Short communication

Large lungs in divers: a risk for pulmonary barotrauma?

Robert A van Hulst[1], Pieter-Jan AM van Ooij[2,3]

[1] *Department of Anesthesiology/Hyperbaric Medicine, Amsterdam University Medical Center, location AMC, Amsterdam, the Netherlands*
[2] *Royal Netherlands Navy Diving and Submarine Medical Centre, Den Helder, the Netherlands*
[3] *Department of Pulmonology, Amsterdam University Medical Centre, Amsterdam, the Netherlands*

Corresponding author: *Professor Robert A van Hulst, Department of Hyperbaric Medicine, Anesthesiology, Meibergdreef 9, 1100 DD, Amsterdam, the Netherlands*
ORCiD: *0009-0002-6945-5508*
r.a.vanhulst@amsterdamuc.nl

Keywords
Air embolism; Lung function; Risk factors; Vital capacity

Abstract

(van Hulst RA, van Ooij PJAM. Large lungs in divers: a risk for pulmonary barotrauma? Diving and Hyperbaric Medicine. 2024 30 September;54(3):225–229. doi: 10.28920/dhm54.3.225-229. PMID: 39288928.)
This retrospective study analysed a series of investigations on lung function in military divers and the importance of computed tomography (CT) scans concerning fitness to dive. We examined the incidence of blebs and bullae in a population of military divers with large lungs prompted by six cases of pulmonary barotrauma. All of these divers' medicals were normal apart from having large lungs (FVC > 120% predicted). A subsequent survey of the database of all divers and submariners of the Royal Netherlands Navy (RNLN) found another 72 divers/submariners with large lungs who were then evaluated by a CT scan. This resulted in the identification of three further individuals with blebs and/or bullae, who were then declared unfit to dive. In total, the incidence of these lung abnormalities in this cohort was 11.5%. We discuss the possible consequences for fitness to dive with regard to the current literature on the subject, and also consider the most recent standards of reference values for pulmonary function indices. Based on our results and additional insights from other studies, we advise using the Global Lung Initiative reference values for pulmonary function, while performing high resolution CT scans only in divers with clinical indications.

Introduction

The occurrence of pulmonary barotrauma during scuba diving is relatively rare but it poses a serious event that can lead to fatalities. It is caused by the expansion of gas during voluntary or pathological air trapping during decompression. As per Boyle's law, upon ascent from a dive, as the ambient pressure decreases, the air in the lungs increases in volume. Any air trapped during ascent can cause rupture of the alveoli, resulting in pneumothorax, pneumomediastinum, subcutaneous emphysema, and/or air entering the pulmonary veins, developing a so-called arterial gas embolism.[1] These accidents are not related to the duration or depth of the dive and are observed mainly in inexperienced divers or in the case of 'blow up' (i.e., rapid) ascents.[2,3]

The Royal Netherlands Navy (RNLN) faced six cases of pulmonary barotrauma in experienced divers within two years (2009–2011). All six of these divers had been medically examined according to international standards, including chest X-ray at initial examination and extensive pulmonary function testing (spirometry and body-box plethysmography) every year.[1,4] Retrospective analysis of their medical files (including X-rays) did not demonstrate abnormalities except that all had 'large lungs' based on the reference values at that date. However, computed tomography (CT) scans made after the diving accidents showed abnormalities in all six cases, although they differed in terms of pulmonary pathology presentation, e.g., blebs, bullae, cysts, or air-trapping, which are contra-indications for fitness to dive [1,4] After extensive discussions with radiologists, pulmonary physicians, and diving medical officers, it was concluded that these abnormal findings were pre-existing and not related to the accidents. Although initial chest X-rays were routine, we must realise this technique was not sensitive enough to detect minor pathology.

Large lungs are defined by spirometric volumes, and more specifically, according to the European Respiratory Society (ERS) standards at the date of these cases, as having a forced vital capacity above 120% of predicted value.[5] Large lungs in divers have been have been reported in the previous literature, and are probably related to increased work of breathing during diving due to the density of the breathing gases.[6,7] Furthermore, the healthy worker effect may also account for this observation.[8]

Based on the above, our primary objective in this retrospective study was to identify abnormalities on CT scans in the Netherlands military diving and submariner population with large lungs.

Methods

According to national law, retrospective analyses are exempt from evaluation by a medical ethics committee.

The Royal Netherlands Navy Diving and Submarine Medical Center (DMC) performs yearly medical assessments of military divers in compliance with international standards,[4] while submariners are examined to the same standard every five years. Based on the six diving accidents resulting in pulmonary barotrauma in individuals identified as having large lungs, the Surgeon General of the Royal Netherlands Navy approved the protocol suggested by the National Military Board that the annual assessment of divers with large lungs should, in addition to spirometry, include body plethysmography, diffusion capacity and a CT scan (Min Def U138/DMC.MV/10-9 Dec 2010).

DATA COLLECTION

We retrospectively surveyed the Royal Netherlands Navy (RNLN) database of all divers and submariners to identify those with large lungs, which was determined as per the ERS guidelines at that time and identified another 72 subjects. The identified cohort were subject to CT scans in accordance with the National Military Board protocol described above, allowing this investigation of any lung abnormalities in this population.

PULMONARY FUNCTION TESTING

Pulmonary function was measured by qualified respiratory technicians using the Vmax Encore testing system (Cardinal Health, Bilthoven, the Netherlands) and performed according to the European Respiratory Society guidelines at that date (2010–2011).[5] Calibration of the testing apparatus was performed according to the manufacturer's guidelines. Reference values were calculated using validated prediction equations.

CT PROTOCOL

All CT scans were performed in the Military Hospital, Utrecht, in the Netherlands. In the six pulmonary barotrauma cases, the CT scans were made within one week of the accident. The additional study subjects were scanned in the period December 2010 to June 2011.

Volumetric paired inspiratory and expiratory CT was performed in all subjects and all examinations were conducted using the same scanner (Brilliance 16P, Philips Healthcare) in a single centre. Settings were 120 kVp at 130 mAs for inspiratory CTs and 90 kVp at 20 mAs for expiratory CTs in all subjects. Images were reconstructed with a slice thickness of 1 mm at 0.7 mm increments using a sharp reconstruction kernel (L- and E-filters, Philips Healthcare).[9]

STATISTICAL ANALYSES

After collection of the CT data, the population was split into two groups: those with no anomalies on the CT scan (CT-) and those with anomalies (CT+). All data were tested for normality using the Shapiro-Wilk test. Student's *t*-test was employed to compare data between the CT- and CT+ groups if normally distributed. If there was a non-normal distribution, the Wilcoxon rank-sum test was used. A P-value of < 0.05 was considered significant. Analyses were performed using Stata BE software (version 18, StataCorp, USA).

Results

Table 1 shows the age, years diving, and spirometry data pertaining to the original six pulmonary barotrauma cases. Including these six, a total of 78 out of 316 subjects complied with the selection criteria of large lungs and were included in this study. The demographic data of this total group of Navy divers with large lungs are presented in Table 2. In the newly found individuals with large lungs ($n = 72$), upon performing CT scans, we found three additional cases of substantial air trapping or blebs, and these individuals were declared unfit for duty as divers or submariners; in total individuals with pulmonary abnormalities made up 11.5% of this cohort. In another three cases, we found extra-pulmonary findings: haemangioma around one thoracic vertebra, and thymus residuals in two divers; these divers were not excluded from any further diving.

Lung function data, including spirometry and body box plethysmography, are shown in Table 3. Although there was a significant difference in forced vital capacity percent (FVC%) and forced expiratory volume in one second percent (FEV_1%) between the groups, with CT+ having lower values, the FEV_1/FVC data did not differ between the groups. Finally, the peak expiratory flow (PEF) and PEF% were also significantly lower in the CT+ group compared to the CT- group. In our opinion these differences, although significant, are not relevant from a clinical perspective.

Discussion

In this retrospective study of healthy divers and submariners with large lungs, we found an 11.5% (9/78) rate of abnormalities that rendered individuals either unfit for diving

Table 1
Spirometric data in six cases of pulmonary barotrauma; AGE – arterial gas embolism; CT – computed tomography; FEV_1 – forced expiratory volume in 1 second; msw – metres of seawater; ref – reference value; VC – vital capacity; y – years

Case	Age (y)	Smoking (pack years)	Years diving	Dive (depth/ duration)	Type of pulmonary barotrauma	CT findings	Slow VC ml (% ref)	FEV_1 ml (% ref)	FEV_1/VC (%)
1	21	0.1	0	20 msw/5 min	AGE + pneumothorax	Areas of airtrapping in both lungs. No bullae	6,590 (120)	5,300 (118)	80
2	29	0	7	Exit/re-entry 15 msw	Pneumothorax	Area of airtrapping both lungs. CT one year later no anomalies	8,250 (131)	5,870 (118)	71
3	29	4	2	9 msw/? min	Pneumothorax	Several large bullae right lung	7,100 (124)	5,280 (112)	74
4	31	Ex (4 yr) 1.5	8	18 msw/20 min	AGE	Several bullae low dorsal	6,960 (121)	5,140 (110)	73
5	40	0	8	30 msw/? min	Pneumothorax	Subpleural bullae right lung	6,450 (121)	5,130 (119)	80
6	47	0	20	20 msw/45 min	AGE	Bullae in both lungs	5,820 (120)	4,170 (100)	72

or for the free-escape exercises necessary for submariner training. These nine with abnormalities included six individuals who had experienced a pulmonary barotrauma and three who had abnormal CT scans.

High-resolution CT scans (HRCT) effectively detect intrapulmonary anomalies such as blebs, bullae, air trapping, and emphysema, all theoretical risks for pulmonary barotrauma in a population of divers and submariners.[1,2] These abnormalities have an inhomogeneous structure in the lung parenchyma, and lung expansion during ascent may cause lung rupture, leading to pulmonary barotrauma as was found the six cases in the present study.[1,10] However, the relevance of this concept for fitness to dive is still unclear, as the incidence of pulmonary barotrauma in divers is far lower than the occurrence of intrapulmonary abnormalities.[11] It is important that the clinical relevance is defined, as the ruling of an individual as unfit to dive is costly to both the diver and the employer.

The exact prevalence of pulmonary bullae or blebs in the normal population is unknown because it is unacceptable ethically to expose healthy individuals to a dose of radiation without a medical indication. However, two such studies have been made in the diving population over the last 10 years and showed different incidences of blebs and bullae in divers. One study demonstrated a 13% occurrence of abnormalities such as blebs, bullae or air trapping in 330 French military divers,[12] while another found bullae or blebs in seven of 94 subjects (8%).[13] In a systemic bilateral thoracoscopic study, a third study reported the prevalence blebs to be 6% among young healthy individuals.[14] In addition, post-mortem HRCT of 130 subjects without a history of pulmonary diseases found small bullae in approximately 30% of the cohort.[15] This greater incidence is possibly related to a higher radiation dose that can be used post-mortem, as higher dose produces greater sensitivity for detecting smaller blebs and bullae.

In our study, we defined large lungs as 120% above the predicted value of the vital capacity, which was commonly used according to European Respiratory Society standards of that time. Of the divers screened, 24.6% (78 of 316) met this criterion, suggesting that large lungs may be more common in the diving population than the 'normal' population. These European Respiratory Society standards have been discussed extensively due to a lack of accuracy for ethnic groups other than Caucasian, African, and Asian populations. Therefore, in 2008, the Global Lung Initiative (GLI) was established by the European Respiratory Society and the American Thoracic Society to develop all-age reference equations with corrections for gender and ethnic background.[16] Consequently, the Diving Medical Center now uses the GLI-2012 reference values to increase accuracy and prevent medical investigations and/or incorrect assessments of fitness to dive.[17] This protocol has been approved and in use since 2015. Based on the GLI-2012 reference values, we expect to have fewer divers who are outside the 90%

Table 2
Demographic data; data are mean (standard deviation) for normally distributed data, and median (interquartile range) for non-normal data. HRCT – high resolution computed tomography; HRCT- – no CT anomaly; HRCT+ – CT anomaly

Parameter	Total group (*n* = 78)	HRCT– (*n* = 69)	HRCT+ (*n* = 9)	*P*
Age (y)	33.5 (29–45)	34 (29–45)	35 (11)	NS
Height (cm)	184 (7)	184 (7)	184 (5)	NS
Weight (kg)	89 (9)	89 (9)	87 (5)	NS
Smoking (%)	36	33	55	NS
Pack years smokers (y)	1.6 (2.9)	1.6 (3.0)	1.5 (2.3)	NS

Table 3
Lung function values derived from spirometry and body-box plethysmography; †*n* = 76; ‡*n* = 7 (2 missing); FEF – forced expiratory flow; FEV_1 – forced expiratory volume in 1 second; FVC – forced vital capacity; HRCT – high resolution computed tomography; HRCT- – no CT anomaly; HRCT+ – CT anomaly; PSF – peak expiratory flow; RV – residual volume; TLC – total lung capacity

Parameter	Total group (*n* = 78)	HRCT– (*n* = 69)	HRCT+ (*n* = 9)	*P*
FVC (L)	7.068 (0.725)	7.114 (0.719)	6.726 (0.717)	NS
FVC%	126 (121–134)	127 (121–135)	121 (120–124)	0.038
FEV_1 (L)	5.384 (0.561)	5.423 (0.555)	5.083 (0.545)	NS
FEV_1%	124 (8)	125 (8)	115 (7)	< 0.01
FEV_1/FVC (%)	76 (5)	77 (5)	76 (4)	NS
PEF (L)	12.4 (1.9)	12.5 (1.8)	11.1 (2.0)	0.039
PEF%	125 (16)	127 (15)	112 (19)	< 0.01
FEF25($L \cdot s^{-1}$)	9.75 (8.4–10.9)	9.9 (8.7–10.8)	9.2 (2.5)	NS
FEF25%	115 (22)	116 (21)	107 (29)	NS
FEF50 ($L \cdot s^{-1}$)	5.6 (4.9-6.4)	5.8 (1.3)	5.2 (1.0)	NS
FEF50%	104 (20)	106 (20)	94 (17)	NS
FEF75 ($L \cdot s^{-1}$)	2.15 (1.8–2.5)	2.3 (1.8–2.5)	1.9 (0.5)	NS
FEF75%	84 (74–100)	85 (76–102)	75 (15)	NS
TLC (L)	8.972 (0.982)†	9.018 (0.981)	8.521 (0.942)‡	NS
TLC%	118 (10)†	119 (10)	114 (106–125)‡	NS
RV (L)	1.936 (0.505)†	1.942 (0.482)	187.6 (0.747)‡	NS
RV%	92 (83–113.5)†	99 (22)	99 (43)‡	NS
RV/TLC	21.4 (4.3)†	21.4 (4.0)	21.6 (6.7)‡	NS

confidence intervals (z-score of 1.64) and therefore do not need additional screening (screening is a work in progress).

Recently, the Finnish Navy published a study on air trapping in 57 divers with large lungs (European Respiratory Society standards definition).[18] The amount of trapped air was calculated by subtracting the total lung capacity measured in a single-breath helium test from the total lung capacity in body plethysmography. In addition, extensive pulmonary function tests were performed including spirometry and airway resistance. They found that large lungs were associated with air trapping and concluded that this phenomenon could be disadvantageous for divers. However, they did not have any cases of pulmonary barotrauma in their population.[18] In our population, four of the nine cases with abnormalities had substantial air trapping; two of these were in the original pulmonary barotrauma case cohort and two were found during later screening.

In our recent follow-up studies based on these original data, we compared routine chest X-rays and HRCT findings in asymptomatic military divers.[17] We concluded that HRCT detects more abnormalities, but the relevance for fitness to dive is still open to discussion. Therefore, we advise currently that HRCT is performed only in divers with clinical indications, not in all with large lungs. Abnormalities such as blebs bullae or air trapping found either by initial examination or later in the career leads generally to unfitness to dive.[1,4,10]

Conclusions

This study showed that large lungs (as defined by the older European Respiratory Society criteria) do not have a higher incidence of the blebs, or bullae whose presence is thought to pose a higher physiological risk for pulmonary barotrauma in divers. To avoid unnecessary unfit to dive rulings, we suggest using the newer GLI reference values in current populations of divers for interpretation of spirometric data. This is expected to narrow the definition of abnormal lung function and thus reduce the number of individuals deemed to have large lungs. High resolution CT should only be performed in divers with a clinical history or abnormal pulmonary function.

References

1 British Thoracic Society Fitness to Dive Group. British Thoracic Society guidelines on respiratory aspects of fitness for diving. Thorax. 2003;58:3–13. doi:10.1136/thorax.58.1.3. PMID: 12511710. PMCID: PMC1746450.
2 Mitchell SJ, Bennett MH, Moon RE. Decompression sickness and arterial gas embolism. N Engl J Med. 2022;386(13):1254–64. doi: 10.1056/NEJMra2116554. PMID: 35353963.
3 Vann RD, Butler FK, Mitchell SJ, Moon RE. Decompression illness. Lancet. 2011;377(9760):153–64. doi: 10.1016/S0140-6736(10)61085-9. PMID: 21215883.
4 Health and Safety Executive. The medical examination and assessment of commercial divers (MA1, rev 5, 2023). [cited 2024 Mar 1]. Available from: https://www.hse.gov.uk/pubns/ma1.pdf.
5 Quanjer PH, Tammeling GJ, Cotes JE, Pedersen OF, Peslin R, Yernault JC. Lung volumes and forced ventilatory flows: report working party standardization of lung function tests, European Community for steel and coal. Official Statement of the European Respiratory Society. Eur Respir J Suppl. 1993;16:5–40. PMID: 8499054.
6 Adir Y, Shupak, Laor A, Weiler-Ravell D. Large lungs in divers: natural selection or a trainings effect? Chest. 2005;128:224–8. doi: 10.1378/chest.128.1.224. PMID: 16002939.
7 Crosbie WA, Reed JW, Clarke MC. Functional characteristics of the large lung found in commercial divers. J Appl Physiol Respir Environ Exerc Physiol. 1979;46:639–45. doi: 10.1152/jappl.1979.46.4.639. PMID: 457539.
8 Tetzlaff K, Thomas PS. Short- and long-term effects of diving on pulmonary function. Eur Respir Rev. 2017;26(143):160097. doi: 10.1183/16000617.0097-2016. PMID: 28356403.
9 Mets OM, van Hulst RA, Jacobs C, van Ginneken B, de Jong PA. Normal range of emphysema and air trapping on CT in young men. AJR Am J Roentgenol. 2012;199:336–40. doi: 10.2214/AJR.11.7808. PMID: 22826394.
10 Wendling J, Nome T. Medical assessment of working divers. Fitness to dive standards of European Diving Technology Committee.1st ed. Biele- Biene; hyperbaric edition. [cited 2024 Mar 1]. Available from: http://www.edtc.org/EDTC-fitnesstodivestandard-2003.pdf.
11 Lafère P, Germonpré P, Guerrero F, Marroni A, Balestra C. Decreased incidence of pulmonary barotrauma after discontinuation of emergency free ascent training. Aerosp. Med Hum Perform. 2018;89:816–21. doi: 10.3357/AMHP.5003.2018. PMID: 30126514.
12 Bonnemaison B, Castagna O, de Maistre S, Blatteau JÉ. Chest CT scan for the screening of air anomalies at risk of pulmonary barotrauma for the initial medical assessment of fitness to dive in a military population. Front Physiol. 2022;13:1005698. doi: 10.3389/fphys.2022.1005698.2022. PMID: 36277200. PMCID: PMC9585318.
13 Wingelaar TT, Bakker L, Nap FJ, van Ooij PJAM, Endert EL, van Hulst RA. Routine chest X-ray are inaccurate in detecting relevant intrapulmonary anomalies during medical assessments for fitness to dive. Front Physiol. 2021;11:613398. doi: 10.3389/fphys.2020.613398. PMID: 33488401. PMCID: PMC7816860.
14 Almajid FM, Aljehani YM, Alabkary S, Alsaif HS. The accuracy of computed tomography in detecting surgically resectable blebs or bullae in primary spontaneous pneumothorax. Radiol Med. 2019;124:833–7. doi: 10.1007/s11547-019-01044-6. PMID: 31134432.
15 de Bakker HM, Tijsterman M, de Bakker-Teunissen OJG, Soerdjbalie-Maikoe V, van Hulst RA, de Bakker BS. Prevalence of pulmonary bullae and blebs in postmortem CT imaging with potential implications for diving medicine. Chest. 2020;157:916–23. doi: 10.1016/j.chest.2019.11.008. PMID: 31759963.
16 Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. Eur Respir J. 2012;40:1324–43. doi: 10.1183/09031936.00080312. PMID: 22743675. PMCID: PMC3786581.
17 Wingelaar TT, Clarijs P, van Ooij PA, Koch DA, van Hulst RA. Modern assessment of pulmonary function in divers cannot rely on old reference values. Diving Hyperb Med. 2018;48(1):17–22. doi: 10.28920/dhm48.1.17-22. PMID: 29557097. PMCID: PMC6467825.
18 Wuorimaa T, Haukka J, Tikkinen J, Parkkola K, Piirilä P. Large lungs may predict increased air trapping in Navy divers. Physiol Rep. 2022;10(4):e15153. doi: 10.14814/phy2.15153. PMID: 35212176. PMCID: PMC8874342.

Conflicts of interest and funding: nil

Submitted: 4 March 2024
Accepted after revision: 7 June 2024