A review of diving practices and outcomes following the diagnosis of a persistent (patent) foramen ovale in compressed air divers with a documented episode of decompression sickness

Christopher W Scarff[1], John Lippmann[2,3], Andrew W Fock[1,3]

[1] *Department of Intensive Care and Hyperbaric Medicine, Alfred Hospital, Melbourne, Australia*
[2] *Australasian Diving Safety Foundation, Melbourne, Australia*
[3] *Department of Public Health and Preventive Medicine, Monash University, Melbourne, Australia*

Corresponding author: *Dr Christopher W Scarff, The Alfred, PO Box 315, Prahran 3181, VIC, Australia*
c.scarff@alfred.org.au

Key words
Decompression illness; Persistent (patent) foramen ovale (PFO); Safety; Education; Diving research

Abstract
(Scarff CW, Lippmann J, Fock AW. A review of diving practices and outcomes following the diagnosis of a persistent (patent) foramen ovale in compressed air divers with a documented episode of decompression sickness. Diving and Hyperbaric Medicine. 2020 December 20;50(4):363–369. doi: 10.28920/dhm50.4.363-369. PMID: 33325017.)
Introduction: The presence of a persistent (patent) foramen ovale (PFO) increases the risk of decompression sickness (DCS) whilst diving with pressurised air. After the diagnosis of a PFO, divers will be offered a number of options for risk mitigation. The aim of this study was to review the management choices and modifications to diving practices following PFO diagnosis in the era preceding the 2015 joint position statement (JPS) on PFO and diving.
Methods: A retrospective study was conducted of divers sourced from both the Alfred Hospital, Melbourne and the Divers Alert Network Asia-Pacific during the period 2005–2015. Divers were contacted via a combination of phone, text, mail and email. Data collected included: diving habits (years, style and depths); DCS symptoms, signs and treatment; return to diving and modifications of dive practices; history of migraine and echocardiography (ECHO) pre- and post-intervention; ECHO technique(s) used, and success or failure of PFO closure (PFOC). Analyses were performed to compare the incidence of DCS pre- and post-PFO diagnosis.
Results: Seventy-three divers were interviewed. Sixty-eight of these returned to diving following the diagnosis of PFO. Thirty-eight underwent PFOC and chose to adopt conservative diving practices (CDPs); 15 chose PFOC with no modification to practices; 15 adopted CDPs alone; and five have discontinued diving. The incidence of DCS decreased significantly following PFOC and/or adoption of conservative diving practices. Of interest, migraine with aura resolved in almost all those who underwent PFOC.
Conclusions: Many divers had already adopted practices consistent with the 2015 JPS permitting the resumption of scuba diving with a lowering of the incidence of DCS to that of the general diving population. These results support the recommendations of the JPS.

Introduction

Decompression sickness (DCS) was first described in the latter part of the 19th century by Paul Bert, though it was not until almost 150 years later that the patterns of cutaneous, inner ear and neurological DCS were associated with intracardiac right-to-left shunts.[1,2] The incidence of right-to-left shunt was higher in a cohort of divers with a history of DCS (especially with severe symptoms), than in some cohorts of healthy individuals (although the methods for shunt detection differed).[3] The majority of these shunts were found to be due to a patent (sic) foramen ovale. Persistent (patent) foramen ovale (PFO) can be identified in 25–33% in the population[4] but, owing to non-specific symptoms and signs, there is a reliance on echocardiographic examination for definitive diagnosis upon clinical suspicion raised by family history, migraine with aura,[5] transient ischaemic attack, cryptogenic stroke,[6] shunt-induced cyanosis[4] and DCS suggestive of PFO.

The risk of DCS in association with scuba diving is in the order of 1.9:10,000 with the presence of PFO potentially increasing that risk almost fivefold.[7–9] This makes affected divers more susceptible to DCS even on dives that would normally not be considered provocative in accordance with commonly used decompression recommendations and accepted conservative diving practices (CDP).[8] PFO closure (PFOC) is not a guarantee against further DCS, nor is it a risk-free procedure. However, as well as reducing the likelihood of DCS, it may have benefits in conditions such as migraine with aura[5] and cryptogenic stroke.[10,11] Thus, the decision matrix can be complex.

In light of this, the South Pacific Underwater Medical Society (SPUMS) conducted a symposium on the topic, resulting in a consensus statement in 2015.[12] This included recommendations made on the basis of both evidence and expert opinion, aiming to provide guidance for diving physicians when offering advice to divers to reduce the risk of DCS in the presence of a PFO. The recommendations include measures such as diving cessation, adoption of (more) conservative practices and/or PFOC.

The aim of this study was to review closure procedures undertaken and any changes in the diving practices and outcomes of divers who presented with documented PFO following DCS over the period 2005 to 2015 prior to the publication of the Joint Position Statement of 2015. We enlisted two cohorts: divers who presented to the Hyperbaric Unit of the Alfred Hospital, Melbourne for treatment or advice for DCS, and divers who reported to the Divers Alert Network Asia-Pacific (DAN AP) that they had been diagnosed with an intracardiac shunt following a presentation for DCS.

Methods

Approval for this retrospective cohort study was obtained from the Alfred Hospital Ethics Committee 07/05/2015 (Number 236/15).

Patient histories from the Hyperbaric Unit at the Alfred Hospital, Melbourne and cases involving Australian residents reported to the DAN AP over a ten-year period (2005–2015) were reviewed for the following diagnoses: dermatological, vestibular, central neurological or spinal DCS. These histories were then examined for the presence of documented or suspected PFO. Patients without documented evidence of PFO were excluded from further assessment and analysis.

All patients were contacted via mail and/or email prior to subsequent telephone interview(s) and/or receipt of a written questionnaire. Informed consent for collection of data was obtained from participants who supplied relevant diving history and medical information. Data collected included: demographics; history of migraine pre- and post-PFOC; diving habits (years, style number of dives and depths); DCS symptoms, signs and treatment; return to diving and practice modifications; echocardiography reports pre- and post- closure, where available; success or failure of PFOC, and technique for closure.

Defects noted at echocardiography as 'large', 'significant', requiring a 25 mm device or having bubble transit at rest were allocated to the 'large' group. Defects noted to be 'small', requiring a device less than 25 mm or only demonstrating bubbles upon provocation were allocated to the 'small' group. Information on device type was not always available.

Descriptive statistical analyses (Microsoft Word 15.25) were performed. The incidence of DCS was calculated pre- and post-diagnosis of PFO. Difference in incidence rates between pre- vs post-diagnosis periods and the corresponding 95% confidence intervals were determined using the incidence rate procedure available in Stata software version 15 (StataCorp, Texas, USA).

Results

Two hundred and fifteen presentations to the Alfred during 2005–2015 resulted in 24 eligible subjects: 50 patient histories satisfied the original research criteria; 14 patients were lost to follow-up and 12 had a history consistent with PFO but had either a normal echocardiogram or had not been investigated. Over the same period, 77 DAN AP members or prospective members declared having been diagnosed with a right-to-left shunt, resulting in 49 subjects: 24 declined enrolment, two were lost to follow-up, and the two divers common to both cohorts were counted amongst the Alfred cohort. The combined population of 73 had a mean age of 47.6 (SD: 11.2) and comprised 51% males. Fifty-five (75%) patients had undergone one or more procedures to close a PFO and/or other septal defects and 18/73 (25%) did not undergo closure. At the time of interview, 68/73 (93%) had returned to diving, four had ceased compressed air diving and one was planning to resume diving once lifestyle and family commitments had improved.

DCS SYMPTOMS AND SIGNS

The symptoms and signs reported (total numbers of the 73 divers) were typical for a cohort suffering DCS related to PFO: rash (46), headache (35), altered balance (32), paraesthesia (31), altered vision (29), swelling (26), fatigue (17), altered hearing (14), vertigo (13), nausea/vomiting/diarrhoea (12), confusion (11), pain-other (7), collapse (3), and tinnitus (2). Multiple divers reported multiple symptoms and/or signs.

DIVING HISTORY AND SEQUELAE

Based on self-reported diving history, the median (interquartile range, IQR) number of dives prior to assessment was 345 (153, 800) over a median (IQR) of 14 (8, 25) years; giving an average of approximately 38 (21, 68) dives per year. The median (IQR) number of dives that were conducted after the DCS event that had precipitated the assessment with or without PFO closure was 130 (50, 250).

Prior to assessment, there were 80 reported cases of DCS in the 73 divers during 50,107 dives giving an incidence of 16.0 cases per 10,000 dives. There were three reported cases after PFO management that were consistent with DCS during 19,118 dives, giving an incidence of 1.6 cases per 10,000 dives. The rate of DCS differed significantly from

Table 1
Diving style before and after PFO diagnosis. Data are *n* (%). msw = metres' seawater

Phase	Not diving	Recreational 0–30 msw	Deeper > 30 msw	Technical	Commercial
Pre-intervention	–	8 (11.0)	31 (42.5)	31 (42.5)	3 (4.1)
Post-intervention	5 (6.8)	25 (34.2)	14 (19.2)	25 (34.2)	4 (5.5)

Table 2
Comparison of PFO repair status and change in diving practice

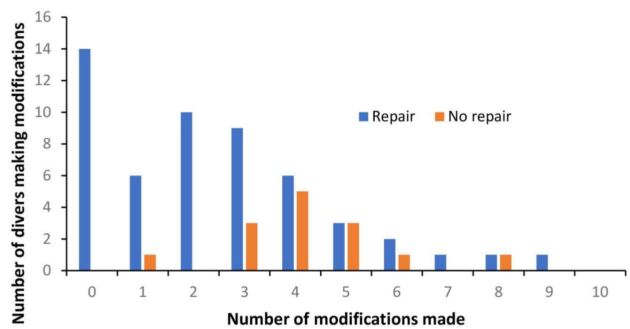
PFO status	*n* (%)
Closure and no change	15 (20.1)
Closure and CDP	38 (52.1)
Closure and no diving	2 (2.7)
Not closed and CDP	15 (20.1)
Not closed and no diving	3 (4.1)
Total	73 (100)

pre- to post-: 14.4 cases per 10,000 dives (95% CI 10.5 to 18.3 ($P < 0.0001$).

Six divers reported that, on multiple occasions, they had symptoms consistent with DCS, but these were unconfirmed so are not included for the calculation of incidence. Examples of their reports include 'symptoms over years', 'regular skin bends' and 'bent a number of times'. Of the three divers who had DCS following successful PFOC, only one reported symptoms similar to their original DCS, that being paraesthesia, rash and bruising. This diver described his dives as 'provocative', which was supported by the dive profiles; i.e., air dives to 50 and 60 metres' seawater (msw) with a surface interval of 3.5 h. Repeat transthoracic echocardiography (TTE) with bubble contrast and Valsalva after this event failed to reveal a shunt. This diver is now adhering to more conservative practices. The other two divers had symptoms that were less indicative of a PFO, with one freely claiming that the dive had been provocative and this has resulted in the subsequent adoption of safer practices. Neither of the last two divers had medical contact for these episodes prior to this study. There were three divers who reported symptomatology that was ambiguous and did not require medical attention. These were not included for the calculation of incidence.

Twenty-eight (38%) of the divers decreased their maximum dive depth following their DCS incident whilst 10 of the 73 (13.7%) increased their diving depth. Four ceased diving permanently with one diver planning to resume once lifestyle factors permit. Divers were allocated to one of four groups based on self-reported diving history: 'Recreational' and 'Deeper' for amateur divers with the cut-off being 30 msw, 'Technical' for cave divers and those utilising trimix, and 'Commercial' (Table 1).

Figure 1
Diving modifications post-presentation for divers with and without PFOC



RETURN TO DIVING AND MODIFICATIONS TO DIVING PRACTICE

All of those who returned to diving without PFOC and 38/55 (69%) of those who had PFOC adopted more conservative diving practices (Table 2). Many divers utilised multiple practices to mitigate risk with these modifications generally applied for all dives. The modifications included: the use of nitrox (n = 29), shallower dives (n = 27), initiation or increased use of safety stops (n = 26), decrease in 'no-deco' limits (n = 22), dropping from multiple to single dives in a day (n = 19), decrease in repetitive dives per day (n = 17), increase in surface interval (n = 16), increased hydration (n = 14), reduced exertion during dives (n = 12), slower ascents (n = 5) and cessation of diving (n = 5). Fifteen divers made no modifications whilst the others made between one and nine modifications. Divers who underwent PFOC were less likely to adopt more conservative diving practices than those who did not undergo closure (Figure 1).

INFLUENCE OF DEFECT SIZE ON RETURN TO DIVING AND CHANGES TO DIVING PRACTICES

There were 38 patients with 'large' defects, of which 33 returned to diving after repair (25 adopted more conservative practices and two now dive deeper), two returned without repair and two have neither undergone repair nor returned to diving. One diver reported that PFOC was successful but that additional defects were noted. These were not corrected, and the diver has resumed diving with a conservative approach and at interview has had no further incidents.

Twenty-six 'small' defects were noted and 12 of these patients have returned after repair (six modified practice conservatively and two went deeper), 12 returned without repair (all modified their diving), one underwent repair and plans to return pending lifestyle improvements and one has ceased diving.

Nine were not classified as there was no reference made to size of defect or bubble numbers in the echocardiography report; seven returned after repair, one repaired but has not returned and one has returned without undergoing repair.

MIGRAINE

Thirty-four of the divers suffered migraine with an almost equal gender distribution (16/18 male/female). Eighteen were associated with aura. Of the 23 of who underwent PFOC, 17 showed partial or complete cessation of migraines and six had no resolution. Three reported improvements in their symptoms, despite not having undergone PFOC. In the repair group of 23, the size of the defect was documented in 19: Twelve had a large defect (eight of these with aura), seven were small. Only one patient of the 18 with aura failed to improve following PFOC.

SIDE EFFECTS OF PFOC

Two divers who reported suffering 'palpitations' prior to their episode of DCS had symptomatic improvement in their palpitations following PFOC: one was also associated with resolution of migraine, the other reported that they no longer suffered palpitations at depth. Atrial fibrillation was reported in two patients following PFOC. One of these has, with the passage of time, had complete resolution and continues to dive, and the other has ceased diving. There were four reports of residual defect after closure on follow-up echocardiography. Two of these patients subsequently achieved PFOC whilst undergoing unrelated cardiac procedures, one during angioplasty for angina pectoris and the other during open cardiac surgery. Two patients continue to have PFO. One of these is awaiting a repeat procedure whilst the other has resumed diving despite continuing to report slight chest discomfort. One person ceased diving due to procedural complications of PFOC (he was not forthcoming as to the specifics), but is otherwise well.

Discussion

This retrospective study of 73 divers diagnosed with PFO over the period 2005–2015, revealed presentations that were typical for those suffering from DCS and included divers with a wide range of ages, years of experience and diving practices. We found that many among this cohort of divers adopted strategies that were to later be codified in the Joint Position Statement (JPS) on PFO and Diving of 2015,[12] with only five deciding not to continue with scuba diving. Whilst none of our cohort underwent PFOC purely for the management of migraine, almost all those with migraine associated with aura reported symptom resolution following PFOC.

An example of the local recommendations for the adoption of conservative diving practices (CDPs) can be seen in a recent publication which formed the basis for our questionnaire.[13] These recommendations and others are noted widely[14–16] and, as with many guidelines, there is often a low level of concordance. The Lippmann document[13] has similar recommendations for CDPs to those in statement five of the JPS and other earlier publications. For the management of the diver with a PFO, three options were proffered including cessation of diving, adoption of CDPs and closure of the PFO. Discussion of PFOC came with the overriding caveat that it is no guarantee against further DCS, and that the adoption of CDPs was not mutually exclusive of PFOC. This study group followed four strategies which included cessation of diving, closure without CDP, closure with CDP, and CDP without closure. All those opting for no repair modified their diving practices as did more than half of the divers after undergoing PFOC, and 53 of the 73 divers, independent of PFO closure status.

The questionnaires did not delve deeply into how the various modifications were used or seek quantification of these changes. For example, respondents who indicated that they had adopted the use of nitrox usually did not specify whether or not it was used based on air decompression times, which would reduce DCS risk. On the other hand, if nitrox was used to extend dive times it would not necessarily reduce risk and would not be a CDP.

The observed reduction in the incidence of DCS post-PFO diagnosis is similar that seen in other studies[4,17] and suggests that PFOC and CDP, whether alone or in combination, may lower the risk of DCS, especially for those with a large PFO. The reported incidence also reflects the caveat in the JPS that, although the risk of DCS may reduce to that of the general diving population,[9] it does not decrease to zero. The reported complications post-PFOC (8%) were comparable to those reported by Vanden Eade (7%)[18] and Rayhill (6.8%)[5] suggesting that PFOC is generally well tolerated. Of note, a third study (in divers) reported a much higher incidence of complication (19%) in a similar cohort.[17]

The risk of DCS is not related purely to the presence or size of a PFO but is also a function of other right-to-left defects.[19] These include other atrial septal defects and non-specific pulmonary shunts. Such persistent anomalies must be accounted for when counselling divers on the risks of further DCS following PFOC. One of our cohort volunteered that further shunts had been identified but not occluded. He continues to dive as per the JPS recommendations with a more conservative profile and at follow-up interview had not reported any adverse sequelae.

It is recommended in the JPS[12] that closure be confirmed by echocardiography. One study[18] notes that two of four divers who suffered DCS 'post-closure' had their assessment performed by a junior trainee which may explain why a residual defect 'post-closure' was not identified. Experienced cardiological opinion must be sought. At the Alfred Hospital, referrals are limited to two cardiologists, both of whom have an interest in diving medicine.

INCIDENCE OF DCS

The calculated incidence of DCS was based upon self-reporting of confirmed cases which may have led to an under-estimation. The unconfirmed self-reported cases were confined to a small number of divers but if correct would have increased the incidence markedly. The incidence post-intervention is likely to be more accurate due to divers being more aware of DCS and there often being less time between interview and incidents. Unlike a recent report in which subjects were enrolled on the basis of PFO with or without DCS,[17] all of our subjects had DCS confirmed by a diving physician, although some were not recompressed as the manifestations were considered relatively minor (e.g., mild cutis marmorata only) or presentations were delayed such that treatment was inappropriate.

Presentations to the Alfred for diving-related DCS requiring hyperbaric oxygen (HBO) have declined by more than 70% over the past 25 years from more than 70 per year in the early 1990s to less than 36 per year by the mid-2000s and down to 20 per year by the late 2010s. Despite there being an approximately 40% reduction in the entry-level certification numbers in Australia from 2007 to 2013,[20] other general diving activity data do not demonstrate such a reduction[21] and do not adequately account for the decreased presentations of DCS. It is possible that the drop in observed DCS cases may be reflective of better education leading to the adoption of more conservative and therefore safer diving practices (as seen in almost three quarters of our cohort) along with slower ascent rates and the incorporation of safety stops.

Transoesophageal echocardiography (TOE) has been suggested by some experts[22] as the gold standard for PFO investigation. Our experience is rather the contrary in that TOE requires the patient to be sedated and therefore unable to perform a Valsalva manoeuvre. While TOE is essential for placement of the closure device, we do not recommend it as a screening tool. On the other hand, transthoracic echocardiography (TTE) can be a very effective tool in detecting a right-to-left shunt when used by an experienced technician and with the aid of bubble contrast and provocative manoeuvres, such as Valsalva and sniffing.

MIGRAINE

Guidelines in the neurology literature are inconsistent regarding PFOC and migraine.[5,23] This study demonstrates that for divers with migraine associated with aura, PFOC may resolve their migraines. This cohort, while small, had an almost complete resolution of migraine with aura which has had significant positive impact on their quality of life. The benefits of PFOC must be balanced against the small risk of complications[5] and these probably preclude recommending PFOC for migraine. The use of PFOC in prevention or recurrence of cryptogenic stroke[11] and other conditions continues to be debated and should be referred to appropriate specialists.

FURTHER RESEARCH

Echocardiography

The echocardiologic nomenclature to describe PFO is inconsistent making comparisons between studies difficult. Variables described include size (large/small, millimeters, length, width etc), bubbles (number, +/- Valsalva, timing, transit time), patency (pencil, probe or not), grade (0–3), intensity of atrial opacification, mobility of septum, and words such as 'significant'.[6,8,29,30,10,15,17,24–28]

It is unclear whether these variations are due to individual sonographers, general sonographic practice or cardiological reporting. The present study condenses these reported variables to form two groups referred to as 'large' and 'small'. To strengthen further studies, a consistent vocabulary should be agreed upon and implemented.[31]

Advice to divers

In a retrospective audit of 105 divers undergoing PFOC for DCS in the period 2005–2014,[15] 81 of 95 "*were cleared to resume unrestricted diving*". One episode of cutaneous DCS was noted in a diver who had residual shunt following 'PFOC'. The number of dives post-PFOC was not noted and although 'unrestricted diving' was permitted, it is unclear as to whether there were any recommendations for CDP. Our results were similar with regard to number of divers, side effect profile and migraine resolution but there was a difference in diving practices post-PFOC with 69% of our cohort altering diving behaviour after being counselled to adopt CDP. Both these cohorts pre-date the JPS of 2015 and have vastly different approaches: one permitting unrestricted diving with the other recommending CDP. Further study is required to assess if closure and unrestricted diving is as safe an approach as closure with the adoption of CDP, particularly in light of the JPS of 2015.

LIMITATIONS

DCS presentations

The Alfred Hospital, Melbourne houses the sole public hyperbaric chamber for the state of Victoria. As such, independent of where a diver has suffered their DCS or received their HBO, if resident in Victoria, their follow-up is generally at the Alfred. The DAN AP cohort, on the other hand, included residents from throughout Australia. That there were only two divers common to both data sets, most likely reflects participation rates in scuba diving and membership of DAN AP not being spread evenly across the country.

DCS incidence

Our quoted incidences for DCS are subject to recall bias as dive experience was self-reported with regards to frequency, experience and dive profile. It is unclear how the 26 divers who were lost to follow-up would have altered our data. While the number of episodes of confirmed DCS were easy to quantify, a number of divers volunteered events before diagnosis that were difficult to clarify: 'multiple/regular skin bends', 'symptoms over years', 'bent a number of times', 'slight feeling of chest discomfort' and 'sometimes itchy in the chest'. Thus the 'true' numerator may be higher and the denominator different. The combination likely results in potential under-reporting of the incidence for DCS pre-diagnosis.

The two melded data sets were collected following slightly different methodologies, questionnaires and follow-up. The main difference between them was the format of reporting diving depths pre and post diagnosis. For simplicity, the non-technical divers were allocated to two groups: 'recreational' and 'deeper' with an arbitrary cut-off at 30 msw.

Conclusions

This study demonstrates that between 2005–2015 there were a number of mitigation strategies being enacted by divers diagnosed with a PFO after suffering an episode of DCS. These strategies included the management of the PFO and modifications to diving practices similar to those subsequently recommended in the JPS of 2015. That these strategies have appeared to lower the risk of DCS in this cohort provides further validation for the recommendations in the JPS. This should encourage the dissemination and use of conservative diving practices and the JPS guidelines to divers and their practitioners. There is significant variation in the terminology for PFO assessment which renders direct comparison between studies difficult. This situation could be remedied by the adoption of a simple and reproducible grading system.

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Acknowledgements

The authors wish to thank Assoc. Prof A Walton (Cardiology), Dr D McGaw (Cardiology) and Dr E Paul (Statistics) for their assistance. We would also like to thank the study participants for their time in completing questionnaires and interviews.

Conflicts of interest and funding

No conflicts of interest were disclosed. Part of this study was funded by the Australasian Diving Safety Foundation (previously DAN Asia-Pacific).

Submitted: 14 May 2020
Accepted after revision: 01 August 2020