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A MEDICAL RISK ASSESSMENT OF PRESSURIZED SUBMARINE ESCAPE TRAINING

by

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SUMMARY PAGE

THE PROBLEM

NSMRL was tasked by CNO (N-879) to answer the specific question: "At what maximum depth of water could we realistically train students in submarine escape procedures and have a high level confidence for the safety of the student?"

METHOD

Reports of submarine escape training were reviewed and supplemented by obtaining updated information from several, cooperating nations.

FINDINGS

Hooded ascent appears to be the safest technique, with an incident rate of between 0.1 to 0.6 per 1000 escapes and a fatality rate 10 to 50 times lower. For each method of escape, there appears to be a trend toward a higher incidence rate with increasing depth.

ADMINISTRATIVE INFORMATION

The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. The work was carried out under Work Unit #63713N M00099.01A-5602, "Submarine Rescue and Escape." This report was approved for publication on 7 June 99 and designated as NSMRL Report 1212.

ABSTRACT

A review of the available literature on injuries attributed to pressurized submarine escape training was undertaken. Additionally, the most recent mortality and morbidity statistics from cooperating nations, which undertake pressurized escape training, was requested, collected and analyzed.

Currently, submarine escape training is undertaken in two ways: 1) buoyant ascent, in which a buoyancy aid is worn to assist the escaper to the surface and during which controlled exhalation is required to avoid pulmonary overinflation; and 2) hooded ascent, in which the escaper breathes normally from air retained in a hood worn over the head. The maximum safe depth of escape is constrained by the rate at which the central nervous system can clear nitrogen, which it has accumulated during the compression and early part of the ascent. For survivors in an unpressurized submarine, this depth has been demonstrated to be more than 500 feet (152.4m) of sea water. There appears to be a random component to the risk of pulmonary overinflation and, consequently, any form of pressurized training carries some risk of this condition.

Injury data were obtained from 11 nations that have conducted, or currently conduct, training from depths ranging from three to more than 100 feet (30.48m). Hooded ascent appears to be the safest technique, with an incident rate of between 0.1 to 0.6 per 1000 escapes and a fatality rate 10 to 50 times lower than that. For each method of escape, there appears to be a trend toward a higher incidence rate with increasing depth. The overall frequency of incidents and the risk of injury to an individual trainee will be reduced by limiting the number of training ascents that are conducted. Medical screening of escape training candidates, with particular reference to lung size, may further reduce the risk.

A MEDICAL RISK ASSESSMENT OF PRESSURIZED SUBMARINE ESCAPE TRAINING

This report was written in response to the question: "At what maximum depth of water could one realistically train students in submarine escape procedures and have a high level of confidence in the safety of the students?" The specification of maximum depth of water for realistic training was interpreted to include depths that have been used for that purpose, i.e., three to 100+ feet (0.91 to 30.48m). For "safety of the student," we took a broader view. We undertook to perform a quantitative risk assessment of medical hazards encountered in submarine escape training. We placed a very high premium on objective statistical summaries and theories with substantial support and sought to avoid opinion polling. We specifically avoided evaluating any of the positive benefits of the training as outside our charge. We also minimized any speculation on safety improvements for which at least some direct data are not available.

Quantitative risk assessment has matured beyond the use of frank opinion, and beyond the use of "conservative" quantities to predict whether a hazard is above or below an acceptable level. In favorable cases, it is possible to link equations representing the mechanistic events leading to a failure. Statistical distributions of possible values of important quantities are estimated from relevant theory and/or experiments. The distributions are mathematically combined to provide the risk manager with a continuum of possible outcomes, to allow that person to choose the case producing an acceptable probability of the undesired outcome. Such a process, with attention paid to explicit chances of bias and variability, has been endorsed by the U.S. National Academy of Sciences for adoption by Federal agencies whose resources for mitigating risk are not infinite (NRC, 1994).

As will be explained below, the major hazard associated with submarine escape training is arterial gas embolism (AGE), in which bubbles of air enter the arterial circulation via the pulmonary veins and are carried to vulnerable organs, the brain and the heart, via the cerebral or coronary arteries, respectively. These emboli initially occlude the circulation to these essential organs and subsequently initiate a complex inflammatory response resulting in tissue injury. Either of these may occasionally result in the death of the victim. The cardiac death is commonly immediate; death from brain injury may be delayed for a few hours.

Less serious injuries may also result from rapid changes in the volume of gas in other air containing organs and structures, e.g. ear drum rupture, facial sinus pain, and tooth pain. While these injuries may be painful (with appropriate management), they do not result in permanent disability.

At the outset of this project, we envisioned the "perfect" product, which is presented as a hypothetical graph in **Figure 1**. On the abscissa (X-axis) is plotted training depth, the focus of our specific question. On the ordinate (Y-axis) is incident risk, expanded logarithmically. We sought to generate the physical and biological functions relating those two to be well documented and plottable, based on sound statistical summaries. We were prepared for contradictory reports from different sources which could be plotted and which could provide a better basis for choosing specific training alternative procedures and equipment.

Hypothetical Risk Summary

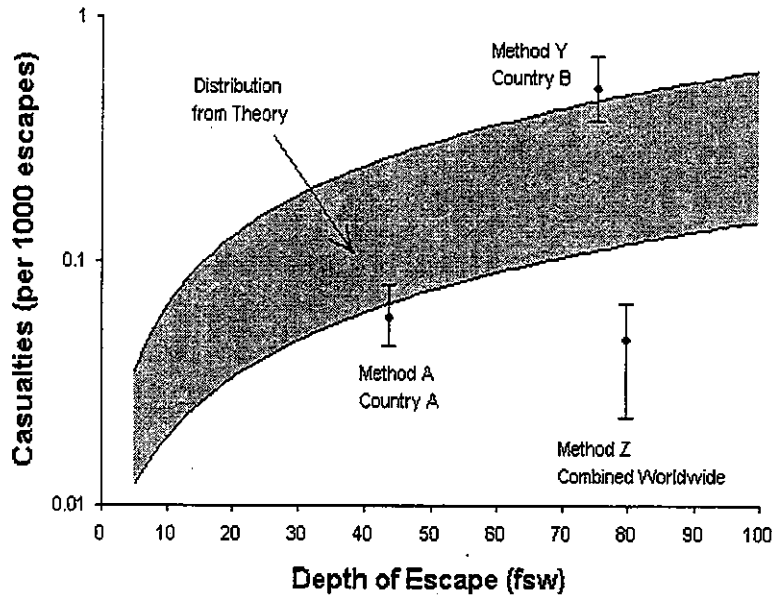


Figure 1. Hypothetical representation of "perfect" product based on a survey of the literature concerning injuries related to submarine escape training.

The Naval Submarine Medical Research Laboratory (NSMRL) was given a tight deadline to achieve the task and in the time available only a partial completion of this most desired product was achieved.

METHOD

We started by gathering technical reports from the NSMRL library. From cross-references, medical journal searches, and polling colleagues, we obtained many other references.

To gather current statistics, a two-page form was designed (Appendix A). It was distributed to nations at the April 1997 meeting of the NATO Submarine Escape and Rescue Working Party (SMERWP). A few additional countries received the form by FAX. Most countries were then contacted by telephone. Positive responses were received from Australia, Denmark, Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden, Turkey, and the United Kingdom. The individuals in each nation who provided information are cited in the

bibliography. Not surprisingly, most nations did not have sufficiently complete information for our purposes.

RESULTS

RISKS ASSOCIATED WITH SUBMARINE ESCAPE TRAINING

Minor Risks: This report does not attempt an exhaustive enumeration of the relatively minor risks that accompany virtually any human activity. Therefore, we omit consideration of scrapes from tripping on the stairs entering the training facility, transmission of a viral "cold" from a classmate, and were prepared to omit the occasional heart attack if it were not clearly a result of the training itself. The focus here is on substantial hazards which follow from water immersion and pressure.

Drowning. Perhaps surprisingly, drowning, a frequent and serious hazard associated with immersion in water in other circumstances, is essentially absent in submarine escape training. Presumed reasons, as explained below, are:

- a. during most of the evolution, air is naturally rushing out of the lungs, preventing the entry of water.
- b. the close supervision of trainees.

Decompression sickness. Another common concern in pressurized environments is decompression sickness. The maximum safe depth from which an escape can be made from a submarine is determined by the kinetics of inert gas uptake and release from body tissues. With increasing escape depth, tissues take up more inert gas (nitrogen) during the pressurization phase, bottom time and the early part of the decompression phase of an escape pressure profile. Most of this gas has to be removed during the remainder of the ascent to the surface if bubble formation and tissue injury are to be avoided. Extensive experience in the 1930s with the Submarine Escape Appliance documented the absence of decompression sickness even with exposures of many minutes duration at training depths to 100 feet and deeper (Shilling and Hawkins, 1936). More recent human observations document the absence of decompression problems, unless the escape depth is more than about 500 feet (Donald, 1970; Haydon and Fox, 1988).

Construction of a very deep facility is not anticipated, so concerns over decompression sickness are limited to one warning and one reassurance. The warning relates to instructor staff who might accumulate substantial time under pressure during repetitive dives in a busy day. Indeed, several escape training staff have probably suffered "the bends" (Benton, et al., 1994; Peirano, et al., 1955). The reassurance is that overall safety is not affected even if our assertion is wrong. Modern undersea medical guidance in diagnosis and management (Francis, et al., 1993) does not require differentiation between decompression sickness and gas embolism. Both receive the same initial treatment, i.e. prompt recompression, and that treatment is well over 90% effective for both conditions in the military setting (Gorman, et al., 1987).

Pulmonary Barotrauma. The major mechanism whereby a submariner may be injured during an escape is by pulmonary barotrauma (PBT). Although this injury can be inflicted deliberately (by the escaper holding his breath), in many instances the reason why PBT occurs remains elusive even after a detailed investigation.

Gas retained in hollow organs of the body obeys Boyle's Law during the pressure profile of a submarine escape. This means that the product of pressure and volume remains constant. Thus, as the pressure increases, the volume of each pocket of gas will decrease, and, during decompression as the submariner ascends to the surface, it will increase in volume. Taking a 10 ml pocket of gas in the bowel during an escape from 528 feet (160.93m) of sea water (17 atmospheres absolute) as an example. This gas will be compressed rapidly to one seventeenth of its volume (0.59 ml) during pressurization of the trunk and will gradually expand back to its original volume during the ascent to the surface. The relationship between pressure and volume in this example is shown in **Figure 2**.

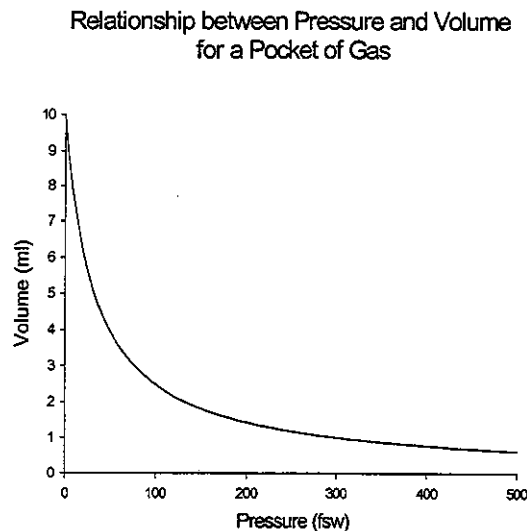


Figure 2. The inverse relationship between pressure and volume of a pocket of gas within the lungs is governed by the equation $PV = k$

No injury is caused to the bowel in this example because having a flexible wall, it is able to adjust to the changing volume of gas within it. The same principle applies to gas in the chest. However, in this case, the airways of the lung are open to the outside and the submariner is either able to breath during the escape (if a hood is worn over the head) or exhale during a buoyant ascent. During compression, if the submariner breathes normally, there will be little difference between the pressure inside the lung and that outside and the volume of the chest remains reasonably constant. In the same example, the chest will contain approximately seventeen times the number of gas molecules at the maximum depth of the escape as it did prior to pressurization.

During ascent to the surface, these additional molecules of gas have to leave the lung if there is to be no pressure differential across the chest wall. The rate at which gas has to leave the lung (the slope of the graph in Figure 2) is greatest near the surface (if ascent rate is linear; Benton et al 1994). If for any reason gas fails to leave the chest at the required rate, the pressure within the lung will exceed that outside, leading to overinflation of the lung. Eventually the elastic limit of the structural fibers of the lung will be exceeded, and the lung tissue will tear allowing the pressurized gas to escape.

Gas which escapes from the lung in these circumstances may migrate to a number of sites. The consequences of this migration depend upon the final destination and the route taken by the gas. This ranges from a trivial injury if the gas leaves the chest to reside under the skin of the neck to a life-threatening crisis if it enters the blood stream to form gas emboli which are then distributed to the brain or heart. The latter is referred to as arterial gas embolism.

A number of factors are known to be associated with PBT. These include: the rate of ascent (with rapid ascent being more hazardous); some pre-existing lung diseases (Liebow, et al., 1959; Saywell, 1989) and small lung size in relation to body size (Benton, et al., 1994). In divers, PBT is associated with open water rather than chamber dives, and inexperience and/or panic. Despite this, there remains a substantial number, perhaps even a majority, of cases for which no predisposing condition is identified. In other words, it is a condition which occasionally appears to happen by chance.

There are a limited number of measures which can be taken to reduce the risk of PBT in pressurized escape training. In the submarine escape scenario, a rapid ascent is required for the early part of the profile in order to limit the amount of gas taken up by the brain. A means of slowing the later ascent would be useful. However, at present no practical means of achieving this in open water has been developed. The medical screening of candidates for escape training should serve to reduce to a very small number the number of personnel who undertake escape training with a clinically detectable, pre-existing lung disease. The association between the incidence of PBT during submarine escape training and trainees with smaller than predicted lungs is sufficiently strong to recommend that those with a vital capacity more than two standard deviations below the predicted value should be excluded (Benton, et al., 1994). The provision of adequate classroom training before ascents are made should serve to reduce incidents associated with panic or inexperience. Nonetheless, it must be recognized that given the apparently stochastic nature of the condition, incidents will occur despite controlling, as well as possible, the factors which are known to be associated with PBT.

TYPES OF ESCAPE PROCEDURES AND EQUIPMENT

There are four procedures that differ by the extent of provision of additional buoyancy and breathing apparatus:

a. - Free (Naked). No special devices used. This crudest category is not preferred by any modern Navy, but is the method probably responsible for the largest number of survivors from actual wartime submarine escapes (Willmon, et al., 1951). Substantial effort is required by the

escaper to achieve a positive buoyancy by careful slow breath exhalation; and/or fighting a negative buoyancy by swimming. It has been noted that several percent of normal sailors are not positively buoyant - they will sink even with full lungs (Alvis, 1952). Disorientation from a sudden cold and dark immersion is said to make even choosing the direction of "up" a major problem (Willmon, et al., 1947). The US and other countries' navies still provide this training for their divers, especially Special Warfare Forces.

b. - Buoyant. Additional positive buoyancy is provided, commonly by an inflated life vest. Travel toward the surface is assured, but breath control is still crucially important. One report (Parker and Hall, 1970) states that a 300-400 feet per minute ascent rate can be attained with a buoyant life jacket. We note that many reports do not specify equipment sufficiently to conclude that positive buoyancy is assured. Also we find that when the term "free ascent" is used, sometimes it means naked and sometimes buoyant.

c. - Rebreathing. This term applies to use of a small air bag with inhalation and exhalation hoses, CO₂ scrubber, and an integral pressure relief valve. It allows the trainee to breathe in and out, which is considerably easier than mastery of controlled continuous exhalation. In the USN, rebreather-assisted ascent used the Submarine Escape Appliance, also called the Momsen Lung, or just the "lung" (Mankin, 1930). A similar device used in the UK was called the Davis appliance (Davis, 1951).

d. - Hooded. Currently considered the best apparatus. It is a combined breathable and buoyant hood or stole which covers the trainee's head and face. It allows regular breathing and vision and keeps water off the individual's face. In the US, the current design is called the Steinke hood (Bond, et al., 1960). In the UK, the Submarine Escape and Immersion Suit (SEIS), which has undergone several modifications, both provides for ascent, and for surface flotation and insulation (Baker, 1988). Ascent rates with these devices are speedy: measured ascent in the Steinke Hood is about 340 feet/minute (103.63m/min)(Bond, et al., 1960), and over 500 feet/minute (152.4m/min) in the Mark VIII SEIS (Haydon and Fox, 1988).

e. - Breath-hold. Not part of the regular escape curriculum, breath-hold diving is used extensively by training staff. The instructor inhales at the water surface then swims down to the escape trainee for various reasons. This avoids the need to worry about lung rupture for the staff, and usually (but not always) also avoids problems of decompression sickness (Paulev, 1965). We mention the practice here only as a reminder that staff injuries are complicated by numerous complex pressure exposures.

WORLDWIDE TRAINING PRACTICES AND EXPERIENCE

United States

The most extensive experience world-wide in terms of the number of training escapes performed is from US training facilities, especially the tank at SUBASE NLON. Formal training of large numbers started in 1930 (New London) and 1932 (Pearl Harbor). The only major technique initially presented was rebreathing (Momsen lung), until 1946 when free ascent was

also taught in large numbers until 1957. Buoyant escape (inflated life jacket) training started in 1956 (Bond, 1964) and continued thereafter. Steinke hood training went from 1963 until all training ceased in the 1970s. Current instruction in use of the Steinke hood only uses immersion to a depth of three feet (0.91m). Deeper facilities for instruction of free and buoyant ascent are available in Panama City, FL, and Coronado, CA, for divers; we do not have casualty records from those facilities.

Various statistical summaries of the data from New London are presented in Table 1. No records were available from Pearl Harbor. Breakdown by year does not follow a natural sequence in training changes, but corresponds to time periods covered by authors of various reports, whose presentation format do not match (Shilling, 1947 and 1979; Peirano, et al., 1955; Moses, 1964; VanGenderen, 1967; Neuman, 1974). Over 530,000 escapes were recorded with about 50 serious casualties and five deaths, but data have not been published in a manner that conveniently allows analysis for an effect of training depth (see Notes to Table 1). The several deaths which occurred outside New London (at Pearl Harbor and at sea) cannot be included in the statistical summaries at all, since we were unable to find the total numbers of training escapes made from these other locations, and, hence, cannot calculate an incidence rate.

Table 1
US Navy Experience (only SUBASE NLON)

	<u>Total Escapes</u>	<u>Serious Incidents</u>	<u>Rate</u> (per 1000)	<u>Deaths</u>	<u>Rate</u>
Submarine Escape Appliance (Momsen Lung)					
1930-1944					
18 ft (5.49m)	46,536	2	0.02	0	
50 ft (15.24m)	29,806	4	0.13	0	
100 ft (30.48m)	6,332	2	0.16	1	
All depths	82,674	8	0.07	1	0.012
1945-1957					
18 feet	41,000	0	0	0	
50 feet	41,000	3	0.07	0	
100 feet	41,000	2	0.05	0	
All depths	123,700	5	0.04	0	0
Entire period					
18 feet	88,000	2	0.02	0	
50 feet	71,000	7	0.10	0	
100 feet	46,000	4	0.09	0	
All depths	206,374	13	0.063	1	0.005
Free Ascent (Naked)					
1946-1957					
12-18 feet (3.66-5.49m)	8,200	0	0	0	0
35-50 feet (10.67-15.24m)	5,500	11	2.0	2	0.4
85-110 feet (25.91-33.53m)	2,700	3	0.9	0	0

All depths	16,397	13	0.8	2	0.12
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Table 1 (cont.)
US Navy Experience (only SUBASE NLON)

Buoyant Ascent (Life Jacket)

1956-1957					
All depths	6,555	3(all from 50 ft)	0.5	1	
1958-1966					
All depths	125,500	12(11 from 50 ft)	0.1	0	
1967-1973					
All depths	19,500	6	0.3	0	
Entire Period	151,600	21	0.14	1	

Hooded Ascent (Steinke hood)

1960-1966					
All depths	47,379	7(all from 50 ft)	0.1	0	
1967-1973					
All depths	14,293	5	0.3	0	
Entire Period	61,762	12	0.2	0	

Notes for Table 1:

For earliest data, Shilling (1947) lists the numbers trained with the Momsen lung at each depth for each year in New London (total of 82,674 escapes; Moses (1964) disagrees slightly). Thereafter, numbers for each depth were not reported. Based on case descriptions in Peirano et al (1955), Moses (1964), and Van Genderen (1967) the following appears to have been the depths (feet) used per trainee:

<u>Year</u>	<u>Momsen</u>	<u>Free</u>	<u>Buoyant</u>	<u>Hooded</u>
1947		12,12,18,18,35		
1948	18,18,50			
1950	18,50,100,100	18,18,18,50..		
1952	18,50,100	18,18,18,50,50..		
1953		18,35,50,50		
1954		12,18,50,100		
1955	18,50,100	18,18,50,50		
1957			18,50,50	
1960			50,50	
1961			50,85,85	
1964			50,50	50,50
1966			50,50	50,50

The following are mentioned in passing in reports:

1964		18,50,50	(Moses, 1964)
1967	All entries are for 50 feet		(VanGenderen, 1967)
<u>Notes for Table 1: (cont.)</u>			
1968		50,50	50 (James, 1968)
1970	(Rec. by Parker)	50,50,100	50,100
1974		50	50 (Neuman, 1974)

From this fragmentary information, we make the following assignments of depths assumed for escape ascents:

1945-1957	Momsen Lung: 1/3 from 18 feet, 1/3 from 50 feet, 1/3 from 100 feet
1946-1957	Free Ascent: 1/2 from 18 feet, 1/3 from 50 feet, 1/6 from 100 feet
1957-1966	Buoyant Ascent: 1/6 from 18 feet, 2/3 from 50 feet, 1/6 from 85-100 feet
1960-1966	Hooded Ascent: Nearly all from 50 feet

In the overall tabulation of numbers, we omit cases in training staff, and in the few others with a complex depth profile.

United Kingdom

The UK has a long-standing interest in submarine escape. Records on early training in rebreathing techniques using the Davis appliance have not been located. Since 1954, British (and some other nations') submariners have trained at the Submarine Escape Training Tank at HMS DOLPHIN (Benton, et al., 1994). The sequence of escapes has varied somewhat over time. From 1954-1962, a 15 foot (4.57m) free (no artificial buoyancy) ascent was used. From 1954, a buoyant escape using an "inflatable stole" (similar to the US life jacket) was conducted from 30, 60, and 100 feet (9.14, 18.29 and 30.48m). The 100 foot step was eliminated in 1975, but trainees still perform one or two free ascents from the shallower depths. Escape from 95 feet (28.96m) wearing a full SEIS hooded suit started in 1966 and continues today. Changes in the number and order of the various techniques and depths have occurred as well.

Two major reviews (Pethybridge and Pearson, 1985; Benton, et al., 1994), and a current update (UK, 1997) present incident statistics. All told, nearly 300,000 escapes have been conducted producing about 150 casualties and five trainee deaths. Numbers of casualties in summary tables differ between the two major reports due to differing diagnostic criteria - we present the more recent tabulation in **Table 2**. It should be noted that these data are inclusive and not limited to decompression-related injuries. This choice acknowledges that not all of the data presented will be comparable, since we have not reviewed every case from the US and elsewhere to ensure full consistency with the 1994 UK standards. Training staff casualties are omitted from the detailed breakdown, but they are real, amounting to 24 incidents including one fatality.

Table 2
UK Royal Navy Experience (only HMS DOLPHIN)

Buoyant Ascent	Total Escapes	Serious Incidents (per 1000)	Rate	Deaths
1954-1974				
30 feet (9.14m)	76,421	24	0.3	1
60 feet (18.28m)	44,632	16	0.4	0
100 feet (30.48m)	27,402	52	1.9	1
1975-1995				
30 feet	55,459	7	0.1	0
60 feet	18,540	17	0.9	0
Entire Period				
30 feet	131,880	31	0.24	1
60 feet	63,172	33	0.52	0
100 feet	27,402	52	1.9	1
All depths	222,454	116	0.52	2
Hooded Ascent (SEIS)				
1966-1974				
95 ft (28.96m)	24,195	12	0.5	2
1975-1995				
95 ft	35,928	27	0.8	1
Entire Period	60,123	39	0.65	3

Note: Uses injury criteria of Benton et al. (1994) updated by UK (1997). Initial trainees and requalifiers are combined, but injuries to instructors are excluded, since their exposure history is usually much more complex.

Other countries

Australia

In 1988, Australia opened a training facility patterned after the British system. The full description of their experience has not been published, but some data were made available to us (AUS, 1997). Free ascent is only taught to instructors; prior to 1995 trainees performed:

- a. Two buoyant ascents from 9m (29.53 feet) wearing the Submarine Escape Jerkin (SEJ).

- b. One buoyant ascent from 22m (72.18 feet) wearing the SEJ.
- c. One hooded ascent (compartment escape) from 22m.
- d. Two hooded ascents from 22m.

Since 1995 trainees perform:

- a. Two buoyant ascents from 9m wearing the SEJ.
- b. No buoyant ascents from 22m.
- c. No hooded (compartment escapes) from 22m.
- d. Two hooded ascents from 22m.

Through late 1995, 13 incidents had occurred in 821 trainees who had performed about 4000 escapes (a relatively high rate of about 3.0 incidents/1000 escapes). Not enough data was provided to estimate the effect of depth. Another 15 incidents were recorded among training staff, spread over an unknown number of exposures. Procedural steps were undertaken in 1995 to avoid the unusually high ratio of staff to trainee incidents.

Denmark

Denmark sends about 30 submarine trainees per year to Sweden for free, buoyant, and hooded (SEIS) ascent training (DEN, 1997).

Germany

Germany's submarine escape training reflects the fact that they operate single compartment submarines without escape trunks so that individual (hooded) escape is not possible. Their training is limited to buoyant ascent using a buoyant collar (URK-80) said to be similar to the one on a Steinke Hood. Starting in 1973, training depths have been 33, 66, and 98 feet (10.06, 20.12 and 29.87m); but the deeper depths were discontinued in the early 1990s. No published report is available, but notes from a 1996 seminar indicate an incident rate of 9/7,020 from 98 feet; 5/21,060 from 66 feet; one (from 18) out of a combined 42,120 from 18 and 33 feet. Instructors accounted for almost 1/5 of the victims. All casualties fully recovered (GER, 1997).

Japan

Japan has trained submariners in buoyant and hooded (Steinke) ascents since 1973 (Ikeda and Oiwa, 1994; JPN, 1997). The buoyant ascents are from three feet (0.91m), twice, and 10 feet (3.048m), once, using a life jacket. Two hooded ascents are made from 33 feet (10.06m) but, unlike US practice, the trainee spends several seconds at the bottom before ascending. A diver accompanies the trainee the entire trip, and the ascent rate is slowed to about 200 feet/min (60.96m/min). No incidents of barotrauma were reported in 14,798 Steinke hood ascents (Ikeda and Oiwa, 1994), and none are said to have occurred since (JPN, 1997).

The Netherlands

The Netherlands has had submarine escape training since about 1982. Approximately 130 submariners are trained per year in both naked and buoyant escape from 80 feet (24.38m)

and hooded (SEIS) from 100 feet (30.48m). In a recent conversation, the only incident disclosed was a successfully treated gas embolism from about 20 years ago (NETH, 1997).

Norway

Norway has a small escape training program which trains approximately 110 submariners/year and 100 divers. In addition, 30 civilian divers are trained and 50 Dutch submariners. Training began in 1962 and involves two buoyant ascents from 33 feet (10.06m) and 66 feet (20.12m) and a 66 foot hooded ascent (SEIS). Additionally, a small number of ascents are made each year from an actual submarine at about 33 feet. There are about two recompression-requiring incidents per year, and one death occurred in 1977 from AGE following a 33 foot buoyant ascent (NOR, 1997).

Spain

Spain's escape training program started in 1996, and uses hooded escape from 33 feet (10.06m). No more details were provided (ESP, 1997).

Sweden

Sweden has a long history of escape training. From 1944 to the mid 1960s, rebreathing ascent using the Davis appliance was used from 70 feet (21.34m). Hooded ascent training started in 1967, and since 1986 has employed a variant of the UK SEIS from a single escape tower located below 75 feet (22.86m) of water. In the early 1970s, free ascent consisted of a progression of depths: 5, 16, 33, 57, 60 feet (1.52, 4.88, 10.06, 17.37, 18.29m) (Ingvar, et al., 1973). About 350 submariners are trained in a year (since 1990), along with a larger number of divers which use the same facility. Much of the recent human physiology studies on escape have also occurred there (Ingvar, et al., 1973; Linnarsson, et al., 1993; Gennser, et al., 1995). Detailed incident statistics are not available, but no pulmonary barotrauma has been reported in submarine hooded escape training. More casualties, including two deaths, occurred in diver free ascent training (SWE, 1997). A death from AGE occurred recently, and further details are awaited.

Turkey

Turkey has trained about 800 men per year in escape since 1977; buoyant escape from 30 and 60 feet (9.14 and 18.29m) and hooded (Steinke) from 60 feet. No incidents are reported in about 21,000 escapes (TUR, 1997).

ANALYSIS

In the following section we compare and combine observations in an attempt to identify a technique and depth effect. For most of the countries, the data are not useable, since we have no information on the proportion of total ascents performed at each depth. When considered reasonable, an estimate is made.

Effect of technique

In the data reviewed above, rates are seen to span at least two orders of magnitude from below 0.1 per thousand to over 10 per thousand. The most important factor seems to be the equipment/techniques used. Free (naked) ascent has a higher risk than other forms. This difference was observed in single facilities using different training modalities, and across programs. Buoyant ascent with an inflated vest is slightly safer. Allowing the trainee to breathe (in as well as out) using a rebreather or a hood appears safer than the exhale-only techniques.

Effect of depth

In rebreathing ascent, a definite depth effect can be seen in the US data (Table 1). Both in the precise data from 1930-1944 and in the less precise 1945-1957 data, escape from 18 feet (5.49m) is seen as safer than from a deeper depth. No safety difference can be discerned in rebreathing ascent between 50 and 100 feet (15.24 and 30.48m). Both these conclusions pass a Chi-square test at $p < .05$, but our estimation of how many escapes were from each depth makes literal acceptance of that test statistically foolish.

A similar definite depth effect is seen in free (naked) escape in the US data. The uncertainty in depth assignment makes comparison of 50 feet and 100 feet incidence problematic. However, in the roughly equal number of "shallow" (12-18 feet) (3.66-5.49m) and "deep" ascents (about 8000 each), the observation of no shallow casualties vs. 14 deep casualties is definitely non-random.

There exists no good data base of the outcome of buoyant and hooded ascent training in the US. It appears from Table 1 that most ascents in NLON for both types of ascent occurred from 50 feet (15.24m), but several tabular entries in the cited reports indicate that not all were. The great majority of casualties occurred on 50 foot runs, but no meaningful depth relationship can be established.

The UK data (Table 2) does provide useful information regarding safety vs. depth of buoyant ascent. The substantially higher injury rate associated with ascents from 100 feet compared to those from the two shallower depths was observed, resulting in the discontinuation of the deepest run in 1974. Since then the data from 30 and 60 feet (9.14 and 18.29m) training depths show a convincingly better safety record for 30 feet ascents over the whole period. The raw incidence difference between ascents from 30 and 66 feet (9.14 and 20.12m) is statistically significant (p about .05). The British reports discuss several factors, other than depth, that bear on interpretation of the safety records.

Data from Germany support the depth dependence in buoyant ascent. Assuming that their shallow training is equally divided between 18 and 33 feet (5.49 and 10.06m), the following rough incidence rates can be calculated:

18 feet: $0/21,000 = 0.0$ Per 1000
(95% c.i.: 0 to 0.15 per 1000)
33 feet: $1/21,000 = 0.05$ Per 1000
(c.i.: < 0.1 to 0.25 per 1000)
66 feet: $5/21,000 = 0.25$ Per 1000

(c.i: 0.1 to 0.5 per 1000)
 98 feet: $9/7,000 = 1.3$ Per 1000
 (c.i.: 0.4 to 2 per 1000)

where c.i. represents confidence intervals.

(18 feet = 5.49 m, 33 feet = 10.06 m, 66 feet = 20.12 m and 98 feet = 29.87 m).

All estimates of buoyant ascent incident rates are plotted in **Figure 3** and labeled by country of origin. Error bars are approximately one SE, so overlap of bars can be interpreted as failing to support a statistically significant difference.



Figure 3. Graphical representation of various reported incident rates (+/- 1 SD) associated with depth from which submarine escape training is conducted. UK refers to reports from the Royal Navy, US refers to reports from the U.S. Navy, and GER refers to reports from the German Navy.

No training facility has conducted a large number of hooded ascents at more than a single depth. Therefore, the most direct comparison of safety versus depth is unavailable. Even comparing across nations, SEIS training facilities in UK, Sweden, and Australia use depths not very different from each other (95, 75, 73 feet, respectively) (28.96, 22.86 and 22.25m). (Swedish incidence is estimated as 0 incidents in 2000 escapes.) For Steinke hood use, data from Turkey is too sparse, and their training depth of 60 feet (18.29m) is so close to NLON's 50 feet (15.24m) that other differences in training would mask any depth effect. (Turkey's rate is taken as 0 incidents in 7000 escapes). Japan, however, has used 33 feet (10.06m) with no reported casualties in about 15,000 escapes (a raw incidence of 0 to 0.2 per 1000 at approximate 95% confidence limits). That incidence is probably lower (p between 0.03 and 0.07) than the NLON

overall rate of 12 casualties in over 60,000 escapes (mostly from 50 feet). Considering the myriad of variables between the two facilities, we view this "depth effect" as somewhere between intriguing and convincing.

All estimated incidence rates for hooded escape are plotted in **Figure 4**, with the same conventions as in Figure 3, but with an expanded ordinate axis, since overall hazard is lower than buoyant ascent.

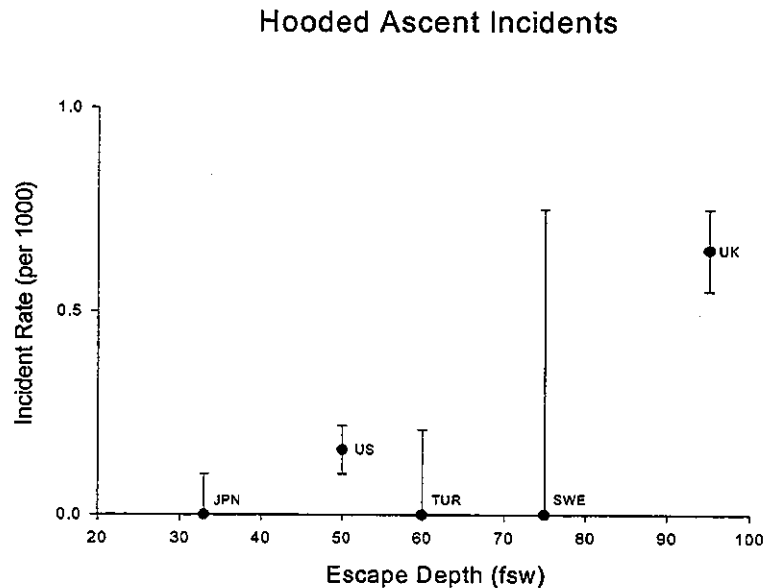


Figure 4. Graphical representation of reported incident rates (± 1 SD) while using hooded ascent from various depths during submarine escape training. UK refers to reports from the Royal Navy, US to the U.S. Navy, JPN to the Japanese Navy, TUR to the Turkish Navy, and SWE to the Swedish Navy.

The death rate versus training depth for buoyant and hooded ascents are shown in **Table 3**. Because the number of deaths is small, there is no statistically significant relationship between depth and death, or difference in the death rates of the countries shown.

Sources of Uncertainty in This Assessment.

Compared to environmental questions, this risk assessment is overflowing with data. The mechanism of serious injury has been qualitatively understood for decades, and direct animal experiments have established cause and effect. Moreover, there is a substantial data base of well controlled human experience. Rather than wondering about orders of magnitude, serious questions can be probably answered to within a factor of two or three.

The raw statistical variability caused by a binomial event (incident or no-incident) is dealt with most easily. In this low incidence range with 10 or more cases per category, the standard deviation of the number of "hits" is approximately the square root of the number of "hits". Thus,

for example, 16 casualties in 40,000 ascents (point estimate of incidence 0.4 per 1000) has one SD limits of 12 and 20 casualties, for a 66% confidence band on incidence of 0.3 to 0.5 per 1000. Therefore the approximate 95% confidence band is 0.2 to 0.6 per 1000. Other uncertainties exist. Data collected in several countries over five decades will have some recording error. We had to make some educated guesses as to how many escapes occurred from which depths. In addition to conscious differences in diagnosis, standards tend to change over time, and this report has data collected over a 60 year period.

Table 3

Reported rates of death associated with various depths used in buoyant and hooded escape training. The data are presented as deaths per total escape evolutions.

<u>Death Rates</u>				
Depth (fsw)	Buoyant Escape		Hooded Escape	
3 (0.91m)	0/14,798	Japan		
10 (3.05m)	0/7,399	Japan		
18 (5.49m)	0/21,060	Germany		
30 (9.14m)	0/14,000	Turkey		
	1/131,880	United Kingdom		
33 (10.06m)	1/19,720	Norway/Netherlands	0/14,798	Japan
	1/21,060	Germany		
	0/7,400	Japan		
50 (15.24m)	0/2274	Australia	0/61,762	United States
	1/101,000	United States		
60 (18.29m)	0/63,172	United Kingdom	0/7,000	Turkey
	0/14,000	Turkey		
66 (20.12m)	0/19,720	Norway/Netherlands		
	0/21,060	Germany		
73 (22.25m)	0/821	Australia	0/4359	Australia
92 (28.04m)			3/60,123	United Kingdom
98 (29.87m)	0/7,020	Germany		
100 (30.48m)	1/27,402	United Kingdom		
114 (34.75m)			0/2450	Sweden
Totals:	5/499,986		3/153,092	

DISCUSSION

Given the brief time period in which data could be collected, it was apparent that a study of original case reports would not be possible and that this report would have to rely on statistics compiled by the nations which were prepared to provide data. This has served to limit the amount of data available for study because not all the nations have collected information on submarine escape training incidents. The time to acquire adequate data was further shortened by the requirement to direct our inquiry through the appropriate diplomatic channels.

In this analysis we have had to rely on the definition of "incident" employed by the author of each report. The data analyzed in this report spans a considerable time period (1930 - present day) during which the principles and practice of diving and submarine medicine as well as occupational health and safety practices have evolved considerably. An event which today in the UK might be described as an "incident" and be classified as "mediastinal emphysema" may not have been treated in the same way in the US in 1940. Because of the wide diversity of diagnostic standards and terminology, no attempt has been made to classify the incidents on the basis of the likely injury which the trainee sustained.

We considered using information on the use of recompression therapy as an index of the severity of an incident, but chose not to attempt this analysis. A previous study from the UK (Benton, et. al., 1994) highlighted that recompression therapy has not been applied consistently. Although casualties with an indication for recompression by modern standards have occasionally been denied in earlier times (Peirano, et. al., 1955), more frequent instances have arisen where scrutiny of the case report has failed to identify an indication for returning the trainee to pressure. In other words, they were recompressed for no obvious reason. Equally, recompression is not indicated for two serious and potentially life-threatening complications of pulmonary barotrauma which involve collapse of the lung (bilateral and tension pneumothorax). We concluded that whether or not a casualty was recompressed represented a poor index of the severity of the incident.

An end-point for which the diagnostic standard has not changed over the period under study and which is undoubtedly associated with the severity of the injury is the death of the casualty. Because this is a relatively rare event in submarine escape training, the mortality statistics have wide confidence intervals. In contrast, the greater number of incidents provide a more precise estimate of 'morbidity' associated with escape training although it is less precisely defined. It is the experience in the UK and US that an overwhelming proportion of those who survive an incident return to full duty. The morbidity reflected in the incidence data is, therefore, temporary.

Risk of submarine escape training:

Training in escape from a disabled submarine carries real risk. The data show that a serious incident (lung rupture with evidence of gas embolism to the brain) can be expected in 0.1 to one per 1000 ascents. Of those with a serious incident, between 1% and 10% will probably

die despite the best available treatment. There is a substantial random component to the incidence of pulmonary barotrauma such that we cannot predict very well when an incident or death will occur. In both Figures 3 and 4, the UK incidence rates appear to be significantly higher than for other nations. This does not necessarily mean that UK training is intrinsically more risky. It may reflect the quality and inclusive nature of their record-keeping.

Risk versus technique:

The various types of escape training procedures do not have equal risk. Free ascent training (no equipment) is more hazardous than buoyant ascent (using a life jacket). Use of rebreathing apparatus, e.g. Momsen lung, is even safer. Modern hooded escape devices (e.g. Steinke hood or the UK SEIS) provide a measure of safety over free or buoyant techniques. Differences in specific training techniques over time and among different facilities appear to be important for reasons that we do not understand.

Risk versus depth:

The depth of water from which the training ascent is made appears to be important, but less so than technique. For each technique analyzed, there was a progressive increase in hazard with depth. The trend is noticeable over the well documented range of about 30 to 100 feet (9.14 to 30.48m), but we do not have data to show trends in the shallow portions. Use of a 10 foot (3.05m) depth may be safer than 30 feet, but we cannot prove it. Even *very shallow conditions are not completely safe*, as a serious incident has been documented from a depth of only three feet (0.91m) (Benton, et al., 1996).

Some practices can mitigate the risk. As each ascent appears to have a finite degree of associated risk, an obvious way would be to limit the total number of escapes done per trainee. Intrinsic variability keeps a man at risk, even when he has had previous successful experiences. More incidents will occur per year if a training cycle is five ascents per trainee than if it is a single ascent. Repetitive exposure is even more of a factor in incidents among training staff.

Screening can remove some men at higher risk before the exposure occurs. Attention to lung X-rays and pulmonary function can guard against the otherwise innocuous lung disease that has been seen in some fatalities (Liebow, et. al., 1959; Saywell, 1989). However, screening is far from 100% effective: the UK estimates that only about 20% of their serious casualties could have been avoided by pulmonary function screening. Since avoiding injury requires the trainee to breathe in an unusual manner in a hostile environment, psychological factors are very important, but are beyond the scope of this report.

The hazards discussed in this report relate directly to the "realism" desirable in a training environment. In all programs we have reviewed, some aspects of realism have been deliberately avoided. Nobody trains in the dark, in cold water, or uses air with elevated levels of carbon dioxide and other contaminants. Nobody ascends "alone". Indeed, constant instructor surveillance and intervention undoubtedly prevents a much higher incident rate.

Selection of training depth seems to provide only a minor component of "realism." Deeper escapes take longer for the trainee to reach the surface. However, the maximum risk is nearest to the surface. The ascent time also depends on velocity through the water, but with hooded escape terminal velocity is largely fixed by geometry of the hood itself. Deeper training can ensure that the trainee actually accelerates to full terminal velocity, but it is uncertain whether that is an important perception for training purposes.

CONCLUSIONS

1. There is a substantial random component to the incidence of pulmonary barotrauma in pressurized submarine escape training, which means that there is no completely safe training depth.
2. Hooded ascent is safer than buoyant ascent.
3. There is a general trend to higher incident rates with deeper escape depth.
4. The overall frequency of incidents and the risk of injury to an individual trainee will be reduced by limiting the number of training ascents which are conducted. This will also serve to reduce the frequency of incidents in trainers.
5. Medical screening of escape training candidates, with particular reference to lung size, may further reduce the risk.

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