponential kinetics determined by a time-constant parameter, labeled τ_i for the i^{th} compartment. On return to a lower pressure, the nitrogen tension in each compartment may be higher than the ambient nitrogen partial pressure. The compartment is “supersaturated” and can be described as having an “inert gas burden,” which is expressed as a partial pressure. The total tissue gas burden is the sum of this inert gas burden and the

partial pressures of the metabolic gases present (oxygen, carbon dioxide, water vapor). The degree of supersaturation may be expressed as the relative supersaturation ratio:

$$(1) \quad \frac{Pt_{iss_i} - P_{amb}}{P_{amb}}$$

where Pt_{iss_i} is the total tissue gas burden for tissue i and P_{amb} is the ambient pressure.

The gas is eliminated from the compartment using the same exponential kinetics as those for uptake, unless the total tissue gas burden exceeds the sum of P_{amb} and a linear-exponential crossover pressure parameter, Pxo_i . At this point the compartment is assumed to switch to linear gas elimination, giving a slower overall elimination rate, emulating a reduced gradient for gas elimination simulating the effect of the presence of gas bubbles in the tissues. If Pxo_i is set to a sufficiently large value, the linear elimination of gas will never be invoked; such models are usually referred to as “exponential-exponential” (EE) models.

A risk of DCS is assumed to be incurred due to the presence of a tissue gas burden. For each compartment a threshold pressure, Thr_i , is defined as the total tissue gas burden that the compartment can withstand with no accumulation of risk of DCS symptoms. The instantaneous risk of DCS for each compartment is then taken as:

$$(2) \quad r_i = \frac{G_i(Pt_{iss_i} - P_{amb} - Thr_i)}{P_{amb}}$$

where G_i is a weighting factor, usually termed the “gain.”

This original form of the function will be denoted here as risk function A , since other forms of risk function have been used within this study. The total instantaneous risk of DCS to the individual, r , is the sum of the r_i over the n compartments. Thus for each compartment there are four parameters, the values of which can be estimated in order to give the best fit of the model to a set of data: τ_i , Pxo_i , Thr_i and G_i . Since this model does not attempt to simulate all aspects of the physiological processes involved in DCS, it may be referred to as semi-empirical or quasi-physiological.

Risk integrals and the likelihood of decompression sickness

For any given pressure exposure, the time-integral of the instantaneous risk is transformed into a probability of DCS as follows:

$$(3) \quad P_{dcs} = 1 - e^{-\int r \cdot dt}$$

In order to compare the models’ predictions with trials’ data, a dataset of pressure exposures is required in which the decompression outcome of every exposure is known. For exposures where DCS occurred, the time of DCS is required. The time at which DCS was diagnosed by a physician or, in the case of animal trials, by an investigator is referred to as T_2 . The time prior to T_2 , at which the diver was last known to be entirely free of DCS symptoms is referred to as T_1 . Exposures are assigned a value of 1 or 0 for DCS/no DCS occurrence. Exposures with equivocal outcomes where determination of very mild DCS symptoms is unclear and apparent symptoms resolve without treatment are referred to as “niggles” or “marginals” and assigned an outcome value of 0.1.

The model can be used to calculate a predicted likelihood of the actual measured outcome of an exposure as follows: If there is no DCS on an exposure, the predicted likelihood of the actual outcome is the calculated probability that DCS will not occur, that is:

$$(4) \quad 1 - P_{dcs} = e^{-\int r \cdot dt}$$

If DCS does occur following an exposure, the predicted likelihood of the actual outcome is the product of the calculated probability that DCS will not occur before T_1 and the probability that DCS will occur in the interval $T_1 - T_2$:

$$(5) \quad P_{dcs} = (e^{-\int_0^{T_1} r \cdot dt}) (1 - e^{-\int_{T_1}^{T_2} r \cdot dt})$$

A likelihood value can be computed for the entire dataset as the product of the calculated likelihoods of all the exposures in the dataset. This value is generally a very small positive number and is more conveniently expressed by its logarithm – the log-likelihood (LL), which is therefore negative.

METHODS

Pressure-time and DCS outcome data from 2,544 manned pressure exposures and 1,194 goat pressure exposures were used in the calibration of the model. These are summarized in Table 1.

U.S. Navy decompression database

The majority of available human calibration data were United States Navy operational dive trials [2]. These data mostly comprise dives with low observed DCS risk resulting from operational exposures with planned staged decompression. There are also data from manned saturation, subsaturation and submarine escape profiles.

Table 1. Summary of calibration data subsets

Dive type	Dataset	Species	Dives (<i>n</i>)	DCS (<i>n</i>)	Marginal (<i>n</i>)
Saturation	SATSESM	Man	38	0	0
	ASATNSMQ	Man	20	4	6
	ASATAREQ	Man	30	2	2
	ASATNMRQ	Man	18	1	0
	NMR9209	Man	48	2	5
	EDUAS45Q	Man	12	2	0
	ASATDC	Man	23	8	1
	SATFR85Q	Man	13	0	0
	SATSESG	Goat	205	92	0
Subtotals:			407	111	14
Subsaturation	6HRGOAT	Goat	60	14	1
	NSM6HR	Man	57	3	2
	EDU849S2	Man	60	13	17
Subtotals:			177	30	20
Saturation/ escape	SATESCM	Man	90	2	0
	pSATESCG	Goat	270	42	0
Subtotals:			360	44	0
Single air dive	SESESCM	Man	254	0	0
	pSESESCG	Goat	272	17	1
	HISTGOAT	Goat	387	61	1
	BESCHLC	Man	112	0	0
	DC4DQQ	Man	321	1	0
	EDU557QQ	Man	110	0	0
	EDU885AQQ	Man	112	4	0
	UPS290QQ	Man	274	4	0
	DC4WQQ	Man	74	3	2
	EDU849LT2	Man	141	26	38
	NMR97NOD	Man	103	3	4
	NMRNSW2Q	Man	37	4	3
	PASAQQ	Man	5	1	0
	SUBX87QQ	Man	115	2	0
	NMR8697Q	Man	477	12	17
Subtotals:			2794	138	66
Totals:			3738	323	100

Body mass data were not available for the exposures in these datasets. Data were included only where the exposures did not provide more than 10 minutes total decompression time. Heliox or trimix dives were excluded, as were any repetitive dives. Data inclusion/exclusion was decided for some exposures by discussion between the authors on a case-by-case basis. Criteria for exclusion were decided and the final datasets compiled before any modeling was carried out. Where exposures were excluded from the original datasets, a letter *Q* has been appended to the dataset name in Table 1.

QinetiQ UK Submarine Escape Simulator data

Data were available for 382 manned exposures carried out in the QinetiQ UK submarine escape simulator (SES). The data include escape exposures for simulated depths ranging from 30 to 120 meters, 24-hour saturation exposures at 0.15-0.16 MPa, or 24-hour saturation exposures at 0.15 or 0.155 MPa followed by simulated escape from between 90 and 120 meters. The datasets are named *SESESCM*, *SATSESM* and *SATESCM*. These data are described in Jurd, *et al.* [3].

Data were available for 807 goat exposures carried out in the SES, excluding 14 cases of pulmonary

barotrauma, for which the model does not account. The data include six-hour subsaturation exposures to 0.16-0.267 MPa, escape exposures for simulated depths ranging from 150 to 290 meters, 24-hour saturation exposures at 0.15-0.235 MPa and 24-hour saturation exposures at 0.15-0.22 MPa followed by simulated escape from 150 to 260 meters. The datasets are named *6HRGOAT*, *pSESESCG*, *SATSESG* and *pSATSESCG*. These data are described in Seddon, *et al.* [4] and White, *et al.* [5].

QinetiQ UK historical manned escape data

Barnard, *et al.* have reported trials carried out in Gosport, UK, detailing 112 simulated manned escapes at depths between 60 and 191 meters with no occurrences of DCS [6]. These data have been compiled in a dataset named *BESCHLC* and included in the model calibration.

QinetiQ UK historical goat data

Available data collected from trials carried out in Gosport, UK, between June 1951 and February 1982 contain the details of 7,302 pressure exposures by 475 individual goats. These “historical data” contain many subsaturation pressure exposures. However, trials design prevents many of the data from being used where the method of calibration assumes the data are taken from a normal population. To avoid possible bias, only the first recorded pressure exposure of any animal was included in the calibration. Of the 7,302 exposures in the historical dataset, 387 were used. The dataset is named *HISTGOAT* (unpublished data).

Adaptation of the LE model instantaneous risk function

The form of risk function *A* constrains instantaneous risk to vary linearly with supersaturation. This constraint was removed through the introduction of a further parameter, β_i , allowing instantaneous risk to vary either linearly ($\beta = 1$) or non linearly ($\beta \neq 1$) with supersaturation, according to risk function *B*:

$$(6) \quad r_i = G_i \left(\frac{(Pt_{iss_i} - P_{amb} - Thr_i)}{P_{amb}} \right)^{\beta_i}$$

Adaptation of the LE model for inclusion of body mass data

DCS incidence has been shown to scale as a function of species body mass [7,8]. It was anticipated that improved model fit to the data might be achieved through

the scaling of DCS risk with body mass. Instantaneous risk function *C* allows a method by which body mass is introduced, the form of risk function *C* being the product of the instantaneous risk function *B* and the subject’s body mass, *M* (in kg), raised to a power, γ_i , an extra parameter to be optimized in the fit:

$$(7) \quad r_i = G_i M^{\gamma_i} \left(\frac{(Pt_{iss_i} - P_{amb} - Thr_i)}{P_{amb}} \right)^{\beta_i}$$

Body mass data were not available for the “historical” animal data described in this report. For these exposures, the goats’ body mass was imputed as 54.0 kg, based on the mean body mass of all goat exposures carried out in the SES.

For manned exposures where body mass data were not available, body mass was imputed as 77.3 kg for exposures carried out prior to 1990 based on an anthropometric survey of submariners carried out by the Royal Navy Institute of Naval Medicine at that time, and 84.0 kg for exposures carried out since 1990 based on the mean body mass of the subjects of the manned trials that were carried out in the SES. Body mass was imputed for approximately 32% of the goat exposures and 84% of the human exposures included in the calibration data.

Model coding and calibration

All model source code and algorithms for parameter optimization were written in *C* and compiled using Microsoft Visual Developer 97 Visual C++ 5.0. Calibration of models was performed using a modified Levenberg-Marquardt algorithm to optimize parameter values to give the maximum LL of the model over the data [9,10]. To avoid the optimization routine becoming trapped in local maxima, at least 95 trials of different initial parameter values were run for each model on each dataset. Models were named by the number – 1 to 6 – of compartments representing the body and the label for the form of the risk function, one of *A*, *B* or *C*. The numbers of parameters that were optimized for each model are shown in Table 2.

Model performance and model selection

Models were assessed for best fit under the Akaike Information Criteria (AIC) (11). The AIC takes account of the number of parameters within a model, allowing comparisons to be made between non-nested models that have been calibrated on the same dataset. For each calibration run, the AIC was calculated as double the

Table 2. Numbers of model parameters optimized

Model name	Number of parameters
1A	4
2A	8
3A	12
3B	15
4B	20
5B	15
5C	18
6B	24
6C	21

Numbers of parameters optimized for different models, the model name comprises the number of compartments and the risk function label *A*, *B* or *C*.

sum of the absolute value of the LL and the number of estimated parameters. The best performing model was selected as that having the lowest AIC value. It should be noted that the AIC does not give an absolute measure of the goodness of fit of a particular model but allows ranking only between competing models.

Use of the bootstrap method for error estimation

From the original calibration dataset of 3,738 exposures, 1,000 further datasets were generated, each containing 3,738 exposures sampled from the original dataset at random and with replacement. Differences between any bootstrap dataset generated by this process and the original dataset should be normally distributed, with the majority of the bootstrap datasets being fairly similar to the original and fewer datasets produced with many repeated or omitted exposures.

The parameters of the best performing model, as determined by its AIC value, were reoptimized against each of the 1,000 bootstrap datasets. Three sets of starting parameter values were used for optimization against each bootstrap dataset to reduce the chance of locating local maxima in the likelihood surface, 3,000 optimization runs being performed in total. This procedure resulted in the generation of a total of 1,000 bootstrap parameter sets individually optimized against the 1,000 bootstrap datasets.

The 1,000 bootstrap parameter sets that have been generated were used to provide estimated confidence limits on predicted risk of DCS. For any particular pressure exposure profile, 1000 estimated values of DCS risk are made using the 1,000 parameter sets;

the mean of these values is taken as the predicted risk of DCS for the pressure profile; the 25th and 975th largest values are taken as the limits of the 95% confidence region about the mean.

Model goodness of fit

Model goodness of fit to the calibration data was assessed with data grouped in four ways: by grouping exposures in deciles by predicted *Pdcs* and using the Hosmer-Lemeshow test [12]; by grouping and plotting data in bins with equal numbers of cases of observed *Pdcs*; by grouping the data by the named datasets as listed in Table 1; and by grouping data by exposure duration and binning by depth.

Prediction of risk of DCS for submarine tower escape

Iso-risk curves for tower escape were generated using the best performing model, as determined from the AIC value. Risk curves were generated assuming the DISSUB crew were exposed to 24 hours, six hours or one hour at raised pressure in the DISSUB prior to escape. The escape profile was assumed to follow the shape of that experienced in an idealized submarine escape tower, with pressure doubling at a maximum rate of once every four seconds and a four-second hold at maximum depth, followed by ascent from the maximum depth to the surface at $2.75 \text{ m}\cdot\text{s}^{-1}$. The 1,000 bootstrap parameter sets were used to provide estimated confidence limits for each point on each iso-risk curve.

RESULTS

Model calibration and selection

Table 3 shows the AIC values for each of the optimized models. Model 5C has the lowest AIC value and was selected as the best performing model.

Optimized parameter values for model 5C are shown with their bootstrap 95% confidence limits in Table 4. Pxo_i is not listed in Table 4, as its value had no effect on the fit to the data.

Model goodness of fit by predicted risk, data binned by equal numbers of exposures

The PredictABEL package [13] of the R statistical environment [14] was used to perform the Hosmer-Lemeshow goodness of fit test. The default settings of the package were used, causing the data to be grouped by predicted *Pdcs* into ten bins with approximately equal numbers of exposures in each bin. Note that exposures with marginal outcomes were

Table 3. AIC values

Model name	AIC value
1A	2692.6
2A	2431.6
3A	1986.2
3B	1853.2
4B	1829.4
5B	1719.2
5C	1702.8
6B	1749.4
6C	1707.4

AIC values for the optimized models.

removed in order to allow input of only binary outcome data to the PredictABEL package. A summary of the binned data is shown in Table 5. For this test, the null hypothesis was that the model predicted values match the observed data. The resulting χ^2 (d.f. = 8) = 12.51, p = 0.1299, so the null hypothesis was not rejected at the α = 0.05 level.

Model goodness of fit by predicted risk, data binned by equal numbers of DCS cases

Figure 1 shows observed DCS fraction plotted against model 5C predicted *Pdcs*. The data were binned to give at least 39 and at most 40 cases of DCS per bin. The line of identity passes through the 95% confidence limits of all points, therefore a lack of model fit is not suggested.

Model goodness of fit, data binned by original named datasets

Figures 2a and 2b show *Pdcs* predicted by model 5C and observed DCS fraction by dataset as listed in Table 1. The figures show that 95% confidence limits

Table 5. Summary of data bins for Hosmer-Lemeshow test

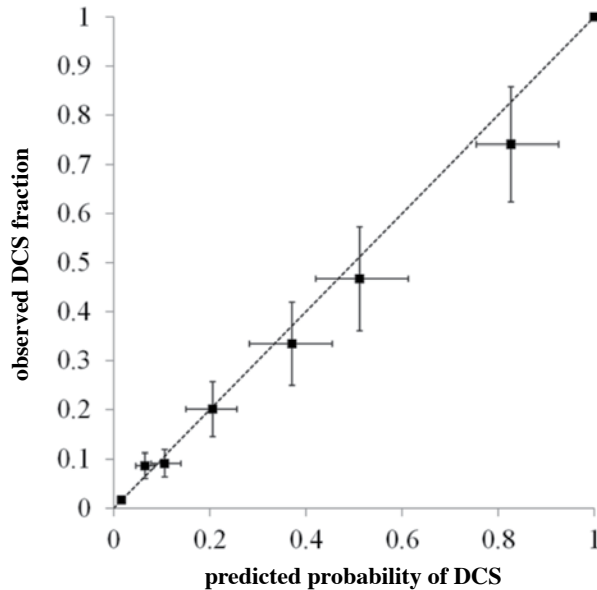
Range of <i>Pdcs</i> for data bin	Dives in bin (<i>n</i>)	DCS predicted by model 5C (<i>n</i>)	DCS observed (<i>n</i>)
0.000009 - 0.0028	367	0.27	0
0.0028 - 0.0066	364	1.51	0
0.0066 - 0.0131	364	3.80	5
0.0131 - 0.0182	371	5.80	7
0.0182 - 0.0267	354	7.86	11
0.0267 - 0.0443	364	12.08	11
0.0443 - 0.0637	364	18.58	28
0.0637 - 0.1004	364	30.25	23
0.1004 - 0.1918	364	46.30	38
0.1918 - 1	363	199.75	202

of predicted *Pdcs* and observed DCS fraction overlap for all datasets with the exception of the *6HRGOAT* dataset, where the 5C model underestimates the observed DCS fraction. Due to this, the model demonstrates lack of fit to the calibration data when grouped by datasets, with χ^2 (d.f. = 27) = 78.67, p < 0.01. The reason for the lack of fit to the *6HRGOAT* dataset is worth further examination. *6HRGOAT* contains records of six-hour “subsaturations” exposures carried out using 60 goats. A further 92 goat exposures of six hours’ duration are recorded among the pressure profiles of the *HISTGOAT* dataset. All these exposures involved “immediate” surfacing with no staged decompression. Figure 3 shows cumulative predicted and observed cases of DCS with depth for the six-hour exposures of these two datasets. The observed rate of DCS increase with exposure depth is quite different for the two datasets, with DCS cases occurring in the *6HRGOAT* exposures at markedly lower depths than in the *HISTGOAT* dataset. Since the observed rates of DCS of these exposures

Table 4. Parameter values for model 5C

i	PARAMETER					
	τ (s)	γ	G (s ⁻¹)	β	Thr (Pa)	
1	33.5 [26 - 48]	0	8.50E-06 [7.0E-06 - 9.8E-06]	4.13 [3.4 - 4.5]	0	
2	904 [670 - 1110]	0	8.51E-07 [7.2E-07 - 1.0E-06]	8.64 [7.9 - 9.3]	0	
3	4915 [4400 - 5400]	0	2.21E-04 [1.8E-04 - 2.6E-04]	7.16 [6.4 - 8.1]	0	
4	9378 [7620 - 11060]	2.54 [2.4 - 2.7]	3.81E-11 [3.0E-11 - 5.0E-11]	0.56 [0.4 - 0.7]	0	
5	20740 [17980 - 23630]	2.02 [1.9 - 2.1]	4.21E-07 [2.5E-07 - 6.4E-07]	5.94 [5.3 - 6.8]	13390 [7960 - 18710]	

Parameter values for model 5C [bootstrap 95% confidence limits]

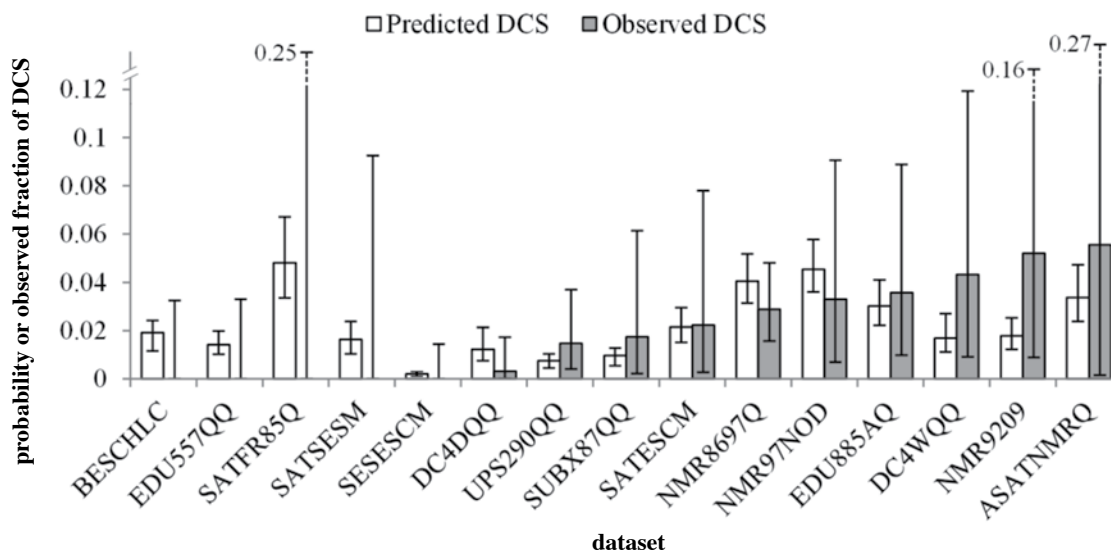
Figure 1. Observed against predicted DCS

Observed DCS outcome against predicted P_{dcs} from model 5C. Plotted points represent bins containing 39 to 40 cases of DCS. Numbers of exposures (n) from lowest to highest P_{dcs} bin are: 2342, 458, 428, 196, 119, 85, 54 and 40. Vertical error bars show 95% confidence limits for binomial proportions, horizontal error bars show bootstrap 95% confidence limits on predicted P_{dcs} . Points from a model that predicted the observed data perfectly would lie on the line of identity, shown dashed.

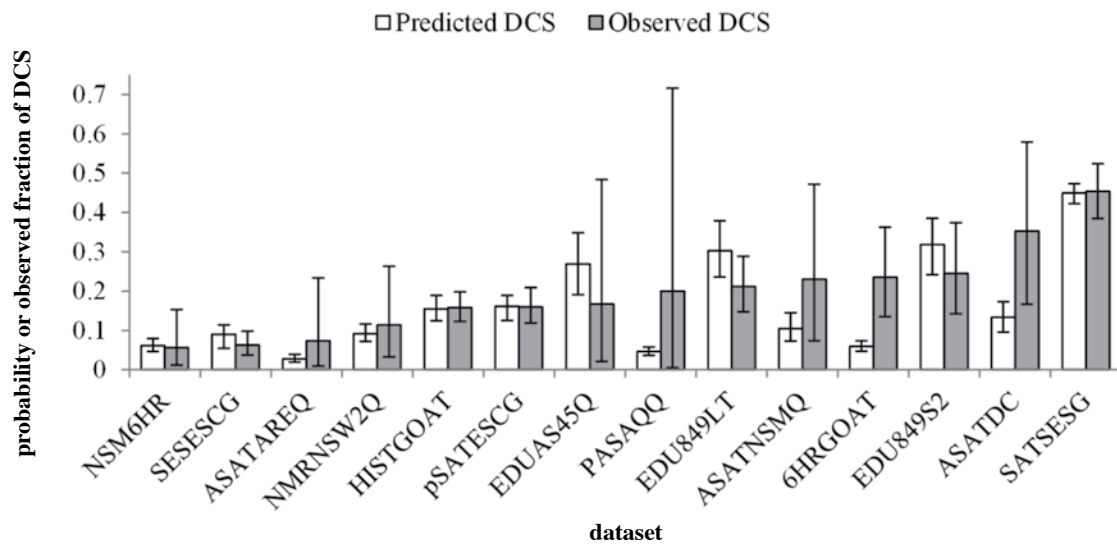
are substantially different while the exposures are of similar duration and depth range, it is not possible for the 5C model to fit both sets of observations. Note that while the model underestimates the rate of DCS for the 6HRGOAT dataset, the rate of DCS for the HISTGOAT six-hour exposures is overestimated. In fact, the only other six-hour exposures in the calibration data are manned exposures in the NSM6HR dataset. This dataset is fit well by the 5C model, the rate of occurrence of DCS with depth lying almost centrally between the low rates observed for the HISTGOAT dataset and the high rates observed for the 6HRGOAT dataset. It seems reasonable to conclude that the model 5C may be relied upon to predict risk of DCS for six-hour-duration exposures despite the underestimation demonstrated for the 6HRGOAT dataset. The marked difference in the 6HRGOAT and HISTGOAT six-hour exposure DCS data may be due to differences in the observers' criteria for diagnosing DCS, possibly combined with other unknown factors and chance.

Model goodness of fit, data grouped by exposure duration and binned by depth

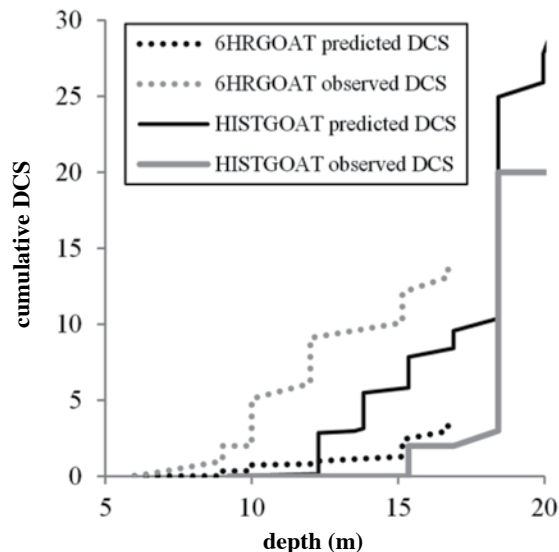
Figures 4 to 8 (a) show bar charts with data grouped by exposure duration and then binned by maximum exposure depth. Figure 9a shows the data for exposures where a simulated submarine escape was carried

Figure 2a. Model 5C predicted probability/observed fraction of DCS

Model 5C predicted probability and observed fraction of DCS for datasets with observed DCS rate $< 0.056\%$. Predicted DCS data are shown with bootstrap 95% confidence limits. Observed DCS data are shown with 95% confidence limits for binomial proportions. In order to preserve legibility, the longest error bars are not shown to scale. These are labeled with the value of their upper extent.

Figure 2b. Model 5C predicted probability/observed fraction of DCS

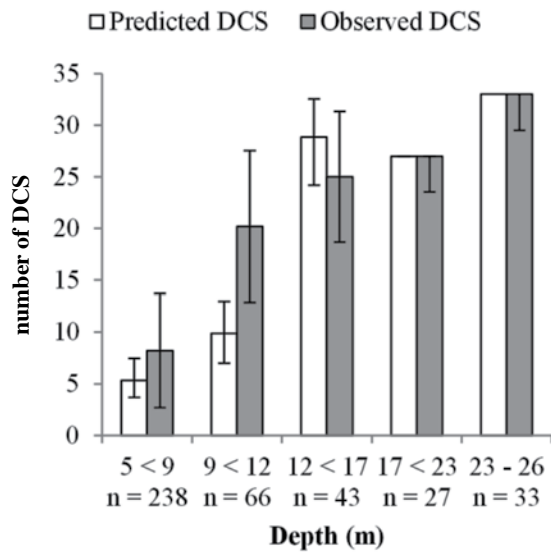
Model 5C predicted probability and observed fraction of DCS for datasets with observed DCS rate > 0.056%. Predicted DCS data are shown with bootstrap 95% confidence limits. Observed DCS data are shown with 95% confidence limits for binomial proportions.

Figure 3. Cumulative DCS cases with simulated depth for six-hour exposures of goats

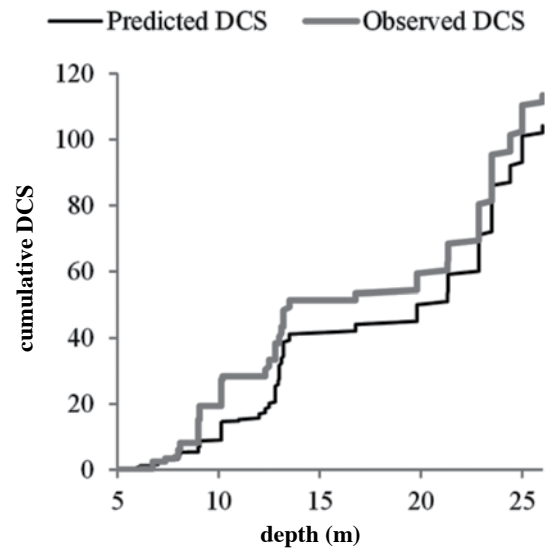
out following saturation; these data have been binned by saturation depth. Bin widths are uneven as certain exposure depths have been used more frequently. Predicted DCS data are shown with error bars of the bootstrap estimated 95% confidence limits. Observed DCS data are shown with error bars of the 95% confidence limits for binomial proportions. In order to avoid the selection of bin width masking information on the goodness of fit, the data are also plotted unbinned, as cumulative predicted and observed cases of DCS in Figures 4 to 9 (b). Exposure duration groups have been labeled as: saturation (duration > 22 hours at maximum depth); subsaturation (350 minutes ≤ duration < 22 hours); long (60 minutes ≤ duration < 350 minutes); regular (15 minutes ≤ duration < 60 minutes); short (0 minutes < duration < 15 minutes, includes submarine escape profiles); and saturation with escape exposures.

Figure 4 shows that the 5C model tends to underestimate against the observed DCS for these saturation data for the depth range 5 to 12 meters (although the 95% confidence bands do overlap).

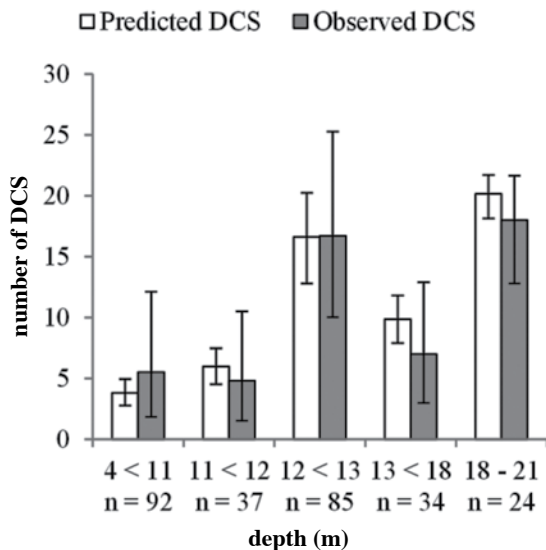
Figure 5 indicates that the 5C model fits observed DCS data for subsaturation well, with small regions of slight underestimation in the 4- to 11-meter depth range and slight overestimation deeper than 13 meters.

Figure 4a. ‘Saturation’ exposures

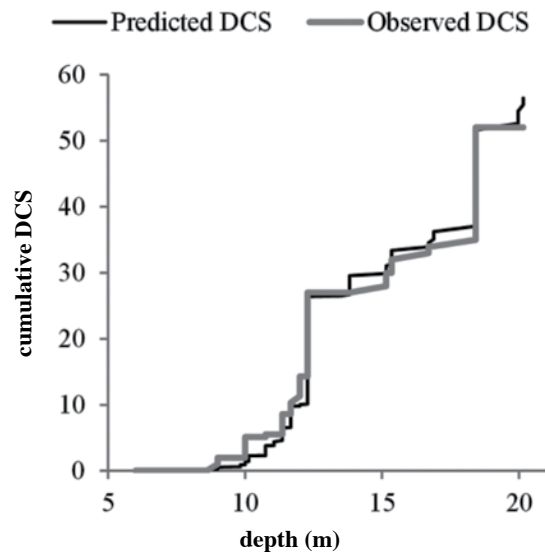
“Saturation” exposures (duration >22 hours at maximum depth), model 5C predicted and observed cases of DCS in n subjects. For exposures deeper than 17 meters, the bootstrap estimated 95% confidence limits are too narrow to display at this scale; observed rate of DCS is 100%: hence the 95% confidence limits for binomial proportions do not extend above the bars of these bins.

Figure 4b. ‘Saturation’ exposures

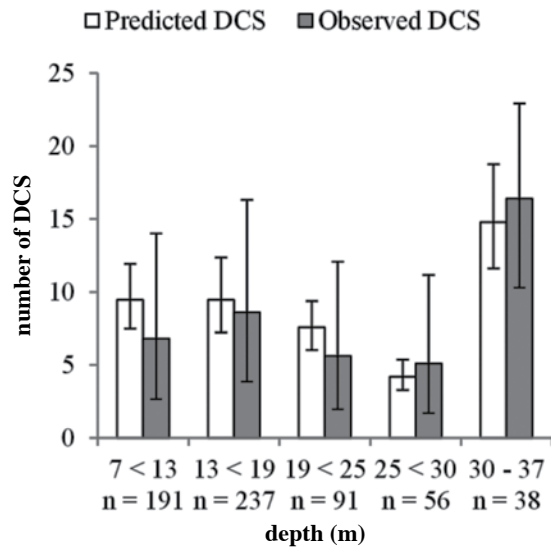
“Saturation” exposures (duration >22 hours at maximum depth), cumulative model 5C predicted and observed cases of DCS with depth.

Figure 5a. ‘Subsaturation’ exposures

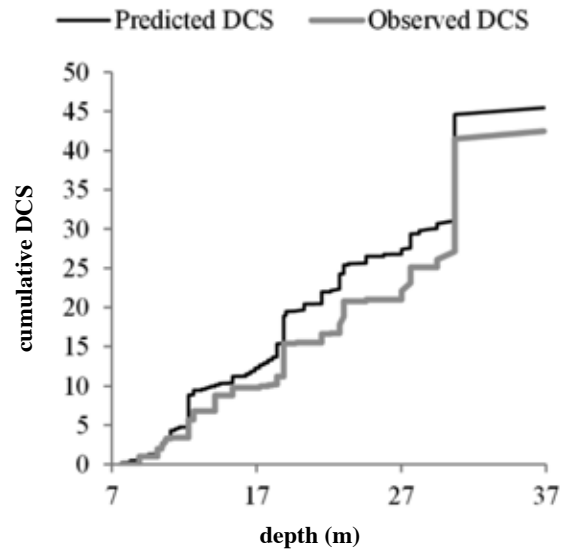
“Subsaturation” exposures (350 minutes \leq duration < 22 hours), model 5C predicted and observed cases of DCS in n subjects.

Figure 5b. ‘Subsaturation’ exposures

“Subsaturation” exposures (350 minutes \leq duration < 22 hours), cumulative model 5C predicted and observed cases of DCS with depth.

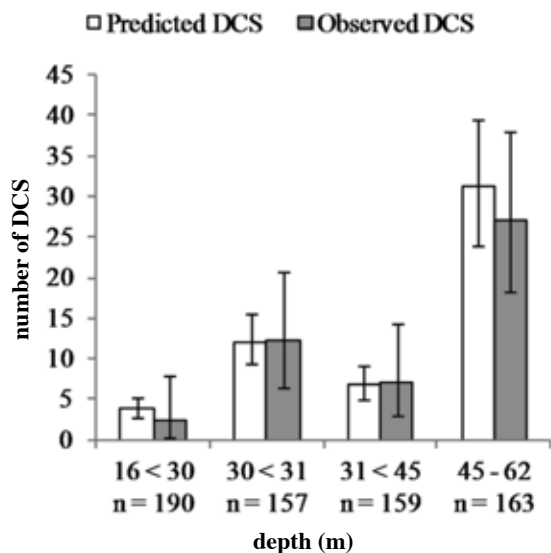
Figure 6a. Long-duration exposures


Long-duration exposures (60 minutes \leq duration < 350 minutes), model 5C predicted and observed cases of DCS in n subjects.

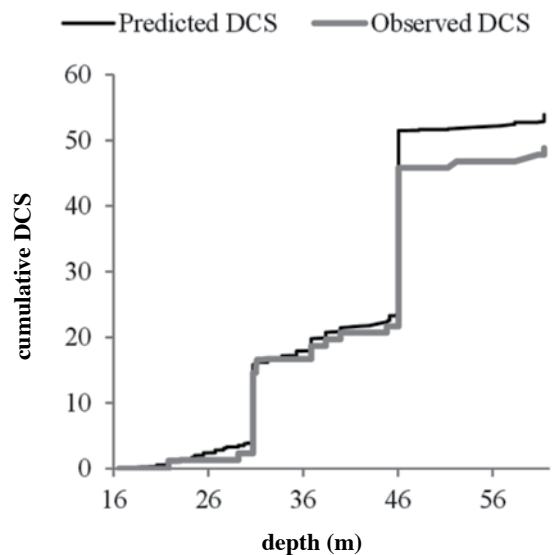
Figure 6b. Long-duration exposures


Long-duration exposures (60 minutes \leq duration < 350 minutes), cumulative model 5C predicted and observed cases of DCS with depth.

Figures 6, 7 and 8 indicate that the 5C model fits observed DCS in the long-, regular- and short-duration exposure data well, with a slight overall overestimation.

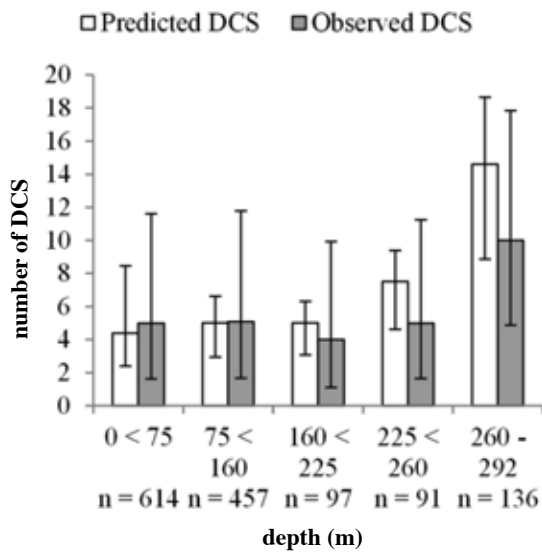
Figure 7a. Regular-duration subjects


Regular-duration exposures (15 minutes \leq duration < 60 minutes), model 5C predicted and observed cases of DCS in n subjects.

Figure 7b. Regular-duration subjects


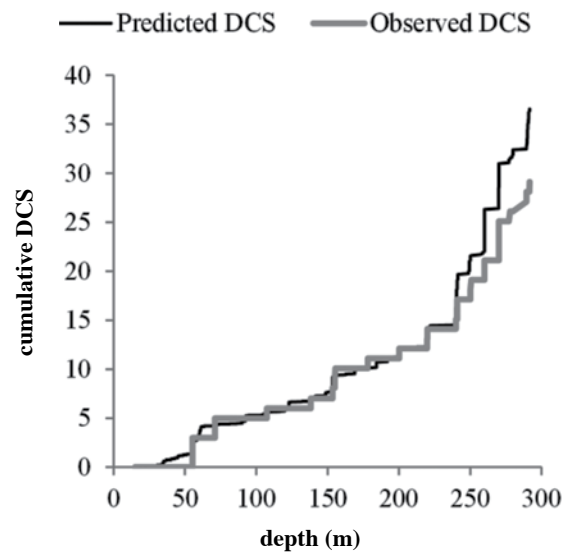
Regular-duration exposures (15 minutes \leq duration < 60 minutes), cumulative model 5C predicted and observed cases of DCS with depth.

Figure 8a. Short-duration exposures



Short-duration exposures (0 minutes < duration < 15 minutes), model 5C predicted and observed cases of DCS in *n* subjects.

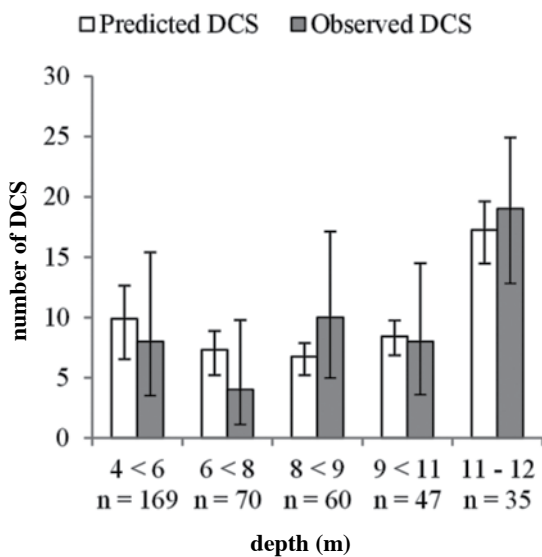
Figure 8b. Short-duration exposures



Short-duration exposures (0 minutes < duration < 15 minutes), cumulative model 5C predicted and observed cases of DCS with depth.

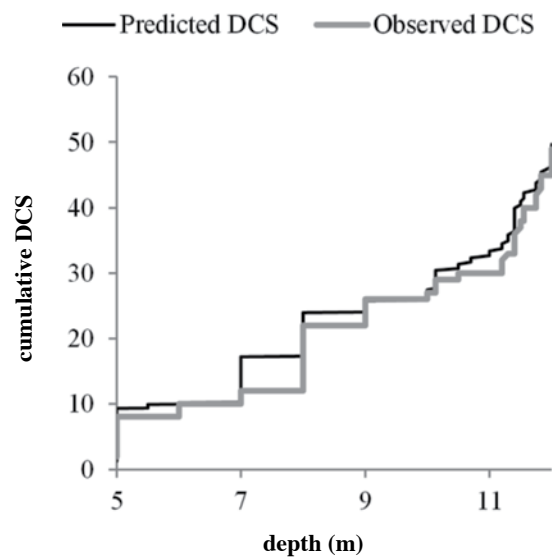
Figure 9 suggests the 5C model fits the observed DCS data well for the saturation exposures with escape, with only slight under/overestimation throughout the saturation depth range 5 to 12 meters.

Figure 9a. 'Saturation with escape' exposures

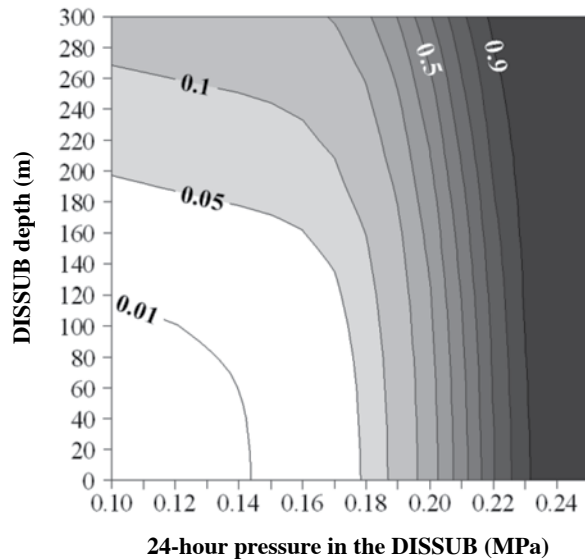


"Saturation with escape" exposures, model 5C predicted and observed cases of DCS in *n* subjects.

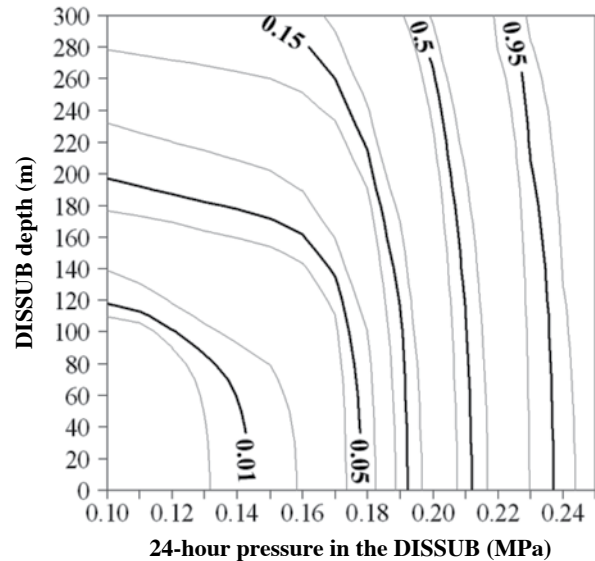
Figure 9b. Saturation with escape' exposures



"Saturation with escape" exposures, cumulative model 5C predicted and observed cases of DCS with depth.

Figure 10. Predicted iso-risk contours for 24-hour ‘saturation’

Predicted iso-risk contours for submarine tower escape following 24-hour “saturation” exposure at raised pressure in the DISSUB for an 80-kg individual. Unlabeled contours are at increments in predicted DCS probability of 0.1.

Figure 11. Confidence regions on predicted iso-risk contours

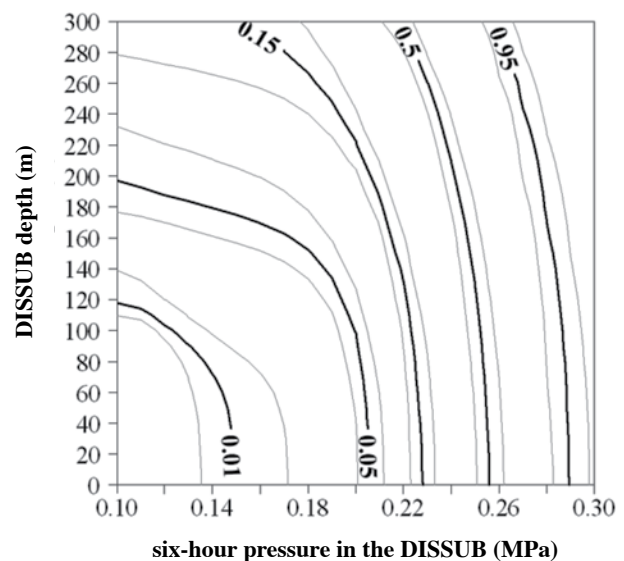
Predicted iso-risk contours for submarine tower escape following 24-hour “saturation” exposure at raised pressure in the DISSUB for an 80-kg individual. Gray contours show the extent of the bootstrap estimated 95% confidence limits.

Prediction of risk of DCS for submarine tower escape

Figure 10 shows contours of equal risk of DCS for submarine escape following exposure to raised pressure in the DISSUB for 24 hours as predicted using model 5C. For clarity, predicted 95% confidence regions are shown in Figure 11 for the same data with a reduced number of contours. Figures 12 and 13 show the predicted effect of reducing the exposure time prior to escape to six hours and to one hour respectively.

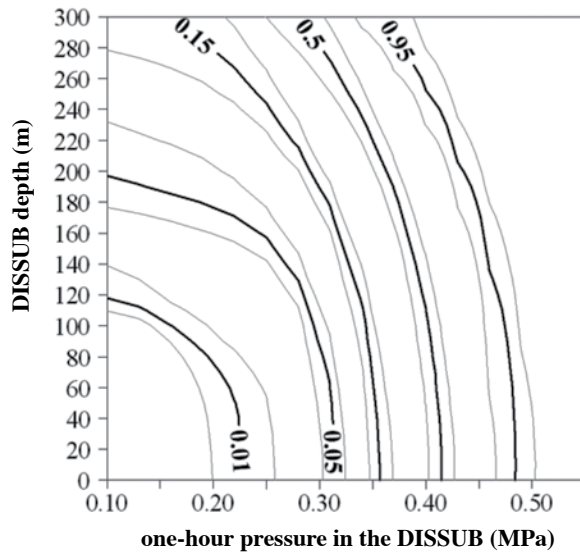
Figures 10 and 11 show risk of DCS is predicted to increase steeply with the pressure the crew is exposed to inside the DISSUB. Increasing escape depth is predicted to have less effect on DCS risk than saturation pressure for escapes at depths down to 300 meters. Figures 12 and 13 show that the effect of internal DISSUB pressure on predicted P_{dcs} is markedly reduced when escape is made within one hour of exposure. However, this benefit is mostly lost by six hours.

Figure 14 shows the model 5C predicted effect of body mass on risk of DCS for a 60-, 80- or 100-kg individual. Higher body mass is predicted to increase risk of DCS for saturation at raised internal DISSUB pressure but to have negligible effect on risk for changes in escape depth.

Figure 12. Predicted iso-risk contours for six-hour ‘subsaturating’

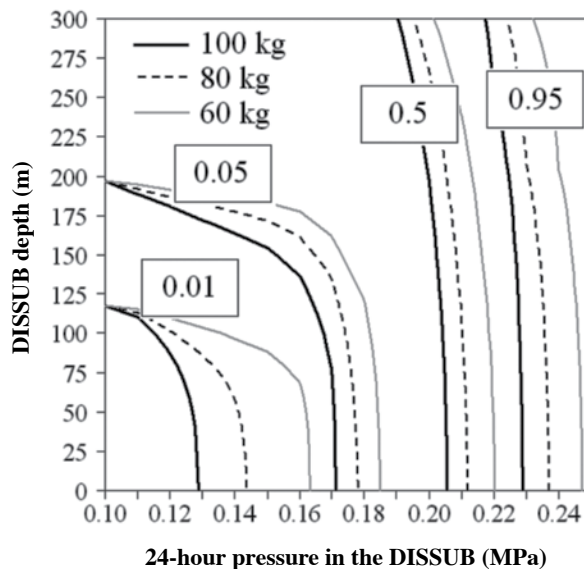
Predicted iso-risk contours for submarine tower escape following six-hour “subsaturating” exposure at raised pressure in the DISSUB for an 80-kg individual. Gray contours show the extent of the bootstrap estimated 95% confidence limits.

Figure 13. Predicted iso-risk contours for one-hour exposure



Predicted iso-risk contours for submarine tower escape following one-hour exposure at raised pressure in the DISSUB for an 80-kg individual. Gray contours show the extent of the bootstrap estimated 95% confidence limits.

Figure 14. Effect of body mass on predicted iso-risk contours



Predicted 1%, 5%, 50% and 95% DCS iso-risk contours for submarine tower escape following 24-hour "saturation" exposure at raised pressure in the DISSUB for a 60-, 80- or 100-kg individual.

DISCUSSION

Use of the bootstrap method for error estimation

As stated in the method, three sets of starting parameter values were used for optimization against each bootstrap dataset. Ideally, a larger number of sets of starting values would have been used, as in the search for the best fitting model, where 95 sets of values were used. The fact that only a small number of starting parameter sets were used here would not affect the predicted values of DCS probability made with the final model but would possibly broaden the bootstrap estimated confidence regions on those predictions.

It is also worth noting that it would have been theoretically possible to optimize all the models against each of the 1,000 bootstrap datasets to determine how often the 5C model was selected as the optimal model. Neither of these approaches would have been practically possible due to time constraints but may become possible for future studies with the availability of greater processing power.

Optimized parameters of the 5C model

During the optimization process, values of the Pxo_i parameter, which determines the crossover tissue tension for exponential or linear nitrogen washout, tended to be pushed toward infinity, indicating that the parameter was having no effect in the fit of the model to the data. The final values of Pxo_i were therefore set so large that there will be no linear washout. Thus the 5C model is an exponential-exponential (EE) model. The value of the threshold parameter Thr_i was set to zero for compartments 1 to 4 since a non-zero value in these compartments was not found to affect the fit of the model to the data.

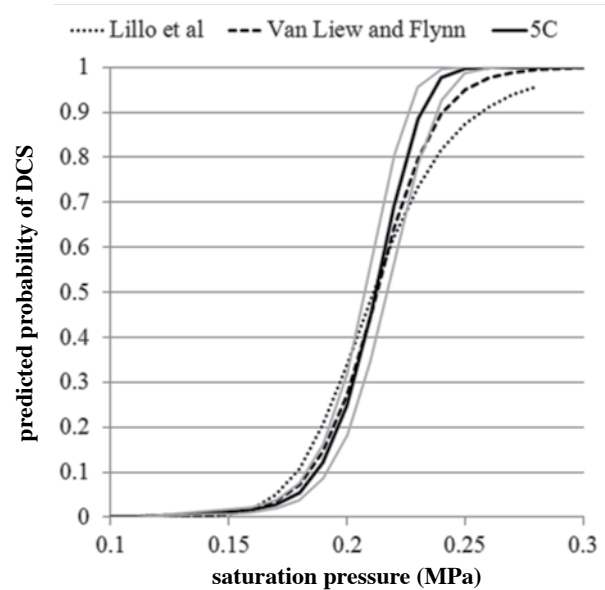
The values of the optimized parameters of the 5C model are shown in Table 4. The value of γ_i was set to zero for compartments 1, 2 and 3 since a non-zero value was not found to affect the fit of the model to the data. Since this parameter is responsible for the scaling of DCS risk with body mass and as compartments 1, 2 and 3 are the three fastest tissue compartments in terms of rate of uptake and elimination of nitrogen, this result suggests that only the slower tissue compartments are involved in the scaling of DCS risk with body mass for the types of pressure exposures in the data. However, it should be noted that in the optimization of a lumped-parameter model, interpretation of the physical meaning of a parameter is not necessarily useful. In this particular case, since the body

mass of most of the goats in the data was lower than that of the humans, then the values of γ_i may include an effect of any differences in interspecies susceptibility to DCS, which could act to increase, or diminish, the apparent effect of body mass. Thus, predictions of risk made by the model may be more likely to reflect outcomes in humans when the body mass is set to a value of around 80 kg and to reflect likely outcomes in goats when the body mass is set to a value of around 50 kg. Several other approaches would have been possible for the problem of interspecies scaling and scaling with body-mass, including allowing the time-constants τ_i to vary with species and/or body mass, or through the introduction of a separate factor for interspecies susceptibility to DCS. Also, it would have been possible to optimize the values used for body mass where there were missing data as part of the calibration process. However, these approaches may have increased model complexity without increased validity of parameter interpretation following optimization.

Comparison with other models

DCS risk on escape from a DISSUB has previously been estimated by Parker, *et al.* [15]. The model provided the best estimate of DCS risk for submarine tower escape given the data available for model calibration at that time. No high-risk data or saturation with escape data were available to the authors of the model at that time. However, conclusions drawn from predictions made with that model were essentially similar to those presented here, with increases in DISSUB internal pressure, rather than escape depth, being the greater concern in terms of likelihood of DCS. Due to the importance of accurate prediction of risk for the saturation part of the exposure, it is worth comparing different models for predicted risk of DCS following direct ascent from saturation. P_{dcs} predicted using model 5C for immediate ascent from 24-hour “saturation” is shown in Figure 15 for an 80-kg individual. Also shown are predictions made using the models described by Lillo, *et al.* [16] and Van Liew and Flynn [17]. The models give similar predicted risk for $P_{dcs} \leq 0.5$, although that might be expected since there is some overlap in the data that each of these models has been calibrated against.

Figure 15. Predicted p_{dcs} for ascent from ‘saturation’



Predicted P_{dcs} by three models for direct ascent from saturation. 95% bootstrap confidence limits for the 5C model are shown in gray.

Appropriate use of the iso-risk curves and 5C model

The iso-risk curves presented here are based on the pressure profile that would be experienced by a submariner using the UK Royal Navy escape system. Risk of DCS will be different for any escape pressure profiles that have altered rates of pressurization, time spent at maximum depth and/or ascent rates.

None of the calibration data contained exposures where there was significant planned (staged) decompression. Use of the 5C model for designing decompression procedures would be inappropriate and could result in the production of decompression tables that might result in injury to the user.

Physiological effects of exposure to raised pressure other than DCS, in particular oxygen toxicity and nitrogen narcosis, are not considered in the model, and prediction of risk for escapes deeper than 300 meters represents an extrapolation beyond the known animal data. Theoretical estimates of oxygen toxicity and nitrogen narcosis in submarine escape have been made by Connor and Ferrigno [18]. However, their estimates,

which predict low risk of oxygen toxicity or nitrogen narcosis effects for submarine escape, cover only a similar range of escape depths to the goat data used in the calibration of the 5C model. Therefore, the 5C model may underestimate DCS risk if used in extrapolation and certainly does not address these other risks, which may be fatal at some depth beyond 300 meters. The model does not account for the possibility of pulmonary barotrauma, which may also be fatal in submarine tower escape. Provided that the escaper breathes correctly during escape, the probability of pulmonary barotrauma is low and the rate of occurrence should be limited by proper training.

Provided these limitations are understood, the authors believe the escape iso-risk curves presented here represent the best current estimate of DCS risk for submarine tower escape.

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Conflict of interest

The authors have declared that no conflict of interest exists with this submission. ■

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Annex 13.

Mikael Gennser, Geoff Loveman, Fiona Seddon, Julian Thacker, S. Lesley Blogg.

Oxygen and Carbogen breathing following simulated submarine escape.

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Oxygen and carbogen breathing following simulated submarine escape

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ABSTRACT

Escape from a disabled submarine exposes escapers to a high risk of decompression sickness (DCS). The initial bubble load is thought to emanate from the fast tissues; it is this load that should be lowered to reduce risk of serious neurological DCS. The breathing of oxygen or carbogen (5% CO₂, 95% O₂) post-surfacing was investigated with regard to its ability to reduce the initial bubble load in comparison to air breathing. Thirty-two goats were subject to a dry simulated submarine escape profile to and from 240 meters (2.5 MPa). On surfacing, they breathed air (control), oxygen or carbogen for 30 minutes. Regular

Doppler audio bubble grading was carried out, using the Kisman Masurel (KM) scale. One suspected case of DCS was noted. No oxygen toxicity or arterial gas embolism occurred. No significant difference was found between the groups in terms of the median peak KM grade or the period before the KM grade dropped below III. Time to disappearance of bubbles was significantly different between groups; oxygen showed faster bubble resolution than carbogen and air. This reduction in time to bubble resolution may be beneficial in reducing decompression stress, but probably does not affect the risk of fast-tissue DCS.

INTRODUCTION

In case of a submarine accident where the submarine is trapped at the bottom of the sea, transfer of the crew to rescue submarines that dock with the disabled submarine is the safest option. However, the situation in the damaged vessel may deteriorate so fast that survivors will not have time to wait for rescue, but will have to perform submarine escape to rescue themselves. Escape from a disabled submarine resting on the sea floor at depth exposes submariners to a risk of decompression sickness (DCS). The rapid compression in an escape lock and the fast ascent through the water column to the surface is known to cause gas supersaturation, especially in the fast tissues (those with the shortest half-times). The initial bubble load that emanates following submarine escape is thought to be indicative of this supersaturation, which may give rise to early onset debilitating central nervous system (CNS) (Type II) decompression sickness [1] while limb “bends” usually manifest later [2]. Therefore, it is the initial bubble, or venous gas emboli

(VGE), load that workers are largely seeking to reduce in testing different submarine escape protocols and gas regimes.

In previous experiments, it was shown that breathing a hyperoxic gas during simulated submarine escape caused the number of Doppler-detectable circulating VGE to decrease more swiftly following both escape and escape following shallow air saturation. However, the initial maximum bubble load was not reduced [2]. Further experiments involving pre-breathing were carried out. In the first series, goats breathed 100% oxygen (O₂) at the surface (0.1 MPa) prior to simulated submarine escape from 240 meters (2.5 MPa), and it was found that the oxygen pre-breathe significantly reduced the time taken for VGE to disappear in comparison to air breathing and also slightly reduced the initial Kisman-Masurel (KM) [3] bubble grade [4]. In a second series, a 15-minute pre-escape breathing session of either oxygen or carbogen (2.5% CO₂, 97.5% O₂) at a raised ambient pressure (0.2 MPa) was carried out.

It was shown that again, pre-breathing oxygen further reduced the time taken for VGE to disappear, while slightly reducing the initial maximum Doppler KM grade [4]. Pre-breathing carbogen reduced the total period over which VGE were present in comparison to breathing air, though not to the same extent as oxygen. However carbogen breathing was the possible cause of two cases of acute oxygen toxicity [4].

In the present study, the effect of both oxygen and carbogen breathing was again examined, though in this case, after simulated submarine escape rather than preceding it. Although oxygen would appear to be beneficial when administered prior to escape, there are issues with the ready availability of gases for escape use following a disabled submarine incident, as supplies may be depleted. Post-escape supplies should prove less of a problem, but there may be a considerable time delay from the point at which the escaper surfaces to the time of rescue. Operationally, it has been suggested the escapers could carry a small oxygen rebreather device, from which they would start to breathe on reaching the surface after removing their escape suit hood while waiting for rescue. It is hoped that this immediate treatment with hyperoxic gas might aid in the washout of the inert gas from the fast tissues.

Although a carbogen pre-breathe proved to give less positive results than oxygen, and also appeared to promote acute oxygen toxicity, its effects when given post-surfacing at atmospheric pressure were still of interest. Originally, the effects of carbogen were investigated as carbon dioxide has a strong vasodilatory effect, especially on the cerebral vasculature, so it was hoped that it would aid the delivery of oxygen to the fast tissues and therefore increase nitrogen washout [5,6]. However, it appeared that during the pre-breathe at 0.2 MPa ambient pressure, carbogen might have functioned to increase cerebral oxygenation above the oxygen toxicity threshold [4]. In the present study, the risk of developing oxygen toxicity while post-breathing carbogen was far lower, as the maximum partial pressure of oxygen at the surface would be only 0.1 MPa. Therefore carbogen could potentially increase oxygen delivery without risk of other ill effects.

Consideration has been given to the provision of a simple oxygen rebreathing device that could be used by the escaper immediately on surfacing. However, use of a breathing device always adds a dead-space, which will increase the inspired carbon dioxide concentration. Therefore, another aim of the present study was to determine that there were no adverse effects of

breathing a gas with a raised content of carbon dioxide directly after surfacing from a submarine escape.

It was hypothesized that by administering oxygen or carbogen immediately on surfacing – and so in theory washing out nitrogen from the fast tissues at the start of VGE evolution – the initial VGE load would be reduced and so protect against CNS DCS.

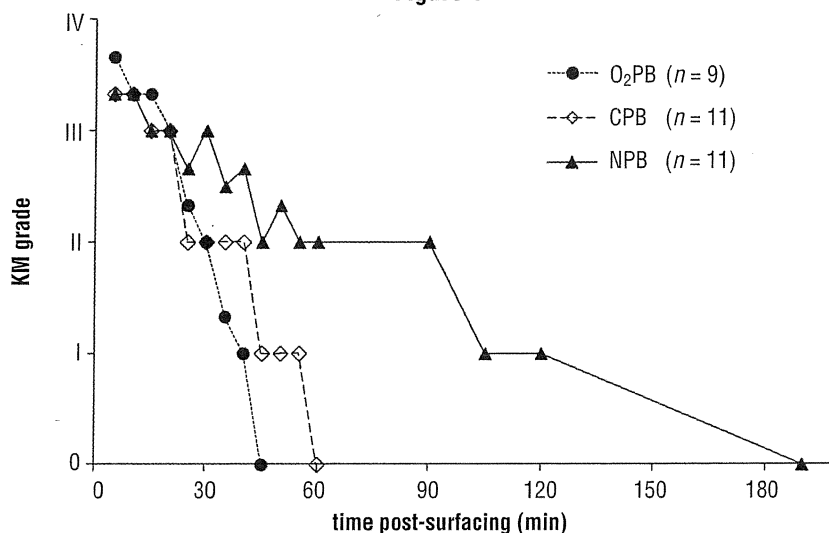
MATERIALS AND METHODS

Thirty-two healthy adult female or neutered male goats in the weight range 35.0-67.0 kg were used. All animals were kept and used in accordance with the UK Home Office Animals (Scientific Procedures) Act (1986) guidelines. Simulated submarine escape profiles from 2.5 MPa were carried out using the Submarine Escape Simulator (SES), a computer-controlled hyperbaric facility at the Defence Evaluation Research Agency (QinetiQ) Alverstoke, United Kingdom. The animals were introduced to the escape chamber in pairs and put into separate restraints. Compression to 2.5 MPa was made over 24 seconds with a four-second hold at pressure, then decompression made to surface at a rate of 2.75 meters/second (0.0275 MPa/second) (for a full description of the SES and escape protocols see [2]).

Directly following escape, the goats either remained in the chamber to breathe oxygen ($n = 10$) (O₂PB) delivered by an adapted face mask connected to the hood inflation system (HIS), or were removed from the chamber, placed in restraints and breathed carbogen (5% CO₂, 95% O₂) ($n = 11$) (CPB) gas from masks connected to the built-in breathing system (BIBS). Regardless of the method of breathing gas delivery, the time taken for O₂PB and CPB groups of animals to switch from air to their respected gases varied from one to four minutes; each goat breathed its test gas for 30 minutes. A Servomex 1440, with paramagnetic oxygen and infrared carbon dioxide sensors (Servomex Ltd, Crowborough, UK), or a mass spectrometer (Airspec QP9000; Airspec Ltd, Kent, UK) was used to monitor the content of the respective gases. Eleven control animals breathed air only (NPB). Regular precordial Doppler monitoring was started at five minutes post-surfacing and continued at five-minute intervals for the first 30 minutes, then at 15-minute intervals until two hours and 60 minutes thereafter until the bubbles disappeared (for technical reasons, the three-hour measurements were carried out at three hours, 10 minutes). Bubbles were rated on the KM scale [3] using the same equipment and operators throughout for uniformity of results.

Table 1 - Results

post-breathe regime	(n)	mass (kg) NS	max median grade (KM grade) NS	time to KM <III (min) NS	time to median grade 0 (min) ***
oxygen (O ₂ PB)	9	46.0 + 5.6	3.66 (IV-)	25	45
carbogen (CPB)	11	46.6 + 5.3	3.33 (III+)	25	60
air (NPB)	11	51.0 + 10.9	3.33 (III+)	25	190
O ₂ PB - Oxygen post-breathe NPB - No post-breathe			CPB - Carbogen post-breathe NS - Not significant		

Figure 1

Doppler-detectable circulating venous bubbles after simulated submarine escape to and from 2.5 MPa, graded using the Kisman Masurel (KM) system. All points denote median bubble grades for the three treatments: oxygen post-breathe (O₂PB), carbogen post-breathe (CPB) and control (no post-breathe; NPB).

Statistics

The Kruskal-Wallis test for ordinal data was used to compare the three groups for peak KM grades, the time over which grades remained greater or equal to KM III and for the time taken for bubbles to disappear (reach KM 0). The Mann-Whitney U test was used as a post-hoc test if necessary, with the level of significance divided by the number of comparisons ($n=3$) to compensate for any repeated testing (p significant if < 0.017).

RESULTS

Following escape from 2.5 MPa and removal from the chamber, one suspected case of DCS, a limb bend, was noted in one animal. It was excluded from further measurements, as it received recompression treatment, leaving nine subjects rather than 10 in the oxygen

group. No cases of arterial gas embolism (AGE) or oxygen toxicity were observed.

The median peak (maximum) KM grades for those animals that had post-breathed air (NPB) or carbogen (CPB) was very slightly lower than that of the oxygen post-breathe group (O₂PB) (Table 1 and Figure 1), but there was no statistically significant difference. The median peak grade occurred at the time of the first measurement for all groups (five minutes post-surfacing). The time point at which the grades dropped below KM III was the same in all three groups (Table 1; NS). The time to the detection of a median grade of zero bubbles was significantly different ($p = 0.0003$), with the bubbles in the NPB group remaining over a longer period than the O₂PB and CPB groups (Table 1). There was no significant difference in the length of the period over which VGE persisted between the O₂PB and CPB groups.

DISCUSSION

Breathing oxygen or carbogen for a 30-minute period post-escape did not give any significant benefit in terms of reducing initial KM grades in comparison to air breathing. It is this period, immediately post-surfacing, when CNS DCS (Type II) is most likely to occur. In contrast to previous studies, where subjects breathed a hyperoxic gas (60%/40% O₂/N₂) during the escape [2], or had a period of oxygen pre-breathe prior to the escape [4], there was no significant difference in the peak bubble grades or time with high bubble grades (KM ≥ III) between any normobaric intervention and air controls. However, the time for the O₂PB group to reach a median KM grade of zero was comparable to that following the other interventions as above (38-45 minutes) [2,4].

The rationale behind delivering normobaric oxygen or carbogen immediately post-dive was to increase the rate of elimination of inert gas. Breathing 100% oxygen at normobaric pressure (0.1 MPa) decreases the partial pressure of inert gases in the arterial blood and subsequently the tissues, therefore creating a higher diffusion gradient from bubble to tissue. In a preliminary study by Flook, *et al.* [7], it was shown that a 15-minute period of oxygen breathing directly after a submarine escape from 240 meters reduced the nitrogen content in the jugular venous blood by 50%-75% below the levels observed when breathing normobaric air. It was also noted that the nitrogen level in the blood 40 minutes after cessation of the oxygen breathing was still significantly lower than in the air-breathing animals.

The results of the present study compare relatively well with the few studies available for comparison. A study investigating post-dive oxygen breathing in pigs decompressed from a 40-meter (0.5 MPa) 40-minute air dive [8] also showed that oxygen breathing (administered from the time that bubble scores were assessed to be maximal, not immediately post-surfacing) did not increase the rate of bubble reduction in comparison to air during the first 15 minutes after administration. After approximately 17 minutes, the bubble load was significantly lower in the oxygen group in comparison to the air controls. Given the fact that the O₂PB group in the present study started from a slightly higher bubble grade than the NPB group and also taking into account the limitations of comparing ordinal data (this study) with continuous data [8], the results of the two studies are surprisingly similar. This

is despite the fact that the dive profiles were dissimilar and that maximum bubble grades in the pig study appeared much later (at around 45 minutes post-dive) than the almost immediate appearance of maximal grade bubbles following simulated submarine escape.

In a human air dive study [9], using a similar profile to that of the pig study described above, it was shown that 30 minutes of normobaric oxygen was sufficient to significantly reduce bubble scores from air controls. Recent observations [10] where normobaric oxygen was given to divers with protracted high KM bubble grades (> III) show that in two subjects (from a total of five), 30 minutes was sufficient to start to reduce the bubble grade, while in the other three, at least 60 minutes of oxygen breathing was necessary to achieve the same. Given the small sample size, differing dive profiles and breathing gases (nitrox and trimix) used in these five examples [10], the results agree reasonably with the studies discussed above [8,9]. Normobaric oxygen has been shown to be a useful first aid treatment for decompression illness (DCI) [11], increasing recompression efficacy and decreasing the number of necessary recompression treatments, if given within four hours after surfacing. It has also been shown that normobaric oxygen given to goats with severe DCS after accelerated decompression from air saturation, improved survival rates [12].

The results from the present study show that in terms of reduction of the initial VGE load, the oxygen-enriched gases given one to four minutes post-surfacing did not have any effect. Comparison with the air group and also previous post-escape trials [2,4] show that the maximum VGE load appears within five minutes after the decompression. Even if the oxygen breathing is started immediately after the escape, the time taken to increase gas washout and reduce the bubble growth is longer than the time to maximum bubbling [7,8].

In a submarine escape scenario it is unlikely that prophylactic gases could be administered to an escaper on the surface any more rapidly than in the present experimental scenario, even if the submariner carries an oxygen-breathing device in his escape suit. If the oxygen breathing could be started before the end of the ascent, it is still unlikely that it would have an effect, as the rapid gas expansion in the lungs in the last 30 meters before reaching the surface causes an outward gas flow during inhalation [13]. Thus, the oxygen would not reach the alveolar membrane before the end of the decompression unless oxygen breathing had been started at a much greater depth.

Although it is unlikely that surface administration of oxygen will reduce the incidence of CNS DCS, the reduction of overall time with VGE does indicate a reduced overall decompression stress, which will likely be of benefit. However, it should be noted that in experiments where bubbles persisted for longer periods (up to an hour), rapid resolution of bubbles via hyperbaric oxygen breathing did not prevent endothelial damage [14].

With regard to the rationale of the administration of carbogen, as oxygen is a vasoconstrictor, breathing a gas containing both oxygen and carbon dioxide should aid oxygen delivery to all tissues. Additionally, it has been shown that hypercapnia improves (particularly peripheral) tissue oxygenation [15]. As there was no significant difference between oxygen and carbogen VGE reduction in the present study, both in terms of maximum grades and time profile, the additional carbon dioxide does not seem to have an effect on total gas wash-out, but neither does it have an adverse effect. There were no problems with oxygen toxicity in the present study. The maximum PO₂ of the post-breathe gases was

only 0.1MPa; given over 30 minutes, this dose is too small to cause any problems with respect to toxicity.

On consideration of the present results, and those from our previous studies examining the use of oxygen as a prophylactic against DCS following submarine escape, it appears that most benefit is gained from a period of pre-breathing oxygen just prior to escape, though of course the decision to use hyperoxic gas must be tempered against the individual situation. This approach might not be advised in a scenario where the survivors have been exposed to a raised PPO₂ and oxygen toxicity is a risk. Oxygen- or carbogen breathing post-escape is still of benefit in terms of reducing the overall bubble load. Given that it is generally accepted that the risk of DCS is close to zero when no bubbles are present [16,17] reducing the time spent with bubbles in the circulation is likely of benefit.

Conflict of interest

The authors have declared that no conflict of interest exists with this submission.



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Annex 14.

Seddon F, Thacker J, Jurd K, Loveman G.

Effects of Valsalva manoeuvres and the 'CO₂-off' effect on cerebral blood flow.

Diving and Hyperbaric Medicine. 2014 December; 44(4):187-92

Original articles

Effects of Valsalva manoeuvres and the 'CO₂-off' effect on cerebral blood flow

Fiona Seddon, Julian Thacker, Karen Jurd and Geoffrey Loveman

Abstract

(Seddon F, Thacker J, Jurd K, Loveman G. Effects of Valsalva manoeuvres and the 'CO₂-off' effect on cerebral blood flow. *Diving and Hyperbaric Medicine*. 2014 December;44(4):187-192.)

Introduction: Previous research has shown that a rapid drop in inhaled carbon dioxide (CO₂) partial pressure reduces cerebral blood flow and may induce faintness – the 'CO₂-off' effect. The aims of this study were to investigate the effects of performing Valsalva manoeuvres while experiencing the 'CO₂-off' effect and whether symptoms occur that are sufficient to jeopardise submarine tower escape.

Methods: Twenty male volunteers, mean (SD) age 34.7 (8.5) years each completed three tests. The first test was to perform Valsalva manoeuvres breathing air. The second and third tests involved breathing a high CO₂ mix (5% CO₂/16% O₂/79% N₂) for 1 h prior to switching to breathe O₂ and performing Valsalva manoeuvres, or switching to breathe air for 1 min then O₂ and performing Valsalva manoeuvres. Blood pressure, cerebral blood flow velocity, electrocardiogram, and respiration were monitored throughout. A subjective questionnaire was administered at intervals to monitor symptom type and severity.

Results: Valsalva manoeuvres breathing air resulted in a 31% reduction in cerebral blood flow. Breathing high CO₂ caused a sustained increase in cerebral blood flow and symptoms of breathlessness and headache. Following the gas switch from high CO₂, some subjects reported faintness, headache and nausea. Cerebral blood flow dropped by 34% when switching from breathing high CO₂ to O₂, by 35% when switching to air then by a further 3% when switching from air to O₂. In both circumstances there was a further drop of 14% after performing the Valsalva manoeuvres. The drop in cerebral blood flow in subjects that reported faintness was greater than that in the subjects who did not, but this difference was not significant.

Conclusion: Transient faintness or headache may occur in the escape tower during pressurisation, but this should be short-lived and not incapacitating.

Key words

Hypercapnia, Valsalva, cerebral blood flow, Doppler, physiology, submarine

Introduction

Royal Navy submarines are fitted with tower escape systems allowing survivors to escape from a distressed submarine (DISSUB). There may be a long wait in the submarine prior to starting tower escape during which the partial pressure of carbon dioxide (PCO₂) may rise despite use of a CO₂ absorbent. Submariners may switch from breathing a hypercapnic and hypoxic atmosphere in the DISSUB to a normocapnic and normoxic atmosphere in the escape tower. The submariner is subject to rapid pressurisation in the escape tower to equalise with the surrounding sea pressure, and then decompression as he ascends to the surface. During the pressurisation the escaper will also be exposed to a hyperoxic atmosphere, with the inspired partial pressure of oxygen (P_iO₂) reaching as high as 398 kPa at the maximum permitted escape depth (180 m).

Fainting usually occurs when a person is in the upright position and can be provoked by anything that reduces cerebral perfusion.¹ CO₂ is a cerebral vasodilator whilst O₂ is a cerebral vasoconstrictor. Thus the switch from breathing a hypercapnic gas in the DISSUB to a hyperoxic gas whilst stood in the escape tower may lead to transient cerebral vasoconstriction resulting in cerebral hypoperfusion, which

could in turn result in fainting. Fainting in the escape tower could endanger the escaper and hinder escape for the rest of the crew by blocking the tower with the escaper's body.

A previous study examined the physiological effects of the rapid replacement of a hypercapnic breathing gas with 100% O₂ – the 'CO₂-off' effect.² Subjects breathed a mixture of 5% CO₂/16% O₂/79% N₂ (high CO₂) for one hour and then switched to breathing O₂ for 15 min. Mild or moderate faintness was the most frequently reported symptom following the gas switch. Transcranial Doppler (TCD) was used to measure middle cerebral artery blood flow velocity (MCAv). There was a significantly greater percentage drop in mean MCAv in subjects who had symptoms of faintness that developed after the switch to O₂ when compared with those who did not.

Submariners are trained to minimise ear discomfort by equalising pressure across the tympanic membrane using Valsalva manoeuvres (Valsalvas). Valsalvas are known to cause a drop in MCAv when in the upright position.³ This is a mechanical effect of the raised intra-thoracic and intra-abdominal pressure causing reduced venous return and cardiac output. Therefore, we hypothesized that performing Valsalvas following a switch from breathing high CO₂

might exacerbate the drop in MCAv caused by the switch in breathing gas previously observed and possibly worsen any symptoms such as faintness or nausea.

Methods

The study was approved by the QinetiQ Ethics Committee (ethical protocol SP792 v 2.0), and carried out at the QinetiQ Hyperbaric Medical Unit, St. Richard's Hospital, Chichester, UK. Volunteers gave their written informed consent and the study was conducted in accordance with the principles of the Declaration of Helsinki (revised 2008).

STUDY DESIGN

It was hypothesised that Valsalvas would further increase the observed drop in mean MCAv caused by a gas switch from high CO₂. A power test (power = 0.8 and alpha = 0.05) using R statistical software (version 2.10.1) determined that 16 subjects would be required to detect a significant increase in the mean percentage drop in mean MCAv of a further 10% over that caused by the switch to 100% O₂ alone. To allow for possible subject withdrawal, or increase in the observed standard deviation in mean MCAv, 20 subjects were recruited.

SUBJECTS

Twenty male volunteers participated in the study, with mean (SD) age of 34.7 (8.5) years; height 179.8 (4.9) cm; body mass 84.4 (14.5) kg. Subjects were requested to refrain from alcohol the day before each test. They were requested to have a light breakfast and their normal caffeinated drink on the morning of each test. The subjects performed each of three test conditions on separate visits with a period of at least 24 hours between each.

PROCEDURES

All tests were carried out at normobaric ambient pressure. British Oxygen Company supplied cylinders of medical quality 5% CO₂/16% O₂ balance N₂, hereafter termed 'high CO₂' (note that in the previous study this was termed 5CO₂/16O₂). Medical O₂ and air were obtained from the hospital supply. Breathing gases were contained in Douglas bags and breathed via plastic tubing and a silicon mouthpiece. A four-way gas switching block (Hans Rudolph Inc.) was used to control the gas delivered.

The three tests were conducted as shown in Table 1. Test 1 was conducted first for all subjects, allowing familiarisation with equipment and procedures. The order of Tests 2 and 3 was randomised.

VALSALVA MANOEUVRES

A calibrated pressure transducer (General Electric, Druck, 800–1200 mbar range) was connected to the mouthpiece

Table 1

Procedures for Tests 1, 2 and 3 (see text for more details)

Time (min)	Test 1	Test 2	Test 3
0	Start air (standing)	Start high CO ₂ (seated)	Start high CO ₂ (seated)
5	6 x Valsalva		
10	End		
50		Stand up	Stand up
60		Switch to O ₂	Switch to air
61		6 Valsalva	Switch to O ₂
62		Switch to air	6 Valsalva
63		Sit	Switch to air and sit
68		End	End

assembly to ensure Valsalvas were performed consistently. Subjects wore a nose-clip throughout. Valsalvas were performed by the subject occluding the mouthpiece exhale valve with the right hand while attempting to breathe out to achieve a mouthpiece pressure of 40 mmHg (5.3 kPa) above ambient for 2 s. A traffic light system displayed when sufficient effort had been achieved. Six Valsalvas were performed in 30 s by each subject.

INSTRUMENTATION

A flow meter (KL Engineering Spirometric module S430A) placed in the inhale tubing allowed measurement of respiratory rate and minute volume. Subjects were instrumented for the duration of the test allowing measurement of:

- brachial blood pressure (BP mmHg) (General Electric, DINAMAP® Pro 1000) from the right arm;
- O₂ saturation (General Electric, DINAMAP® Pro 1000) from a finger on the left hand;
- blood velocity in the middle cerebral artery (measured continuously) using Transcranial Doppler transducer (Comtec TCD II) held in position at either left or right temporal region with a Rimed probe holder LMY2;
- electrocardiogram (ECG) using two independent ECG monitors (LifePulse10 HME Ltd and General Electric DINAMAP® Pro 1000) showing leads I and II;
- inspired and expired O₂ and CO₂ concentrations via a capillary tube from the centre of the mouthpiece to a Servomex 1440 fast-response gas analyser.

DATA RECORDING

Heart rate, BP, respiration rate, respiratory minute volume, and mean MCAv were recorded each minute for 5 min then every 5 min until 60 min then at 1 or 2 min intervals to the end.

A subjective symptoms questionnaire was administered each minute for the first 5 min of high-CO₂ breathing, then after a further 5 min and then at 10 min intervals until the switch, when it was administered more frequently. The subject

Table 2
Mean \pm 95% CI absolute and % change in physiological parameters during Test 2

Test 2	Air baseline	1 min CO ₂	5 min CO ₂	30 min CO ₂	Final min CO ₂	1 min O ₂	Valsalva	1 min air	Final min air
Resp rate (breath·min ⁻¹)	11 \pm 1.8	12 \pm 1.8	13 \pm 2.2	16 \pm 1.9	17 \pm 1.8	15 \pm 1.8	10 \pm 1.9	14 \pm 2.2	13 \pm 1.9
% change		9	18	45	55	36	-9	27	18
Resp minute vol (L·min ⁻¹)	6 \pm 1.0	11 \pm 1.9	17 \pm 2.5	25 \pm 2.4	28 \pm 3.3	20 \pm 2.9	NA	10 \pm 1.9	6 \pm 1.0
% change		83	183	317	367	233	NA	67	0
Mean BP (mmHg)	91 \pm 1.9	96 \pm 3.1	95 \pm 3.1	96 \pm 3.3	105 \pm 3.7	103 \pm 3.3	NA	101 \pm 3.7	96 \pm 3.3
% change		5	4	5	15	13	NA	11	5
Heart rate (beat·min ⁻¹)	61 \pm 3.7	64 \pm 3.1	62 \pm 3.5	63 \pm 3.5	73 \pm 4.3	72 \pm 4.9	79 \pm 6.5	74 \pm 5.3	57 \pm 4.7
% change		5	2	3	20	18	30	21	-7
MCAv (cm·s ⁻¹)	65 \pm 4.9	75 \pm 6.9	79 \pm 7.6	75 \pm 7.3	76 \pm 8.4	50 \pm 6.5	40 \pm 4.7	46 \pm 5.9	63 \pm 6.1
% change		15	22	16	17	-23	-39	-29	-3
ETCO ₂ (kPa)	5.3 \pm 0.2	6.0 \pm 0.2	6.4 \pm 0.2	6.3 \pm 0.2	6.3 \pm 0.2	4.3 \pm 0.8	NA	4.4 \pm 0.4	5.0 \pm 0.2
% change		13	21	19	19	-18	NA	-17	-6

Table 3
Mean \pm 95% CI absolute and % change in physiological parameters during Test 3

Test 3	Air baseline	1 min CO ₂	5 min CO ₂	30 min CO ₂	Final min CO ₂	1 min air	1 min O ₂	Valsalva	Final min air
Resp rate (breath·min ⁻¹)	11 \pm 1.4	12 \pm 1.4	13 \pm 1.6	16 \pm 1.4	16 \pm 1.4	16 \pm 1.4	15 \pm 1.4	12 \pm 2.4	13 \pm 1.8
% change		9	18	45	45	45	36	9	18
Resp minute vol (L·min ⁻¹)	6.5 \pm 1.2	11 \pm 2.0	18 \pm 2.0	24 \pm 2.0	28 \pm 2.9	22 \pm 3.1	13 \pm 2.0	NA	6.5 \pm 1.2
% change		69	177	269	331	238	100	NA	0
Mean BP (mmHg)	92 \pm 2.5	95 \pm 2.9	96 \pm 3.3	96 \pm 3.1	106 \pm 3.3	104 \pm 2.9	101 \pm 3.3	NA	97 \pm 2.2
% change		3	4	4	15	13	10	NA	5
Heart rate (beat·min ⁻¹)	64 \pm 5.3	70 \pm 4.7	65 \pm 4.5	66 \pm 4.7	74 \pm 4.7	76 \pm 5.1	80 \pm 5.3	81 \pm 6.3	58 \pm 3.7
% change		9	2	3	16	19	25	27	-9
MCAv (cm·s ⁻¹)	65 \pm 8.0	76 \pm 7.6	81 \pm 9.6	74 \pm 9.4	79 \pm 10.2	51 \pm 6.9	49 \pm 6.3	37 \pm 5.3	58 \pm 6.8
% change		16	23	14	20	-22	-26	-43	-11
ETCO ₂ (kPa)	5.2 \pm 0.2	6.0 \pm 0.2	6.5 \pm 0.2	6.4 \pm 0.2	6.4 \pm 0.2	4.3 \pm 0.6	4.4 \pm 0.4	NA	5.0 \pm 0.2
% change		16	25	23	23	-16	-15	NA	-4

was required to rate his level of discomfort as: none, mild, moderate, severe or intolerable in each of the categories: nausea, breathlessness, faintness and headache.

TEST TERMINATION CRITERIA

The test would be terminated:

- at the subject's request; on a subjective questionnaire response of 'intolerable' to any aspect;
- on failure of any equipment used to monitor withdrawal variables;
- on recording end-tidal CO₂ (ETCO₂) > 8.5 kPa for more than five consecutive breaths;
- if the subject began to vomit;
- if the subject fainted or requested assistance feeling faint;
- on subjective signs of impending panic;
- if BP was greater than either a systolic of 180 or a diastolic of 110 mmHg, sustained for over 1 min.

STATISTICAL ANALYSIS

The relative percentage change from baseline values in six physiological parameters (respiratory rate, heart rate, BP, MCAv, ETCO₂ and respiratory minute volume) was calculated at different time points. The relative percentage change in mean MCAv was calculated from the value immediately preceding and those following the switch from high CO₂ for Test 2 and Test 3. Data were compared using either paired or unpaired, unequal variance Student's *t*-tests. Differences were considered significant if *P* < 0.05.

Results

SYMPTOMS

All subjects completed each of the three tests successfully; there were no withdrawals and no subject fainted or vomited or was otherwise incapacitated at any stage. Four subjects did not report any symptoms throughout the tests. Fifteen of the 20 subjects reported symptoms during high-CO₂ breathing, compared with seven reporting mild or moderate symptoms of faintness, with headache or nausea after the gas switch and performing Valsalvas.

PHYSIOLOGICAL PARAMETERS

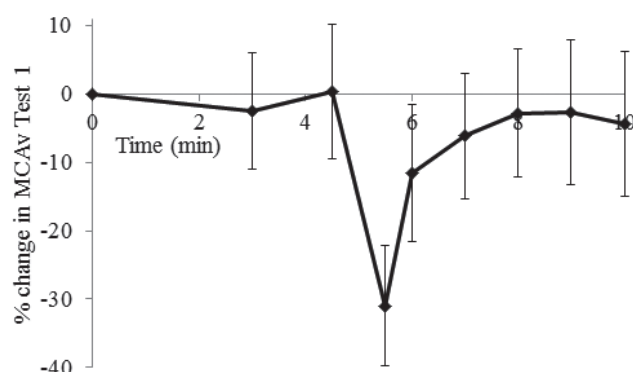
Tables 2 and 3 show absolute and percentage change in the mean physiological parameter values at defined points through Tests 2 and 3 respectively. No data for BP, respiratory minute volume and ETCO₂ are reported for the time at which the Valsalvas were performed, as the subjects were occluding the exhale valve, making these measurements inaccurate.

MCAv

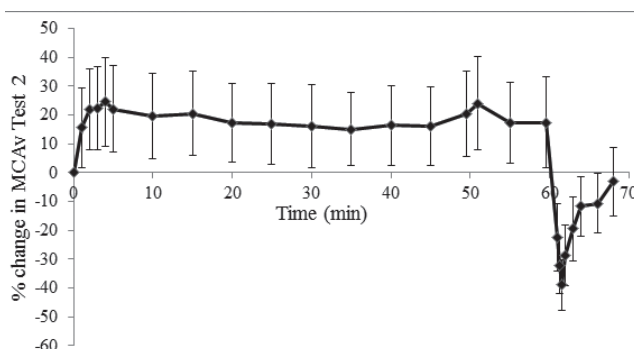
Figures 1, 2 and 3 show the change in mean MCAv during Tests 1, 2 and 3 given as a percentage change from the baseline measurement. During Test 1 mean MCAv dropped by 31% after performing the Valsalvas, and then recovered towards baseline values. The changes in mean MCAv were very similar for both Test 2 and Test 3: MCAv increased to reach a peak of about 23% above baseline at 5 min of

Figure 1

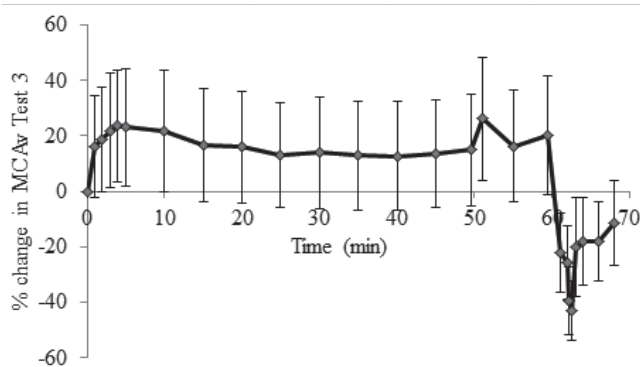
% change in mean MCAv (95% CI shown) from baseline during Test 1

**Figure 2**

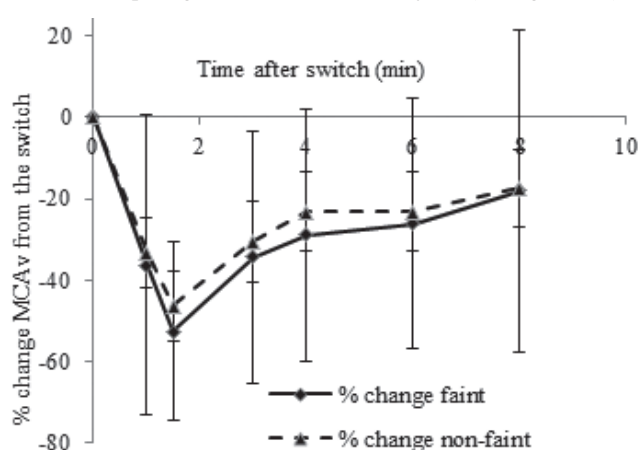
% change in mean MCAv (95% CI shown) from baseline during Test 2

**Figure 3**

% change in mean MCAv (95% CI shown) from baseline during Test 3

**Figure 4**

% change in mean MCAv (95% CI shown) post switch to O₂; Test 2 comparing faint and non-faint subjects (not significant)



breathing high CO₂. There was then a decline; the mean MCAv was around 16% above baseline from 15 min until the subjects stood up when it increased to around 25%. The switch from high CO₂ in both tests caused a drop to around 23% less than the baseline and there were further decreases in mean MCAv with Valsalvas before a recovery towards baseline.

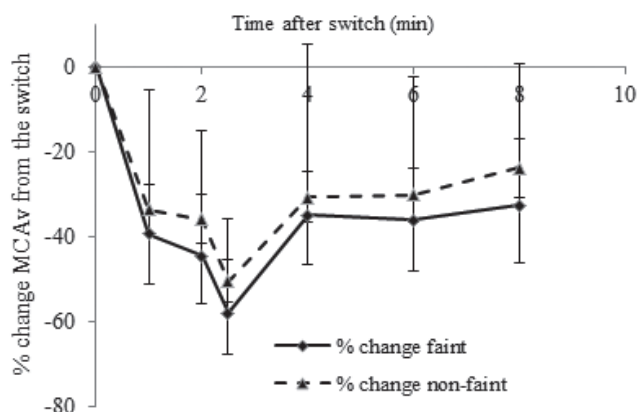
The percentage change in mean MCAv taken from the value immediately preceding the switch was calculated for Tests 2 and 3. During Test 2 the mean MCAv dropped by 34% when switching from high CO₂ to O₂, by a further 14% after performing the Valsalvas and then recovered towards baseline over the final 5 min. During Test 3 the mean MCAv dropped by 35% when switching from high CO₂ to air, by a further 3% when switching to O₂ and then by 14.5% when performing the Valsalvas. Recovery towards baseline values then continued over the final 5 min.

MEAN MCAv WITH OR WITHOUT FAINTNESS

Figures 4 and 5 show the percentage change in MCAv taken from the value immediately preceding the switch from high CO₂ for Test 2 and Test 3. Subjects are grouped as those

Figure 5

% change in mean MCAv (95% CI shown) post switch to air; Test 3 comparing faint and non-faint subjects (not significant)



who did or did not report feeling faint after the switch and/or Valsalvas. The drop in MCAv for the subjects reporting faintness or increased faintness following the switch was

generally greater than the drop in MCAv for those who did not. However, this difference was not statistically significant.

Discussion

CHANGES WHILE BREATHING HIGH CO₂

The most frequently reported symptom while breathing high CO₂ was breathlessness, followed by headache and faintness, which is in agreement with our previous study.² The symptoms of breathlessness and headache were evenly reported between Tests 2 and 3 regardless of which was performed first, whereas symptoms of faintness were more likely to be reported on the first test with high CO₂ rather than on the second; possibly a learning effect, as subjects knew what to expect and therefore did not report as faint. Cerebral blood flow has been shown to increase when breathing 5% CO₂.^{2,4} In the present study, mean MCAv increased by 23% after 5 min of breathing 5% CO₂.

CHANGES AFTER SWITCHING FROM HIGH CO₂

Transient mild or moderate symptoms of faintness, headache or nausea occurring after the switch to either air or O₂ were reported by seven subjects. Faintness or increased faintness was the most commonly reported symptom, being reported by 7/20 subjects (35%, 95% CI 15–59%). This is a higher incidence than in our previous study where 7/34 (20%, 95% CI 8–38%) subjects reported mild to moderate faintness after the switch to O₂. Therefore, proportionately more subjects felt faint after the switch and Valsalva than just from the switch alone, but this was not statistically significant.

Three subjects reported mild headache starting after the switch to O₂ on Test 2; however, this was also around the same time as they were performing Valsalvas. Activity-related headaches are well documented and are reported by sufferers during or shortly after a physical activity which typically incorporates a Valsalva, such as coughing, sneezing or straining while lifting heavy loads.^{5,6} These 'cough headaches' are generally short-lived, lasting between 1 s and 30 min, without other associated symptoms.⁵ It would be unlikely that this would in any way prevent safe escape from a submarine. Any headaches reported by subjects in our trial were resolved by the end of the tests.

Pre-fainting symptoms include headache and nausea and these additional symptoms were reported by subjects who also reported feeling faint. Fainting or feeling faint is associated with a decrease in MCAv and this is most commonly provoked in the standing position.¹ Hyperoxia and hypocapnia both reduce MCAv and the decrease seen in our study could have been caused by cerebral vasoconstriction due to hyperoxia from switching to 100% O₂ (Test 2) and/or the return to normocapnia from ceasing to breathe high CO₂ (Tests 2 and 3) – the 'CO₂-off' effect.

Differentiating between the symptoms reported after the

switch from high CO₂ and those symptoms reported after the Valsalvas was difficult, because of the exact timings of administering the questionnaire at 1 min intervals at this part of the trial. However, in the debrief at the end of the tests, some subjects reported definite symptoms after Valsalvas and two subjects noted light-headedness after performing Valsalvas alone (Test 1).

MCAv AND SYMPTOMS FOLLOWING VALSALVA MANOEUVRES

Other studies have reported that decreases in MCAv of about 50% are associated with faintness. Passive head-up tilt of healthy subjects reduces MCAv and induces feelings of faintness.⁷ In our study, the drop in percentage MCAv for the group that noted faintness or increased faintness following the switch was, in general, greater than the drop for those that did not. However, in contrast to our previous study, this difference was not significant. Our previous study demonstrated a significant difference in percentage drop in mean MCAv between the subjects who had symptoms of faintness after the switch to O₂ and those who did not report faintness (decrease in MCAv of 51% versus 44% respectively).²

Valsalvas performed in the standing position reduce the mean MCAv to 50% of the value obtained during supine rest, whereas during supine Valsalvas the reduction in MCAv is of the order of 35%.³ The authors concluded that in the upright position, expiratory straining may critically compromise cerebral perfusion.

In our previous study, where the subjects switched to breathing 100% O₂ but did not perform Valsalvas, there was a large drop in percentage MCAv in the first minute following the switch to O₂ (similar to the effect observed with this study) – any further drop in percentage MCAv after the first minute following the switch was not significant when compared with the drop in the first minute. Therefore, it is assumed that in our present study, the significant drop in percentage MCAv observed following Valsalvas was, in fact, due to the Valsalvas and not to a continued/prolonged effect of the switch to O₂. Although Valsalvas exacerbated the decrease in cerebral blood flow following the switch from high CO₂, the accompanying symptoms of faintness, headache and nausea were transient and not incapacitating.

RELEVANCE TO SUBMARINE TOWER ESCAPE

The procedure for performing the Valsalvas was a compromise between the operational scenario and achieving a reproducible effect. In submarine escape exercises conducted by RN instructors, the observed method of ear-clearing varies markedly between individuals but is likely to be more frequent.

During the debriefing of the subjects following each test there was a range of comments from the subjects regarding

how they felt, from “*nothing of note*” and “*didn’t notice any difference*” to comments that the transient faintness after the switch and Valsalva was “*pretty grim, I couldn’t have done any physical work at that point*” and “*I couldn’t have made a decision*”. Despite these reports, all subjects successfully completed the six Valsalvas. This required them to coordinate repeatedly closing off the mouthpiece outlet with their hand while simultaneously ensuring that they were reaching the required exhalation pressure, and following instruction on when to inhale and exhale. Submariners are trained in using escape towers and the procedures should be familiar. Following pressurisation, the submariner will be ascending through the water column to the surface, with no physical work or decision making to perform. Submariners simply need to breathe normally during the ascent and by the time they reach surface any transient faintness or headache due to changes in the breathing gas/Valsalva manoeuvres should have resolved.

In the escape scenario, it is likely that the submariners will be at least partially immersed and thus subject to hydrostatic pressure which should help to support systemic BP and cerebral perfusion. The time from the start of flooding of the tower to the start of compression can take up to 190 s, depending on depth and type of escape tower, and this period may give a protective effect on cerebral circulation, reducing the risk of fainting in the escape tower.

Our study examined the effect of acute high CO₂ exposure. The effect of switching to air from a chronic high CO₂ exposure, as may be experienced in a DISSUB environment, is unknown.

Conclusions

The hypothesis that Valsalva manoeuvres would reduce MCAv over and above that caused by a switch from breathing high CO₂ was upheld; there was a further 14% decrease in MCAv. The percentage drop in MCAv occurring following the switch from high CO₂ to 100% O₂ (34%) was similar to that occurring following the switch to air (35%). Therefore, a ‘CO₂-off’ effect seems the best explanation of the observed results.

Seven subjects reported faintness after the gas switch and performing Valsalvas, some with additional symptoms of headache or nausea. Those subjects who reported feeling faint had a slightly lower mean MCAv than those who did not, but this was not statistically significant. Transient faintness or headache may occur in the submarine escape tower during pressurisation, but this should be short-lived and not be incapacitating.

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Annex 15.

Loveman GAM, Seddon FM, Jurd KM, Thacker JC, Fisher AS.

First Aid Oxygen Treatment for Decompression Illness in the Goat After Simulated Submarine Escape.

Aerospace Medicine and Human Performance. 2015 December; 86(12):1020-7

First Aid Oxygen Treatment for Decompression Illness in the Goat After Simulated Submarine Escape

Geoff A. M. Loveman; Fiona M. Seddon; Karen M. Jurd; Julian C. Thacker; Arran S. Fisher

- BACKGROUND:** Personnel responding to a distressed submarine incident require information on likely casualty levels and the severity and progression of decompression illness (DCI). Recompression may not be immediately available. First aid oxygen (FAO₂) can be administered; however, there is no direct evidence of its efficacy in this scenario.
- METHODS:** Trials were conducted between 2004 and 2006. Goats exposed to raised pressure for 24 h ('saturation') were either returned directly to atmospheric pressure (Phase A, $N = 40$) or exposed to simulated submarine escape at a depth of 656 ft (200 m; assumed seawater density = $1019.72 \text{ kg} \cdot \text{m}^{-3}$; Phase B, $N = 39$). The pressure during saturation was selected to provoke 50% DCI. Cases of DCI were randomly assigned to receive FAO₂ or air.
- RESULTS:** DCI cases were: limb pain in 39 subjects, neurological in 6, respiratory in 4, and pulmonary barotrauma in 1 subject. In Phase A, 5/12 subjects in the FAO₂ group and 0/11 in the air control group achieved permanent resolution of DCI. In Phase B, 6/8 subjects in the FAO₂ group and 5/8 in the air control group achieved permanent resolution. In both Phases, levels of venous gas bubbles reduced sooner with FAO₂. Of three cases of neurological DCI receiving FAO₂, two showed permanent resolution. In total, four cases of respiratory DCI occurred; none of these resolved, with three being treated with FAO₂ and one in the air control.
- DISCUSSION:** Oxygen can be an effective first aid measure for DCI following submarine escape. However, it should not be used as a replacement for recompression therapy.
- KEYWORDS:** surface oxygen, Doppler, distressed submarine, DISSUB, decompression illness.

Loveman GAM, Seddon FM, Jurd KM, Thacker JC, Fisher AS. First aid oxygen treatment for decompression illness in the goat after simulated submarine escape. *Aerospace Med Hum Perform.* 2015; 86(12):1020–1027.

Evacuation of a UK Royal Navy submarine is possible via a small airlock, the escape tower. The crew may be exposed to raised pressure within the distressed submarine and subsequently in the escape tower. Rapid return to normal atmospheric pressure puts the crew at risk of suffering decompression illness (DCI). Information on likely casualty levels and the severity and progression of DCI would be valuable for the medical team responding to a distressed submarine event should recompression facilities not be immediately available.

Following World War II, considerable work was carried out in order to determine rates of escape tower pressurization and subsequent ascent that might be safely achievable.¹⁰ These early trials ignored the possible increase in likelihood and severity of DCI due to exposure to raised pressure within the submarine prior to escape. This issue was addressed in later trials described by Bell et al. using goats.² These later trials defined combinations of submarine pressure and escape depth which would result in a rate of occurrence of DCI of 50%. For example, Bell

et al. state that exposing goats to a pressure of 2.0 bar (200 kPa) for 17 h, followed by a simulated submarine escape from 697.2 ft (212.5 m), resulted in DCI being observed in 50% of animals, although confidence limits were not given. In fact, the 50% DCI rate was based on 6 cases of DCI occurring in 12 subjects (unpublished data), which means the observed rate of DCI could have been stated as $50 \pm 30\%$ (Clopper Pearson 95% confidence interval for a sample from the binomial distribution). The UK Ministry of Defense required improved definition of the relationship between the distressed submarine internal pressure (the saturation pressure), the depth from which escape

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is made (the escape depth), and the risk of DCI. Subsequent trials investigating DCI in goats following simulated submarine escape have been previously summarized.^{32,36} This paper presents details of a subset of those trials. Prior to conducting this subset of trials, data were available from 165 previously completed 24-h exposures of goats to raised pressures between 1.5 and 3.59 bar. Based on these data, direct return to 1.0 bar following 24 h spent at a pressure of 2.2 bar was predicted by logistic regression to give a probability of DCI of $50.7 \pm 24\%$ (95% CI).

Following submarine escape, the first external help that submariners are likely to receive will be from the Royal Navy Submarine Parachute Assistance Group, who are equipped to administer 100% oxygen as a first aid measure (FAO₂). In the absence of a recompression chamber, the administration of oxygen, fluid therapy, and an antiplatelet agent are generally indicated in the treatment of DCI.⁶ A study carried out for the UK Health and Safety Executive concluded that there is evidence that normobaric oxygen protects divers against the progression of neurological DCI symptoms and may compensate for delays in administering hyperbaric oxygen.³³ In recreational diving, FAO₂ has been found to increase recompression efficacy and decrease the number of recompression treatments required if given within 4 h of surfacing.²⁵ At a workshop held to discuss management of mild DCI in remote locations, a consensus was reached that some patients with mild symptoms and signs after diving can be treated adequately without recompression²⁷ and administration of 100% oxygen has formed the basis of a nonrecompression treatment pathway for the management of scientific diving operations in the Canadian high Arctic.³¹ However, the efficacy of FAO₂ for the treatment of DCI following submarine escape has not been previously reported.

The trials described here were aimed at determining the simulated saturation pressure which would result in a $50 \pm 10\%$ occurrence of DCI in the goat following direct return from saturation to 1.0 bar and also for saturation followed by a simulated submarine escape from a depth of 656 ft (200 m; assumed seawater density = $1019.72 \text{ kg} \cdot \text{m}^{-3}$). This provided the opportunity to investigate the efficacy of treatment of the resulting cases of DCI using FAO₂ without recompression.

METHODS

Animals

This study was conducted under UK Home Office License according to the Animals (Scientific Procedures) Act 1986. The experimental protocol for the study was reviewed internally by an Ethics Review Committee (protocol number: 042218). The animals used were female or castrated male adult goats weighing 41.0 kg to 81.0 kg, mean (SD) 57.0 (10.4) kg. The goats were maintained under the surveillance of a veterinary surgeon and an animal care welfare officer and certified in good health prior to use.

Equipment

Pressure exposures took place in a purpose-built hyperbaric chamber designed to allow simulation of submarine escape.

Audio Doppler bubble detection was carried out using TSI Doppler Bubble Monitor 9008 (Techno Scientific Ltd., Concord, ON, Canada). Mass spectrometry was carried out using a QP-9000 quadrupole mass spectrometer (Airspec/Morgan Medical Ltd., Rainham, Kent, UK). Expired respiratory gases and respiratory rates and volumes were monitored using Servomex fast-response oxygen and carbon dioxide analyzers (1400 series; Servomex, Sugarland, TX) and a flow meter (Kozak Turbine Compensator, KTC-3-D, KL Engineering, Van Nuys, CA) attached to an oro-nasal mask. The gas analyzers were dual-point calibrated using alpha gravimetric certified calibration gases supplied by BOC (Guildford, Surrey, UK). Calibration of the flow meter was carried out using a 3-L spirometer syringe.

Procedure

By conducting logistic regression on data already available and adding simulated data, it was predicted that 40 animal exposures would be required to reduce the width of the 95% CI on the predicted 50% DCI saturation exposure to $\pm 10\%$. Animals were exposed to raised pressure, initially of 2.2 bar, for 24 h and then either returned directly to atmospheric pressure (Phase A) at a rate of $1 \text{ bar} \cdot \text{min}^{-1}$ or exposed to a pressure profile simulating submarine escape at a depth of 656 ft (200 m; Phase B). The simulated 656-ft (200-m) escape consisted of pressurization from the saturation pressure to 21 bar in 28 s with a 4-s hold at the maximum pressure followed by a linear decompression to 1.0 bar at a rate of $0.275 \text{ bar} \cdot \text{s}^{-1}$. **Fig. 1** shows example pressure/time profiles for Phases A and B.

For the first two exposures in each phase, animals were used in pairs. Following this, animals were exposed in groups of three. After each pressure exposure, a new 50% DCI saturation pressure was estimated based on the accrued data using logistic regression and was used for the next exposure.

A total of 63 goats were used in 79 animal exposures. There were 16 animals used in Phase A that were reused in Phase B. If

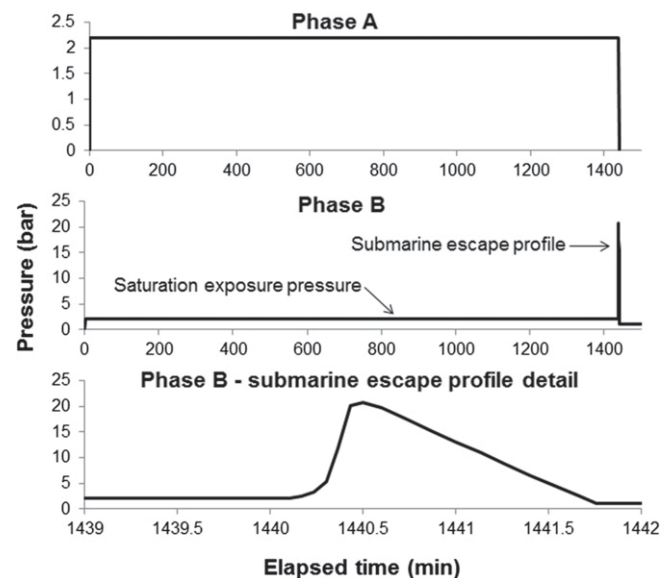


Fig. 1. Example of pressure/time profiles for Phases A and B.

an animal experienced DCI but made a full recovery, it was returned to the herd. There was a gap of 6 mo between Phases A and B.

Following the pressure exposures, animals were observed in an open pen next to the chamber while monitoring procedures were carried out. The following diagnostic criteria were used for the different types of DCI:

- Limb: Limb lifted off the ground, pawing or stamping, walking with a limp.
- Neurological/central nervous system (CNS): Unsteadiness, swaying, collapse, arching of back.
- Respiratory: Fast shallow breathing, increased heart rate, raspy breathing.
- Pulmonary barotrauma: Rapid onset collapse within 2 min, loss of consciousness.

Monitoring was performed for an 8-h period and further observations made intermittently for 24 h following a pressure exposure. Animals that showed signs of DCI were randomly assigned to a FAO₂ group or an air control group.

Air or 100% oxygen was delivered via plastic tubing to a transparent plastic hood with a latex neck seal (Sea-Long Medical Systems Inc., Louisville, KY). Mass spectrometry was used intermittently to give an indication of the actual levels of oxygen being administered. The animals wore the hoods for 1-h periods with the hood being removed for a 10-min air break between each hour. The air breaks allowed assessment of the animals' condition and walking gait, respiratory monitoring, and offering of rehydration fluids (Effydral™, Pfizer Ltd., New York, NY). Air or oxygen administration was continued for 1 h after resolution of all signs. If signs of DCI had not resolved after 3 h then the treatment was ceased; thus, the animals wore the hoods for treatment for a maximum of 4 h.

Careful and constant observation was maintained and all progression or resolution of signs recorded. Pain relief and/or sedation was available, but every attempt was made not to mask the progression of signs. If an animal's signs had not resolved

after 3 h, it was humanely killed by a Home Office approved (Schedule 1) method.²⁰

Audio Doppler bubble detection was carried out before and after each pressure exposure. The animals' left precordial area was shaved prior to the exposure to allow better contact of the Doppler transducer. Ultrasound transmission gel (Aquasonic 100™, Parker Laboratories Inc., Fairfield, NJ) was liberally applied to improve contact between the transducer and the skin. The precordial site was monitored and a bubble grade assigned according to the Kisman and Masurel method ('KM grade').²² Doppler monitoring was completed at 2, 5, and 15 min, then at 15-min intervals to 2 h, and then every hour until 8 h post-exposure or until bubbles ceased. Respiratory monitoring was carried out at 20 min and 1, 2, 3, and 4 h post-exposure.

Statistical Analysis

Nonparametric data were compared using the median and Mann-Whitney *U*-test. Parametric data were compared using the mean and Student's *t*-test. The effect of FAO₂ compared to air breathing controls was compared using Fisher's Exact Probability Test. Differences were considered significant if *P* < 0.05. Where data were compared for individual time points the *P*-value for significance was adjusted using the Bonferroni correction.

RESULTS

A total of 40 animal saturation only exposures were carried out in Phase A. The range of saturation pressure was 2.2 to 2.35 bar, mean [SD] 2.28 [0.04] bar. Of these 40 animals, 23 showed signs of DCI: 12 animals were assigned to the Phase A FAO₂ group and 11 to the air control group. Oxygen level in the hoods during the FAO₂ treatments ranged from 91.5 to 99.3% with a mean of 96.6%.

Results are summarized in **Table I**. The shortest onset time for DCI was 4 min post-exposure and the longest was over 5 h,

Table I. Summary of Results for Trial Phases A and B.

	PHASE A - SATURATION ONLY		PHASE B - SATURATION AND 200-m ESCAPE		
Saturation pressure (bar)	2.28 (0.04)		2.14 (0.05)		
DCI/N	23/40		20/39		
Treatment type	FAO ₂ (N = 12)	Air (N = 11)	FAO ₂ (N = 8)	Air (N = 8)	No treatment (N = 4)
Body mass (kg)	59.2 (11)	62.7 (10)	52.2 (4)	53.0 (13)	56.2 (3)
Saturation pressure (bar)	2.29 (0.04)	2.30 (0.03)	2.16 (0.03)	2.15 (0.05)	2.20 (0.03)
DCI type	10 L 1 L + R 1 CNS + L	10 L 1 L + R	5 L 1 L + R 1 L + CNS 1 CNS + L + R	8 L	3 CNS 1 PBT
DCI onset (min)	38 (27)	88 (95)	30 (20)	28 (13)	11 (6)
Treatment delay time (min)	14 (12)	18 (8)	9 (3)	11 (6)	N/A
Duration of oxygen treatment (min)	156.9 (53)	N/A	166.7 (54)	N/A	N/A
Resolution (observed cases)	6	3	6	6	N/A
Time to resolution (min)	115 (52)	365 (162)	121 (70)	255 (135)	N/A
DCI recurrence	1	3	0	1	N/A

200 m = 656 ft. FAO₂ = first aid oxygen; L = limb pain; R = respiratory DCI; CNS = central nervous system DCI; PBT = pulmonary barotrauma.

Where mean values are given, the standard deviation is shown in parentheses; where multiple signs of DCI were observed in an individual animal, this is indicated in the row labeled 'DCI type'; for example: '1 CNS + L + R' indicates an individual animal with signs of CNS, Limb pain and Respiratory DCI.

with most signs appearing in the first hour. The most common sign noted was limb lifting associated with limb pain, with more than 1 limb affected in 10 animals. One animal displayed signs consistent with mild CNS DCI: it had a hunched posture and was clumsy and slow when changing from standing to lying positions. In two of the animals there were indications of pulmonary compromise, a sign of respiratory DCI. This was manifest as a rise in respiratory rate with a decrease in respiratory exchange.

Of the 12 animals who received FAO₂, 5 achieved permanent resolution to their signs. The remaining 7 had residual or recurring signs. Of the 11 air control animals, 3 showed a resolution of signs, but this was temporary and the signs recurred. There was a significant difference between the effect of FAO₂ compared to air on the permanent resolution of signs of DCI ($P = 0.037$, Fisher's exact probability test).

A total of 39 animal exposures were carried out in Phase B. The range of pressure for the saturation exposures was 2.05 to 2.2 bar, mean 2.14 (0.05) bar, followed by simulated escape from 656 ft (200 m). Of these 39 animals, 19 showed signs of DCI and there was also 1 case of pulmonary barotrauma. The most common sign noted was limb lifting, with more than one limb affected in four animals. Of the 19 with DCI, 3 presented with CNS signs that were severe enough to require an early humane end point without assignment to either the air or FAO₂ group. The remaining 16 animals were randomly assigned to the FAO₂ ($N = 8$) or air control group ($N = 8$). In two of the animals there were indications of respiratory DCI. In the FAO₂ group, 6/8 achieved complete resolution of their signs: the remaining two had residual respiratory signs. It is worth noting that CNS signs occurred in two animals in the FAO₂ group which resolved with treatment. In the air control group, 5/8 also showed complete resolution of signs. All DCI cases in the air group were limb pain only, two were unresolved and one recurred overnight. There was no significant difference in the level of resolution or mean time to resolution between the air and FAO₂ groups in Phase B.

Doppler measurements were continued after a diagnosis of DCI had been made and while the animal was being treated with FAO₂ or air. **Fig. 2** shows the median KM grades for Phase A. There was no significant difference between median KM grades for DCI versus no DCI. KM grades decreased to zero by 8 h post-exposure in the animals without DCI and in those in the FAO₂ group. The grades began to fall earlier in the FAO₂ group than the air control group, with a significant difference between the two groups at 90 min post-exposure ($U(21) = 111$, $z = -2.74$, $P = 0.006$, Mann-Whitney U -test, two-tailed).

Fig. 3 shows the median KM grades for Phase B. As in Phase A, median KM grades in Phase B were not significantly different for animals with DCI compared to those without. The KM grades had decreased to zero in 13 of the 19 animals without DCI by the end of the 8-h monitoring period. **Fig. 3** shows that the median KM grades began to fall earlier in the FAO₂ group than the air control group. At 300 min there was a significant difference between the KM grades for the groups ($U(10) = 33.5$, $z = -2.4$, $P = 0.02$, Mann-Whitney U -test, two-tailed). The

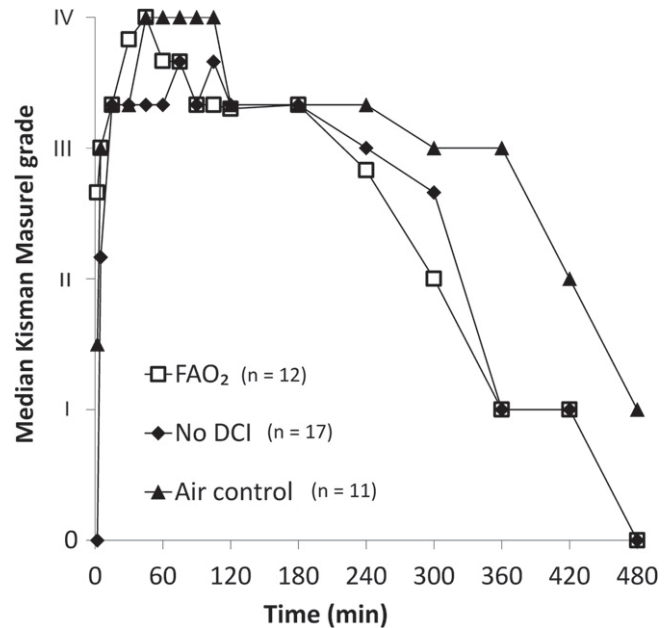


Fig. 2. Phase A median Kisman Masurel grade for no DCI, FAO₂, and air control groups.

median KM grade had dropped to zero by 7 h in the group without DCI and in the FAO₂ group.

The mean onset times to the first signs of DCI were significantly shorter for Phase B than for Phase A ($t(25) = 2.32$, $P = 0.029$, Student's t -test, two-tailed, unpaired, unequal variance). There was a significant difference between the median KM grades at 2, 5, and 15 min in Phase A compared with those in Phase B [2 min: $U(63) = 856.5$, $z = -4.32$, $P < 0.0001$; 5 min: $U(71) = 1065$, $z = -4.4$, $P < 0.0001$; 15 min: $U(74) = 1061.5$, $z = -3.55$, $P = 0.0004$; Mann-Whitney U -test, two-tailed].

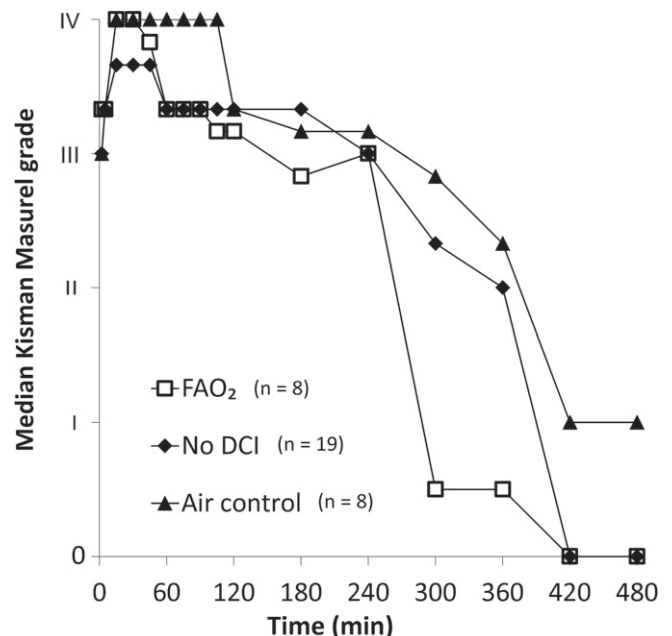


Fig. 3. Phase B median Kisman Masurel grade for no DCI, FAO₂, and air control groups.

DISCUSSION

Based on the results obtained from the trials described here, a saturation pressure of 2.24 bar followed by direct ascent was predicted to provoke an incidence of DCI of $50 \pm 10\%$ based on logistic regression. The pressure which will provoke an incidence of DCI of $50 \pm 15\%$ after a 24-h exposure with a 656-ft (200-m) simulated submarine escape was estimated to be 2.14 bar. These data have been included in the calibration of a model for the estimation of risk of DCI following submarine tower escape, details of which have been previously published.²⁶

No permanent resolution of DCI was seen in the Phase A air control group, whereas signs in the FAO₂ group completely resolved in five animals; this was statistically significant ($P = 0.037$). This indicates that oxygen is an effective first aid measure in resolution of DCI following direct return to surface pressure from shallow air saturation exposures.

It is worth comparing the types and onset times of DCI observed in the two phases of the trial. From the saturation only phase (Phase A), there was a single case of CNS DCI, which was treated with FAO₂ with no resolution. For saturation with a 656-ft (200-m) escape, there were five cases of CNS DCI, three of which were early onset and severe. The other two cases of CNS DCI were treated with surface oxygen, one of which resolved completely, and the other case saw resolution of the CNS signs, but also had respiratory DCI signs which did not resolve. The mean time to resolution of signs for the FAO₂ group in Phase A was 115 min, but there was no resolution in the air control group. In Phase B there was no significant difference between the mean time to resolution of signs in the FAO₂ group (120 min) and the air control group (255 min).

An explanation for the different types and severity of DCI is that deeper saturation exposures (2.24 bar) were required to provoke 50% DCI with no escape. The escape from 656 ft (200 m) increases the risk of DCI, therefore the saturation pressure must be slightly reduced (to 2.14 bar) to induce the same 50% risk. Unresolved limb pain was the predominant DCI type in Phase A, possibly due to the deeper mean saturation pressure of Phase A. Following direct ascent from saturation, a steep increase in likelihood of DCI with saturation pressure is well documented in the literature.²⁴ The lower mean saturation pressure of Phase B apparently gave rise to limb pain DCI cases that were more successfully treatable than those in Phase A, but the addition of the 656-ft (200-m) simulated escape profile increased the risk of CNS DCI. This effect might be due to uptake of nitrogen primarily in the CNS during the rapid pressurization to 21 bar and in the first part of the simulated ascent. Other, less well perfused tissues would not necessarily be affected, since they would take up little nitrogen in the relatively short duration of the escape exposure. The level of respiratory DCI observed was the same in both phases.

The mean onset times to the first signs of DCI were significantly shorter for Phase B than for Phase A ($P = 0.029$). KM grades in Phase B were also higher than those in Phase A for the first 15 min post exposure. These results suggest that the initial high level of circulating venous gas bubbles observed in

Phase B was due to the effect of the 656-ft (200-m) escape exposure and it was this that gave rise to earlier cases of DCI and increased levels of CNS signs. Shorter latency times for detection of circulating bubbles have been associated with increased risk of DCI in other studies^{21,23} and shorter onset times to signs of DCI are associated with a requirement for a greater number of recompression treatments and poorer long-term outcome.^{15,16}

In both phases the KM grades decreased more rapidly after 240 min in the FAO₂ group. This was likely a result of the low partial pressure of inspired nitrogen giving rise to a faster wash-out of nitrogen from the body, an example of the effect of the 'oxygen window'.¹⁹ Commencing oxygen breathing immediately upon surfacing, rather than waiting for signs of DCI, after simulated submarine escape has also been shown to reduce KM grades more rapidly than breathing either air or a 5% carbon dioxide in oxygen mixture.¹⁸

It is worth noting that for the three early onset cases of severe CNS DCI from Phase B, the Doppler technician reported in each case that the level of bubbling 2 min post-exposure (and before the CNS events occurred) was extremely high. Eftedal *et al.* have described a bubble grading system for use with ultrasound imaging in which the highest level of bubbles, where single bubbles cannot be discriminated in an image, is referred to as 'white-out'.¹⁴ They state that they have observed near 100% mortality in animals with this level of bubbles. In our experience, a shortfall in the KM scoring system is that grade IV, the maximal grade that can be assigned, does not allow for differences in extremely high bubble grades which can be discerned by an experienced technician.

Initially selected for use due to their amenable nature and being the largest animal readily available, goats have been shown to display a range of easily recognizable signs of DCI which correspond with signs in man.⁷ Interspecies response to decompression from saturation has been shown to be scalable using body mass as a scaling factor.³ Fig. 4 shows a logistic regression fit to DCI outcome data from the 205 goat saturation exposures available at the conclusion of the trials described here. (Data from 165 saturation exposures were available prior to the trials described here. Only the 40 exposures from Phase A were added in the regression). Saturation pressure and body mass were used as factors in the regression model. Coefficients of the regression model are given in Table II.

It should be noted that both the magnitude of the standard error and the P -value for the coefficient of body mass in the model indicate that inclusion of body mass as a factor did not significantly improve the fit of the model. Body mass has been included as a factor in the model nevertheless since, as already stated, risk of DCI has previously been shown to be scalable with body mass.³ The regression plot shown in Fig. 4 was made for goats with a body mass of 80 kg (estimated 95% confidence limits are shown in gray). Also included in Fig. 4 is a plot of predicted risk of DCI using a model described by Van Liew and Flynn which was fit to DCI data from human no-stop decompression exposures.³⁴ Fig. 4 suggests that estimation of risk of DCI in humans following saturation exposures can reasonably

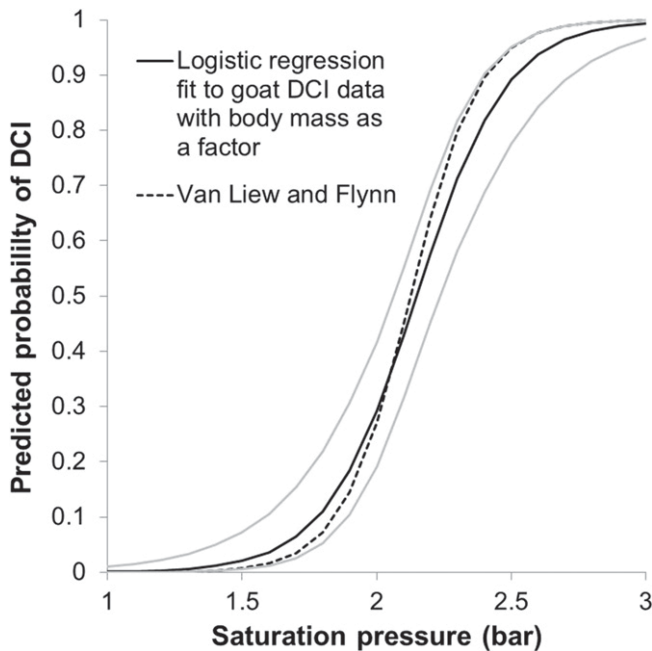


Fig. 4. Logistic regression fit to goat DCI data following direct ascent from saturation shown with a fit to human data from Van Liew and Flynn.³⁴ Body mass was included as a factor in the goat model and the plot shown is for an 80-kg animal; the gray lines show the extent of the estimated 95% confidence limits.

be made based on goat DCI data from similar exposures using body mass as a scaling factor.

This finding is in agreement with Lillo *et al.*, who have additionally shown that combining data from higher risk exposures tested in animals with data from lower risk exposures in man allows improved prediction of the risk of DCI for humans where high risk data are sparse.²⁴ Details of the use of these principles to provide a model for the prediction of DCI following submarine tower escape based on the combination of available data for both man and goat have been previously published.²⁶ Comparison of DCI data in goats and humans for the rapid pressurization and decompression of a submarine escape exposure is more difficult due to the limited human data available. Histological examination has shown similar lesions in the spinal cord of man and goats following spinal DCI.²⁸ However, there is also evidence to suggest that the goat may suffer fewer decompression-induced cerebral lesions than man.²⁹ This may be due to differences in the cerebral vasculature between the two species or possibly due to a postulated higher prevalence of patent foramen ovale in man, which could allow gas bubbles to pass into the arterial circulation via venous-arterial shunt in the heart.⁵

Levels of circulating venous gas bubbles following direct ascent from a range of saturation pressures have been measured

Table II. Summary of Logistic Regression Fit to Goat DCI Data Following Saturation Exposures.

COEFFICIENTS	ESTIMATE	STD. ERROR	z-VALUE	P(> z)
Intercept	-14.6	2.4	-6.1	1.4e-09
Saturation pressure (bar)	5.99	0.97	6.2	7.2 e-10
Body mass (kg)	0.02	0.02	0.9	0.4

in man by Eckenhoﬀ *et al.*^{12,13} Based on these observations, Eckenhoﬀ *et al.* generated models for predicting the probability of observing a peak KM grade greater than each of the bubble grades 0, I, II, and III. These models for predicting levels of venous bubbles in man may be compared with our measurements in the goat. **Fig. 5** shows the observed fraction of animals in Phase A (FAO₂ group excluded) with peak KM grades higher than grade II and the observed fraction with peak grades higher than grade III. All animals in this group ($N = 28$) had a peak KM grade higher than grade II. The two points are plotted at the mean saturation depth for these exposures, which was 2.24 bar. The maximum saturation pressure used by Eckenhoﬀ *et al.* in their manned trials was 1.92 bar, as indicated by the dashed vertical line in **Fig. 5**. The extrapolated predictions for man at 2.24 bar are within the 95% binomial confidence limits of the two points plotted for the goat. This suggests that peak KM grades observed in the goat following direct ascent from saturation may follow a similar pattern to those observed in man.

It should be noted, however, that Eckenhoﬀ *et al.* used KM grades observed in man both at rest and also following a 'flex' movement (a deep knee-bend) and took the peak of these, which generally occurred after the flex movement.¹³ The goats were not induced to make any movement akin to the flex movement. Therefore, the peak grades for the goats might be anticipated to be somewhat lower than those observed in man.

Given the evidence as discussed, it would appear that the response of the goat to decompression stress is not grossly dissimilar, at least, to that observed in man. Assuming the response

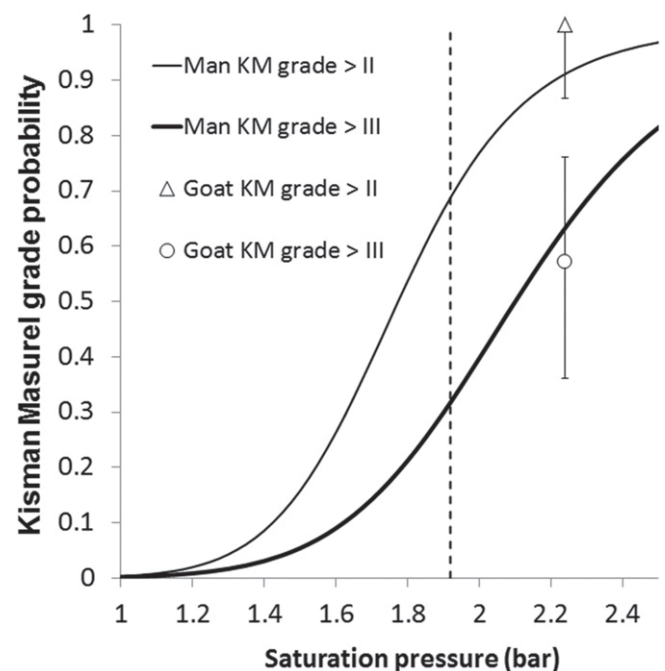


Fig. 5. Observed fraction of subjects in Phase A (FAO₂ group excluded) with peak KM grade > II ($N = 28$) and with peak KM grade > III ($N = 16$); error bars are the 95% exact binomial confidence limits. The solid lines are fits made to human venous gas bubble data from Eckenhoﬀ *et al.*¹² The dashed line shows the upper limit of saturation pressure at which Eckenhoﬀ *et al.* conducted manned trials.

to be similar, then the saturation pressure which elicits 50% DCI results in signs which the authors suggest would not be expected to cause death or prevent a submariner from boarding the one-man life raft that they are equipped with. These signs would be expected to resolve on recompression treatment in the majority of cases.¹ This finding contradicts to some extent the expectations described by Weathersby³⁵ that in the region of 50% DCI risk there would be a range of DCI that may lead to death in some and permanent disability without immediate recompression therapy in most people. Observations from our previous studies, both manned²¹ and animal³² indicate that while this looked unlikely for saturation alone, or saturation with a shallow escape, it may be true for saturation dives with deeper escapes. The cases of CNS DCI that we encountered in Phase B were severely disabling and probably would have prevented the successful rescue of some individuals. In retrospective studies, severe symptoms of neurological DCI have been found to be associated with long-term sequelae even when recompression is available, with time to treatment being found to have either no influence or at most a weak association with likelihood of full recovery.^{4,17} In the distressed submarine scenario, therefore, if medical assistance and recompression were available then the likelihood of survival would be high, but possibly with some respiratory or neurological sequelae. However, it is also possible that some apparently severe neurological DCI following submarine escape may resolve spontaneously. A previous study has described this phenomenon, with cases of neurological DCI after simulated submarine escapes having been observed to resolve untreated after around 20 min.¹¹ The authors postulated that short-duration, high-pressure exposures typical in submarine escape might give rise to venous bubbles with a high oxygen content. This could occur since, with air as the breathing gas during the escape procedure, the inspired partial pressure of oxygen will be as much as 4.0 bar for escape at a depth of 590.6 ft (180 m). Since the procedure is so rapid, there would be little time for this oxygen to be metabolized and, therefore, it could act as a contributor to the gas content of any bubbles that form, a possibility that has been modeled by Parker *et al.*³⁰ These bubbles could resolve in a shorter time than bubbles with a higher inert gas content due to the metabolic use of oxygen in the tissues generating an increased gradient for oxygen diffusion out of the bubble. However, in a distressed submarine scenario, short-duration neurological DCI might still prove fatal, perhaps resulting in drowning, if support were not immediately available upon surfacing.

A further consideration in the context of a distressed submarine scenario is that the crew may be exposed to a raised partial pressure of oxygen within the submarine and that subsequent treatment with 100% oxygen on the surface or during recompression could exacerbate symptoms of pulmonary oxygen toxicity, which can be fatal.^{8,9} Pulmonary oxygen toxicity remains an issue in both the treatment of DCI following escape and in the successful decompression of submariners following evacuation via a rescue submersible.

The trials described here show that oxygen can be an effective first aid measure in the treatment of DCI following

submarine escape. However, the level of DCI signs that remained or recurred show that, although a useful adjunctive therapy, FAO₂ should not be considered as a replacement for recompression therapy as the gold standard in the treatment of DCI.

ACKNOWLEDGMENTS

The trials described here were conducted at QinetiQ Alverstoke in the UK between 2004 and 2006. Following the conduct of these trials, representatives of QinetiQ and the Institute of Naval Medicine agreed that the risks of DCI following submarine tower escape were adequately defined and experimental work using animals ceased.

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