Arterial Gas Embolism Associated with Shallow Water Supplemental Emergency Breathing Device Training

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Case Report

Aviation Water Survival Training is an integral part of the initial and continuing aviation survival training provided to aviators, aircrew, and select non-aircrew personnel. This instruction routinely includes underwater egress training with the Supplemental Emergency Breathing Device (SEBD). The device is essentially a small SCUBA cylinder, designed to provide 1-3 minutes of compressed air breathing at ≤21 feet and improve the odds of aircrew survival during water landings. Over the past 5 years, the Aviation Survival Training Center, Pensacola, FL, has completed more than 27,000 SEBD training evolutions without significant adverse incident. However, in July 2008, a healthy 47-year-old female participating in SEBD indoctrination training altered this previously unblemished record of safety. While performing an underwater SEBD purge procedure, the trainee experienced sudden onset of 8/10-periorbital pain, photophobia and headache. Notably, her symptom onset occurred while breathing from the device in the training pool's shallow end, where the maximum water depth was 3.5 feet. Throughout the SEBD purging procedures, she remained in an upright position with her head never more than 6 inches below the water's surface. Immediately after onset of her symptoms, the patient was removed from the water. Within 20 minutes, she was noted to have developed right trigeminal nerve anesthesia and marked gait disturbances. Due to the antecedent use of a compressed air breathing device, arterial gas embolism (AGE) was suspected. Consequently, the trainee was transported to the Naval Operational Medicine Institute's recompression chamber for further evaluation and treatment. En route to the chamber, she developed intractable vomiting. On arrival at the chamber, the patient was unable to stand. Although her initial, poolside vital signs were normal, re-assessment at the chamber facility demonstrated progressive hypertension and marked bradycardia. Emergent recompression treatment on a US Navy Treatment Table 6 (TT6) was initiated. The compression phase of treatment was without signs of ear or sinus barotrauma and, prior to reaching the prescribed 60' treatment depth, the patient experienced complete relief of her nausea. Within two minutes of initiating oxygen treatment, the patient's headache and photophobia began to subside. After 10 minutes, neurological examination documented complete resolution of her trigeminal nerve anesthesia and objective improvement in her stance and balance. Vital signs taken at pressure demonstrated progressive normalization of the patient's blood pressure and resolution of her associated bradycardia. By completion of one treatment table extension at 60', the patient was without objective neurological abnormalities. Upon return to ambient pressure at the end of the treatment, the patient's only residual complaint was a mild, 2/10 frontal sinus pressure sensation. A head and sinus CT scan conducted immediately after recompression therapy completion was normal. Specifically, there was no evidence of sinus trauma or intracranial air. On follow up the next day, the patient was complaint free.

Pulmonary Overinflation Syndromes

Pulmonary overinflation syndromes (POIS) are a group of barotrauma-related diseases associated with overexpansion of the lung. Such overexpansion is typically due to either failure of expanding gas to escape from the lung during periods of decreasing ambient pressure, or direct exposure to excessive positive pressures. The US Navy Diving Manual delineates a number of diving-related causes of POIS. These include:

- Breath-holding during ascent,
- Rapid uncontrolled ascent (blow-up),
- Unconscious ascent,
- Air trapped in lung, and
- Inhaling while pushing the purge button on a regulator.

The first three causes represent circumstances in which either voluntary or involuntary closure of the glottis prevents the release of the expanding gas via the trachea. In the case of air trapping, gas expanding in accordance with Boyle's Law is still the culprit. However, the trapping occurs more proximally in the bronchiolar or alveolar tree and is generally due to underlying pulmonary disease (i.e. asthma, bronchitis, emphysema). In the fifth identified cause, the intrapulmonary pressure increases are due to pressure transmitted directly from the SCUBA second stage regulator to the lungs. Although no documented reports of such an event actually occurring could be found, the warning against inhaling while pushing the purge button on a single-hose regulator while taking a breath has been retained in the US Navy Diving Manual since at least the 1990's (Revisions 4 through 6). Such admonishment is likely warranted, however, since pulmonary over-pressurization injuries in the non-diving setting are well documented. In particular, barotrauma related to mechanical ventilation is known to occur in both adult and pediatric patients.

Regardless of specific POIS etiology, the common pathology is rupture of the alveolar sacs within the lung parenchyma and spillage of gas into the surrounding tissues. Whereas exposure to increased intrapulmonary pressure of 60 – 70 cm H_2O has been reported to be the upper limit of comfort in trained, healthy volunteers, alveolar rupture typically occurs after the differential pressure across the alveolar membrane reaches 95 - 110 cm H_2O. This corresponds to approximately 0.10 – 0.12 atmospheres, 70-90 mmHg or 3-4 feet of seawater. Once alveolar rupture occurs, the gas which accumulates in the pulmonary interstitium is then free to manifest as one or more of four clinical entities: mediastinal emphysema, subcutaneous emphysema, pneumothorax and arterial gas embolism (AGE).

AGE in the Diving Environment

The US Naval Safety Center data from '00 – '08 reports an AGE incidence of 0.11 per 1000 dives. While this number seems small, it represents approximately 24% of all reported injuries sustained by Navy divers during this period. From the civilian perspective, the Divers Alert Network (DAN) Annual Diving Report notes that AGE was identified as the etiology in 5 -18% (average ~8% annually) of diving-related deaths reported over the past 20 years. In both data sets, the most frequently reported antecedent cause was an inadequate or exhausted gas supply, precipitating rapid ascent by the diver. Of particular relevance to this study, only 10% of reported AGE fatalities occurred in depths < 30 meters.

AGE in the Pool Environment

Although an online diving medicine chat room discusses two recent cases of pool associated AGE involving SCUBA trainees with rapid ascents from 3m and 3.6m, respectively, published reports of AGE associated with swimming pool environment are rare. In 1995, Weiss and Van Meter reported two cases of AGE in SCUBA trainees previously diagnosed as asthmatic. Both events were associated with surfacing during the pool-training phase from depths in excess of 3.6m. A more systematic review of DAN's diving accident database revealed that only one case of pool associated AGE has been recorded since 1989. Again, this case involved an uncontrolled ascent from a depth in excess of 3m.

From the military's standpoint, it appears that AGE cases associated with pool evolutions are equally rare. Despite conducting over 7500 pool-based training dives per year, the Naval Diving and Salvage Training Center has reported only one case since 2001. In this instance, the individual made an uncontrolled ascent from a depth of 3.65m. Reporting perhaps the shallowest know case of ascent induced pulmonary barotrauma to date; Benton et al described an AGE that developed following a one meter ascent during helicopter escape training. This event represents the only previously published account of an AGE induced during pool-associated aviation survival training. While there are additional anecdotal reports of individuals developing AGE symptoms while using the Helicopter Emergency Egress Device System (an earlier version of the SEBD), these cases are described as breath-hold ascents from depths greater than one meter. In terms of the current SEBD device, the Naval Survival Training Institute's records reveal no documented cases of AGE with its use. Indeed, since its introduction of the SEBD five years ago, the second stage regulator of which is formally designated as the SEA LV-2 1.5, there have previously been no significant adverse events in over 27,000 in-water training uses of the device. Consequently, there remain no reports, to date, of an AGE documented as occurring in less than one meter of water.

Potential for Pulmonary Gas Expansion During SEBD Training

The paucity of AGE-related events in the Aviation Survival Training environment is not unexpected. The relatively shallow depths used during SEBD training helps limit the potential for Boyle's Law dependent, lung over pressurization. In this specific case, the maximum potential depth of the shallow portion of the training pool is 3.5 feet (1m). Although ascent from this depth is capable of generating the intrapulmonary pressures (i.e. 0.106 atmospheres or 80 mmHg) necessary to exceed the threshold for the development of AGE, the potential for adverse pressure change is further mitigated by the fact that trainees are required to assume an upright position in the water during initial instruction.

Figure 1 – SEBD Use Initial Training

With the trainee's head located no more than six inches below the surface of the water, the midpoint of the lungs lies at approximately 2-2.5 feet of depth, generating a potential pulmonary expansion pressure of only 0.061 – 0.076 atmospheres (46 - 58 mmHg). This is consistent with the previously demonstrated positive pressure breathing tolerance of trained aviators and well below the demonstrated differential pressure necessary to produce AGE in otherwise healthy adults. Consequently, in this particular case, a POIS mechanism associated with expansion of gas secondary to breath-hold ascent or trapping of gas (i.e. etiologies #1 - 4 of the USN Dive Manual) does not seemingly apply.

Potential for Positive Pressure Exposure During SEBD Training

Given the above theoretical findings, an alternative hypothesis of direct exposure to excess positive pressure had to be considered. Again based on the potential mechanisms delineated in the US Navy Diving Manual, inhalation from the second stage regulator while depressing the purge button was suspected. Indeed, such a mechanism is consistent with the fact that a regulator purge procedure was being performed at the time of patient symptom onset. Thus, after cursory analysis, positive pressure over pressurization would seem the most likely cause. However, two factors reduce the potential that this actually occurred. First, the conspicuous lack of confirmed reports of POIS injury occurring during purge procedures places this potential etiology squarely in the "possible" category. Second, virtually all second-stage regulators, including the SEBD's, are equipped with one or more exhaust ports designed to limit the generation of excessive mouthpiece pressures during normal operation. See figures 2,3(Part #18) & 4.

Figure 2 - SEBD Second Stage

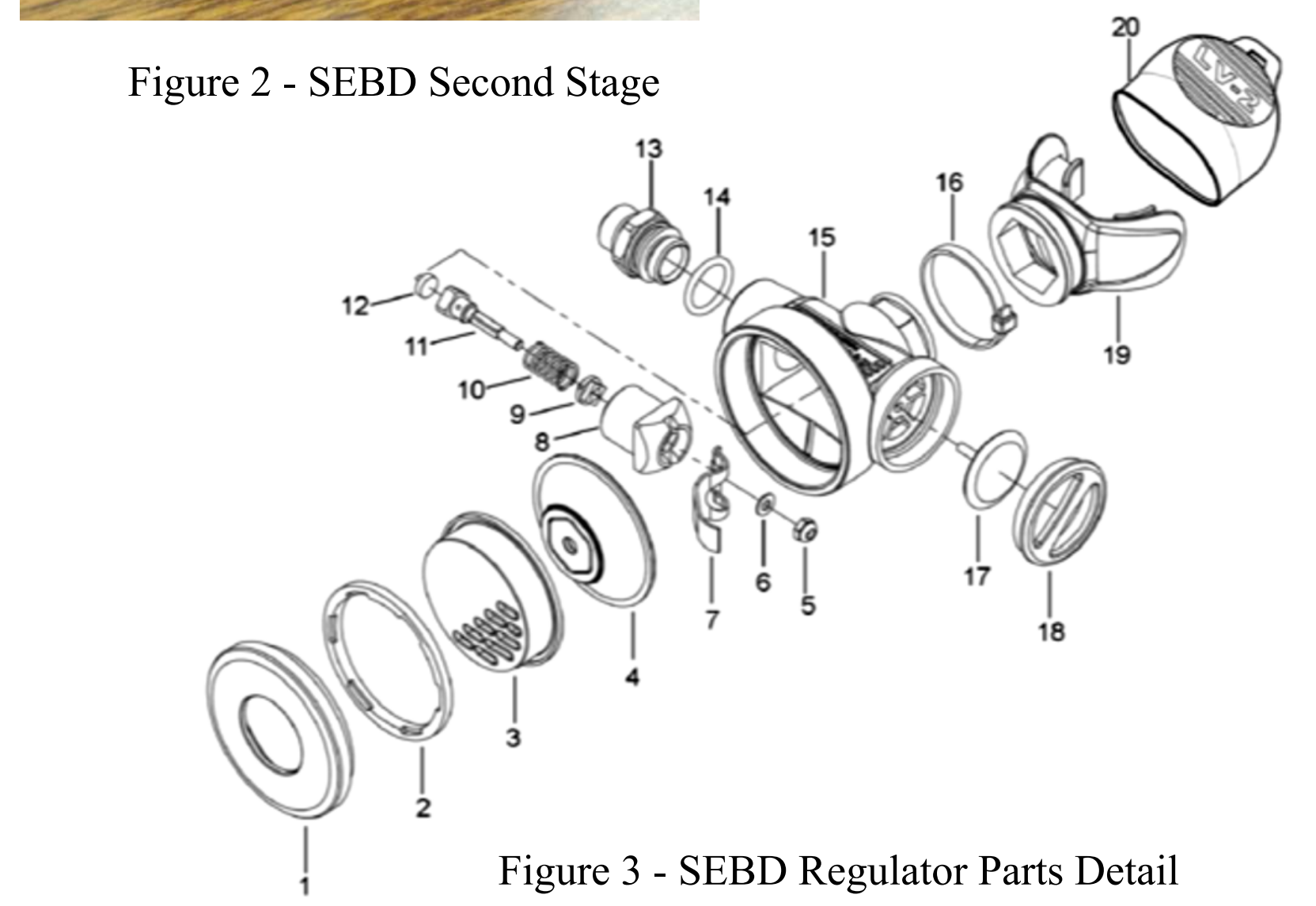

Figure 3 - SEBD Regulator Parts Detail

Figure 4 - Purge with Proper Hand Position

Figure 5 – Purge with Potentially Occluding Hand Position

Thus, we hypothesized that some form of SEBD malfunction or user error most likely occurred. Further evaluation of both the SEBD's design features and user interface procedures identified three potential causative factors:

- Inadequate design (volume / configuration) of the SEBD exhaust port, (i.e. Figure 3 –Parts #15 and #18)
- Failure / sticking of the exhaust port one-way valve (i.e. Figure 3 – Part #17), and
- User occlusion of the exhaust port. (Figure 5 – Purge with Potentially Occluding Hand Position)

SEBD Performance Evaluation

To test these hypotheses, the investigators performed repeated measures of SEBD mouthpiece outlet pressures during each of three, dry SEBD purging conditions:

- No obstruction of the exhaust port,
- Partial (bare thumb) occlusion of the exhaust port
- Complete (hand) occlusion of the exhaust port.

For each test, the SEBD regulator mouthpiece was connected directly to the pressure transducer of a U.S. Navy Model 3666 Automated Pressure Calibration System.

Figure 6 - Automated Pressure Calibration System

The purge button was then manually depressed to simulate a "free flowing" purge state. Three separate SEBD units were tested, with pressure readings measured in the "steady state" whenever possible. As a reference point, factory specifications for the first stage regulator's outlet pressure are 135 ± 20 psi. However, as second stage regulator performance is generally measured under vacuum induction conditions, the gas leaving the second stage regulator outlet is set to conform only to volume specifications. Thus, no factory specifications for second stage outlet pressure are available.

Condition	Free Flow	Partial Occlusion	Complete Occlusion
SEBD #1	0.475 PSIG	0.679 PSIG	23 (22-25) PSIG
SEBD #2	0.559 PSIG	1.884 PSIG	27 (20-35) PSIG
SEBD #3	0.628 PSIG	0.365 PSIG	27 (24-30) PSIG

SEBD Test Result Evaluation & Training Environment Relevance

Based on the above minimal pressure accumulation during non-occluded, free flow states (i.e. an average of 0.55 psi or 28 mmHg), there is no evidence to suggest that the exhaust aperture of the SEBD's second stage regulator is flow limiting under unobstructed use. Although degradation of the rubber, one-way exhaust diaphragm with concurrent generation of exhaust outflow obstruction could theoretically occur (i.e. secondary to dirt accumulation or recurrent pool chemical exposure), this is unlikely to occur in the training environment setting, as the diaphragms are routinely maintained and recurrent use would tend to unseat areas of valve adherence to the SEBD housing. That said, failure of the regulator's one-way exhaust diaphragm to unseat during a purge procedure would functionally replicate the completely occluded state.

In the partially occluded test configuration, the investigator's ungloved thumb was placed over the approximate center of the purge valve, allowing for air escape from the lateral margins on the exhaust outlet.

Figure 7 - Exhaust Partial Occlusion Ungloved

As anticipated, second stage outlet pressure measurements taken in this state were increased relative to the baseline, free flow state. Inherent variability in the percentage of exhaust port occlusion likely contributed to the wider range of recorded outlet pressures recorded under this condition. The average pressure generated again remained below that expected to produce an AGE (i.e. 0.976 psig or 50 mmHg). However, the upper range of pressure seen in this condition did cross the threshold for generation of pulmonary damage (1.884 psig or 97 mmHg). Although it not certain that this situation would be encountered outside of the laboratory setting, there is a potential that the degree of functional exhaust valve occlusion might be increased in the training or operational environment. Specifically, in both environments the aviators and aircrew wear gloves. The increased surface area of the glove relative to a bare hand would tend to increase the potential degree of exhaust port occlusion if a gloved thumb were to be placed over it.

Figure 8 - Exhaust Partial Occlusion Gloved

In the completely occluded state, the average "static state" pressure generated at the second stage mouthpiece outlet far exceeds that necessary to produce pulmonary injury (i.e. 25.66 psig or 1327 mmHg). It must be noted, however, that inducing a completely occluded state in the training or operational environment is extremely unlikely, as a considerable amount of deliberate effort on the investigators' part was necessary to achieve this state. Still, exhaust valve occlusion in excess of that produced by single digit occlusion could be anticipated if the user were to grasp the second stage regulator with both hands.

Figure 9 - Two-Hand Regulator Manipulation

In the training and operational setting, the potential for two-hand regulator manipulation is lessened by the egress-training mandate that one hand be used at all times to maintain a point of reference on the aircraft frame. Nevertheless, it is feasible that in the uncontrolled setting of an aircraft mishap that such attention to detail might be lost. Unfortunately, it is at this specific time that the aviators and aircrew are most vulnerable to sustaining a POIS injury.

Conclusions and Recommendations

This case is likely the first published report of an AGE sustained at a depth of less than one meter while using a self-contained underwater breathing device. To be certain, it represents the first serious injury associated with the training use of a SEBD. Rather than equipment malfunction, it is likely that the AGE documented in this case resulted from some degree of "user error." Specifically, partial occlusion of the SEBD exhaust valve cover during purge procedures likely resulted in excess accumulation of pressure at the regulator's mouthpiece. Subsequently, by either inhaling from the regulator during the purge or by allowing the pressure to accumulate against an open glottis, the patient exposed her lungs to this excess pressure, inducing the pulmonary injury and concomitant AGE. Despite this event, AGE remains a rarely encountered injury in a pool setting. In the modern military training environment, it appears to occur at a frequency of less than one event per 10,000 pool-training evolutions. This incidence is ten-fold less than that reported for operationally-associated AGE in Navy divers over the same time period. Consequently, as designed, the SEBD device should be considered sufficiently safe for continued use. However, if one were to employ the Navy's tradition of Operational Risk Management, it is reasonable to identify steps that might further mitigate such risk. With that in mind, the following recommendations are offered to reduce the risk of lung overpressurization during SEBD use:

- SEBD maintenance and operations check-list procedures should be reviewed to ensure that the one-way exhaust valve is in good repair and free from adherence to the second stage regulator's main housing body (i.e. Figure 4 – Parts #17 and #15, respectively)
- SEBD training should continue to emphasize single-hand manipulation of the second stage regulator and single finger, "closed-fist" operation of the purge button (i.e. Figure 3)
- Borrowing a page from NDSTC diver training book, aviator and aircrew safety might be further enhanced by teaching students to routinely occlude the regulator mouthpiece's orifice with the tongue while performing purge procedures
- To prophylax against exhaust port occlusion in the aircraft mishap setting, the SEA LV-2 exhaust port cover design (i.e. Figure 4 – Part #18) could be redesigned to add ports around the perimeter of the cover to allow exhaust to escape from sites other than the currently unitary exhaust port surface.
- Similarly, the SEA LV-2 exhaust cover could also be re-designed to incorporate a domed vs. flat configuration of its terminal exhaust port surface, thereby further limiting the potential for accidental manual occlusion of the orifice.

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