Spirometric indices and the risk of pulmonary barotrauma in submarine escape training

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Benton PJ, Francis TJR, Pethybridge RJ. Spirometric indices of the risk of pulmonary barotrauma in submarine escape training. Undersea Hyper Med 1999; 26(4):213–217.—Between 1975 and 1997, a total of 115,090 ascents, from depths of between 9 and 28 m, have been made by trainees at the submarine escape training tank HMS Dolphin. During this 22-yr period, 53 incidents have occurred in which, after an ascent, the trainee required hospital or recompression therapy or both. Scrutiny of the incident records revealed unequivocal evidence of pulmonary barotrauma in six incidents with an additional four in which, despite a negligible gas burden, a confident diagnosis of acute neurologic decompression illness with short latency could be made. No causative mechanism other than arterial gas embolism following pulmonary barotrauma can be implicated in these four cases despite the absence of clinical or radiographic evidence of lung injury. In all 10 cases the forced vital capacity (FVC) of the trainees was less than the predicted value for their age and height, revealing a statistically significant \( P < 0.01 \) association between values of FVC below predicted and pulmonary barotrauma. The median FEV, for the 10 cases was also significantly \( P < 0.05 \) less than the predicted value after allowing for age and height. No such association was found for the FEV,FVC ratio. FVC would thus seem to be the measure of lung function most closely associated with increased risk of pulmonary barotrauma. Possible reasons for this finding are discussed. It is concluded that although the association between low FVC and pulmonary barotrauma is statistically significant, it is insufficiently specific for low FVC to serve as an exclusion criterion for submarine escape training.

barotrauma, air embolism, decompression illness, submarine medicine, spirometry

The aim of this study was to determine whether simple spirometric values can be used to identify those individuals who are at increased risk of pulmonary barotrauma during submarine escape.

All Royal Navy submarines are fitted with an escape system which permits escape from a stricken submarine from depths of down to 180 meters of sea water (msw) (19 atm abs). The system comprises a single escape tower (SET), of which there is one in each escape compartment, into which the escapee climbs wearing a Submarine Escape Immersion Suit (SEIS). Once within the SET the escapee "plugs" a connector into a supply of compressed air, maintained at 2 atm abs above ambient pressure, which flows into a lifejacket built into the SEIS. Once fully inflated, overpressure relief valves in the lifejacket open, allowing air to ventilate the hood which encloses the head.

The SET is then flooded and the displaced air is vented into the submarine. The pressure within the SET remains at 1 atm abs until the water reaches the level of a vent pipe positioned approximately 70 cm below the level of the upper hatch. The vent is then closed and the pressure within the SET increases exponentially (doubling every 4 s) until it equals the ambient pressure outside the submarine. The top hatch, which is spring loaded, then opens and the escapee is released. With his head enclosed in a hood filled with breathable air the escapee ascends, breathing normally, to the surface at a rate of approximately 2.75 m \( \cdot \) s\(^{-1} \). There is an opening in the bottom of the hood through which the expanding air in the lifejacket and hood vent to the surrounding water during the ascent.

To instruct submariners in the use of the escape equipment, a SET was installed in the 28-m-deep submarine escape training tower at HMS Dolphin in 1966, the training tower having been originally constructed in 1954. The SET installed at HMS Dolphin is identical to those fitted to Royal Navy submarines, except for the addition of a blister on one side for an instructor who can control the rate of pressurization. The SET enables training ascents using SEIS from 28 m (3.8 atm abs) to be made. Instruction is also provided in the technique of buoyant escape during which a simple buoyancy aid fitted with an overpressure relief valve is worn. Buoyant ascents are made from 9 and 18 m (1.9 and 2.8 atm abs), a steady exhalation through pursed lips being maintained throughout the
ascent to minimize the risk of pulmonary overinflation. Before the introduction into service of the SET and SEIS, buoyant ascent was the primary system of escape. The technique is still taught today because it would be required in the unlikely event of the hood of a SEIS bursting during an ascent, or in an emergency rush escape during which there may be no time to don a SEIS.

Following a review of submarine escape training techniques in 1975, all trainees have undergone simple spirometry with values of forced vital capacity (FVC), forced expiratory volume in 1 s (FEV₁), age, and height recorded on a computer database. Between 1975 and 1982, initial trainees with an FEV₁:FVC ratio of less than 75% and requalifiers with an FEV₁:FVC ratio of less than 70% were excluded from training. From 1982 to the present time, trainees failing to meet these criteria have been referred to the pulmonary function laboratory at the Institute of Naval Medicine for full lung function testing. This includes provocation testing (by exercise), a bronchial challenge, and measurement of lung volumes (by helium dilution) and transfer factor (TLco using the single breath technique). Candidates are excluded from submarine escape training only if some significant abnormality in lung function is confirmed.

METHODS

We scrutinized reports of all incidents that occurred between 1975 and 1997 in which a trainee required hospital and/or recompression therapy after a through-water ascent to identify those in which there was unequivocal evidence of pulmonary barotrauma. This was defined as where there was x-ray and/or clinical evidence of pneumothorax or of extra-alveolar gas in the lung parenchyma, mediastinum, or other site to which gas may track.

Incidents in which a diagnosis of decompression illness (DCI) in the absence of evidence of pulmonary barotrauma could be made were also identified. For a diagnosis of DCI to be made there had to be hard neurologic signs (defined as loss of power, sensory change, impaired coordination, visual field loss, etc.) detected either before or during recompression therapy by personnel trained to perform neurologic examinations.

The values of FEV₁, FVC, and FEV₁:FVC recorded before the incident were then compared to predicted normal values for Royal Navy male non-smokers of the same age and height (1) (there were no female trainees in this period).

Statistics: Comparison between the recorded spirometric values and predicted values of cases was made by calculating the standardized residual of FEV₁, FVC, and FEV₁:FVC as follows:

\[
SR = \frac{\text{Observed} - \text{Predicted}}{\text{Standard Deviation (SD) about Predicted}}
\]

where SR is the standardized residual and the predicted values of FEV₁ (cm³), FVC (cm³), and FEV₁:FVC were calculated using Eqs. 2–4 (height in centimeters and age in years):

\[
\begin{align*}
\text{FEV}_1 &= -6037 + 53.65 \times (\text{height}) + 101.1 \times (\text{age}) - 2029 \times (\text{age}^2) \\
\text{FVC} &= -8590 + 69.98 \times (\text{height}) + 133.0 \times (\text{age}) - 2223 \times (\text{age}^2)
\end{align*}
\]

(2)

(3)

\[
\frac{\text{FEV}_1}{\text{FVC}} = 104.51 - 0.0776 \times (\text{height}) - 0.3322 \times (\text{age})
\]

(4)

(5)

The coefficients in the expressions are parameters of lung function derived from the mid-1980s study of 3788 Royal Navy submarine and diving candidates (1). The equations relate to male non-smokers.

The values of FEV₁, FVC, and FEV₁:FVC among male Royal Navy divers and submariners have been shown to be distributed normally (1). If the null hypothesis, that there is no association between values of FEV₁, FVC, FEV₁:FVC and pulmonary barotrauma after submarine escape training is to be supported, then the SR of FEV₁, FVC, and FEV₁:FVC should also be randomly distributed about the zero value.

RESULTS

Between 1975 and 1997, a total of 115,090 training ascents, 37,711 from the SET wearing SEIS (28 msw) and 77,380 buoyant ascents from the 9- and 18-m locks, have been completed (Table 1). During this period, 53 incidents have occurred in which the trainee required hospital or recompression therapy or both, with 27 incidents after SET ascents and 26 incidents after buoyant ascents from 9 and 18 m. Included in the total is a single fatality which occurred in 1995 after a SET ascent.

Scrutiny of the incident reports identified six cases, including the fatality, in which there was x-ray and/or clinical evidence of extra-alveolar gas. A post-incident chest x-ray of one of these cases revealed a number of well-defined cystic lesions of varying sizes in the right mid and lower zones (2). Thoracotomy, partial pleurectomy, and full pleurodesis were required because the right lung
would not remain inflated due to the presence of a bronchopleural fistula. At operation, the presence of multiple cysts within all three lobes of the right lung was confirmed. Retrospective assessment of the chest x-rays (inspiratory and expiratory views) taken before the ascent revealed distinct areas of low attenuation corresponding to the sites of some of the larger cysts. An additional four cases were identified in which, despite an insignificant inert gas burden (total time under pressure less than 60 s), signs and symptoms of acute neurologic DCI developed rapidly upon surfacing. It is difficult to conceive of a mechanism other than pulmonary barotrauma and arterial gas embolism in these cases. In one of these four cases, a 28-m SET ascent, the subject recalled “forgetting to breathe” during the first 5 m of the ascent, becoming aware of “tingling” in his left hand. Examination on the surface immediately before recompression revealed motor loss in his left hand and arm (2-5).

The SR of FEV₁ and FEV₁/FVC of these 10 cases were distributed about zero with seven negative and three positive values for FEV₁, (SR range -1.92 to 0.54) and five negative and five positive values for FEV₁/FVC (SR range -0.74 to 1.38). However, the SR of FVC for the 10 cases were all negative (SR range -2.01 to -0.40). In terms of original scales, the average residuals for FEV₁, FVC, and FEV₁/FVC for the 10 cases were -0.30 liter (range -0.93 to 0.26), -0.47 liter (range -1.09 to -0.22) and 1.7% (range -5.5% to 8.6%), respectively. Analyses of the SRs by the Wilcoxon test indicate that the median SR for FEV₁ is less than zero (P < 0.05; 1-sided test) and the median SR for FVC is less than zero (P < 0.01; 1-sided test).

In 14 of the remaining 43 incidents, a diagnosis of DCI with no evidence of pulmonary barotrauma was made. However, in these cases, although gas embolism following pulmonary barotrauma could not be definitely excluded, there was no clinical or x-ray evidence of extra-alveolar gas and the individual had a small, but possibly significant, gas burden (10–30 min under pressure at 1.9, 2.9, and 3.8 atm abs) and/or there was a long symptom onset latency (90–210 min from reaching the surface). Both of the individuals who developed symptoms after an ascent from 3.8 atm abs had completed an ascent from 1.9 atm abs (time under pressure 5–10 min) approximately 1 h before the incident ascent.

Scrutiny of the remaining 29 cases revealed a diagnosis other than DCI or pulmonary barotrauma. Included in this group were cases of alternobaric vertigo and simple syncope which, occurring after a rapid ascent in anxious individuals, were initially mistaken for DCI. The policy at the Submarine Escape Training Tower has always been to recompress trainees on the slightest suspicion of decompression illness. This policy, although admirable, has inevitably resulted in trainees being recompressed, and initially labeled as having suffered from DCI, when subsequent review has revealed otherwise.

The SRs of FEV₁, FVC, and FEV₁/FVC for the 14 cases of DCI without evidence of pulmonary barotrauma and for the 29 cases where a diagnosis other than DCI was thought most likely were randomly distributed about zero. The cumulative distributions of the SRs of FVC for the 10 cases of pulmonary barotrauma and 42 cases (another case had no predicted value) in which there was no evidence of pulmonary barotrauma are plotted in Fig. 1. While 27 (64%) of the 42 non-pulmonary barotrauma cases had negative FVC residuals, all 10 pulmonary barotrauma cases had negative residuals. The corresponding cumulative distributions of standardized residuals for FEV₁ and FEV₁/FVC showed only small differences between the pulmonary barotrauma and non-pulmonary barotrauma cases.

**DISCUSSION**

Submarine escape using SEIS and SET involves rapid compression followed by rapid decompression. This dive profile has been adopted to minimize inert gas uptake and thereby permit escapes, breathing air, from as deep as 180

<table>
<thead>
<tr>
<th>Depth of Ascent, m</th>
<th>No. Ascents</th>
<th>Pulmonary Barotrauma</th>
<th>DCI (no evidence of PBT)</th>
<th>Diagnosis other than DCI or PBT</th>
<th>Total No. Incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>58,116</td>
<td>1ª</td>
<td>3</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>18</td>
<td>19,263</td>
<td>3</td>
<td>9</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>28 (SET)</td>
<td>37,711</td>
<td>6ª</td>
<td>2</td>
<td>19</td>
<td>27</td>
</tr>
<tr>
<td>Total</td>
<td>115,090</td>
<td>10</td>
<td>14</td>
<td>29</td>
<td>53</td>
</tr>
</tbody>
</table>

*ª Cystic lesions noted in right lung post-incident. Scrutiny of chest x-ray taken before ascent confirmed presence of lung cysts.

*ª Includes single fatality.

**Table 1: Number of Trainee Ascents and Incidents 1975–1997**
FIG. 1—Cumulative distributions of SRs of FVC for PBT (10 cases) and non-pulmonary barotrauma (42 cases).

msw (19 atm abs), with little risk of DCI from dissolved gas. The 28 m (3.8 atm abs) training escapes carried out at the Submarine Escape Training Tank expose the trainee to pressure for less than 1 min, thus resulting in a negligible inert gas uptake. For this reason previous studies (3,4) have assumed that any neurologic signs or symptoms that occur after an ascent were due to arterial gas emboli secondary to pulmonary barotrauma. An earlier study (1) in which this assumption was also made reported an association between pulmonary barotrauma in submarine escape trainees and values of FVC lower than predicted.

However, the assumption that all neurologic signs and symptoms after an ascent are the result of arterial gas embolism may be invalid. Buoyant ascent training involves groups of up to 12 trainees being compressed to 9 or 18 m (1.9 or 2.8 atm abs) before making their ascents one at a time, with the final trainee being under pressure for approximately 10 min. During initial training, trainees carry out two 9- to 18-m (1.9 atm abs) and one 18- to 28-m (2.8 atm abs) buoyant ascent in a single morning and so can spend up to 30 min under pressure with three rapid decompressions. Even during hooded ascents from 28 m (3.8 atm abs), the time under pressure may exceed 4 min if the trainee has difficulty equalizing middle ear pressure and the compression rate has to be slowed. In such instances the inert gas burden cannot be assumed to be insignificant, and DCI as a result of bubble formation is a plausible differential diagnosis. Since this may result in short-latency neurologic manifestations (5), only cases in which there was indisputable evidence of lung rupture or a negligible inert gas burden were included in this study.

The review of submarine escape training in 1975 determined that airways obstruction was the most probable predisposing factor for pulmonary barotrauma. The lungs can tolerate an overpressure of about 70 mmHg (10 kPa) (6–8). This is equivalent to the pressure change that occurs in the last 1 m of a submarine escape profile, which occurs over a period of about 0.3 s when wearing a SEIS. Clearly, even minor degrees of obstruction to the egress of air, particularly close to the surface, could result in sufficient overpressure to cause the lung to rupture. In introducing a spirometric standard based on indices of obstruction, the intention was to exclude personnel with even minor, clinically insignificant airways obstruction.

Although the population of submariners undergoing SET from 1975–1982 was skewed with respect to obstructive spirometric indices (those who failed to meet the standard—about 12% of candidates—were excluded), this has not been the case over the subsequent 14 yr, with less than 2% of candidates for SET being excluded for abnormal pulmonary function.

That this study reveals a greater correlation ($P < 0.01$) between an index of restriction (FVC) and pulmonary barotrauma than between an index of obstruction (FEV₁, $P < 0.05$) is surprising and merits some analysis. The lung only ruptures when it exceeds its ability to stretch and it is thus vulnerable when its compliance is low. There is good evidence that decreased pulmonary distensibility is associated with pulmonary barotrauma in divers (9,10). In the normal respiratory cycle, the compliance of the lung is at its minimum at total lung capacity (TLC) (11). Once TLC has been reached, only the briefest voluntary or involuntary closure of the glottis, as might occur with a cough, hiccup or sneeze, is required to generate sufficient overpressure to rupture the lungs. Indeed, in one case there is evidence that the subject did hold his breath transiently during ascent.

This study reveals that individuals with "small for size" lungs are at increased risk of pulmonary barotrauma, suggesting that there may be subtle differences between such small-for-size lungs and small lungs that are appropriate for size. Perhaps individuals with small-for-size lungs maintain a proportionally larger functional residual capacity (FRC) and as such are closer to TLC at rest than the "normal" lung. An alternative explanation is based on the knowledge that a healthy lung, which is not restricted by the chest wall, can expand to a volume some 15% greater than TLC before reaching its elastic limit. Perhaps the small-for-size lung, contained within a normal size (or near-normal size) chest is able to expand past TLC during a rapid ascent and so ruptures more easily than the normal lung, which is prevented from expanding beyond TLC by an appropriately sized chest wall. Unfortunately, as only simple measures of lung function (FEV₁ and FVC) were
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recorded it is not possible to prove or disprove either of these theories from the data available.

The association between low FVC and pulmonary barotrauma is insufficiently robust to serve as an excluding criterion for SET training. If all potential trainees with an FVC below predicted had been excluded, this would have prevented 37 incidents (70%), including all 10 cases of pulmonary barotrauma, but at the unacceptable expense of excluding 50% of candidates from becoming submariners. Instead, since the beginning of 1996, all trainees with an FVC 2 SD, or greater, below predicted have been referred for lung function testing at the Institute of Naval Medicine. Since that time, six trainees have been referred on that basis, of which two were assessed as having a clinically significant abnormality in lung function and excluded from pressurized submarine escape. There have been no SET incidents since the adoption of this policy, although in view of the small numbers involved this cannot be considered significant.

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REFERENCES
