REVIEW OF UNDERWATER BLAST SAFETY CRITERIA

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ABSTRACT

Health and safety considerations are paramount to the protection of human bodies underwater, especially in the vicinity of underwater explosions. Experiments involving animals and humans have been conducted in several countries to support the development of underwater blast safety data. However, this field remains less extensively studied compared to air blast safety. While studies are still ongoing, it is critical to stay up to date with international researchers and developments to enhance the understanding of underwater blast effects on divers and the associated underwater blast safety criteria. This article aims to examine past developments and compare the associated experimental results with safety standards from various sources.

Keywords: underwater, explosion, blast, overpressure, impulse

INTRODUCTION

Interest in underwater blast injury escalated during World War II when there were more instances of underwater presence during underwater explosions. It was reported that mortality from such injuries might approach 80% (Wolf, 1970) and that the effects of blasts underwater are more far-reaching and damaging than in air, presumably due to the lower loss of shock wave energy during propagation and more efficient transmission into human body in water (Cudahy & Parvin, 2001). Since then, studies have been conducted with animals and humans to better understand the explosion parameters for the purposes of safety and tolerability.

However, human injury due to underwater explosions remains less extensively studied compared to similar aspects in air blast. Besides, the criteria associated with blast parameters are different among researchers. This review examines several key studies on underwater blast, and compares past experimental results against published safety standards from various sources to promote a better understanding of the rationale behind the published safety standards. With this, it aims to enhance the understanding of underwater blast effects on divers.

KEY UNDERWATER BLAST EFFECTS

During an explosion event, a shock wave propagates spherically away from the charge at high velocities. Upon the arrival of shock front, there will be a steep increase in pressure, followed by exponential decay with time as illustrated in Figure 1.

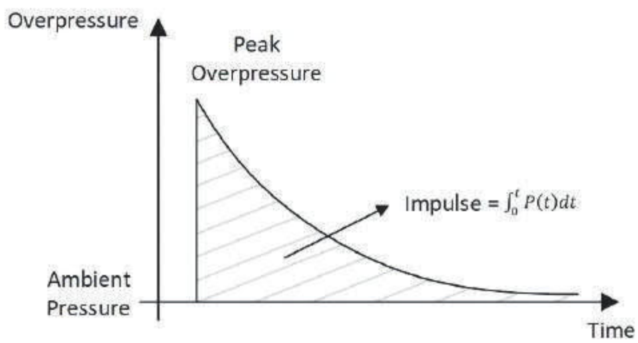

Figure 1. Shock wave characteristics

The shock wave lasts only milliseconds and the associated peak overpressure can be estimated with Equation 1. For example, the peak overpressure experienced by a diver at 500 ft from a 10 lb TNT explosion would be 46 psi. The impulse can be estimated with modelling and simulation in view of the need to consider shock wave reflection effects that are specific to the area of interest.

$$\text{Peak Overpressure (in psi)} = 21{,}600\left(\frac{\sqrt[3]{W}}{D}\right)^{1.13} \quad (1)$$

where W = Net Explosives Weight (TNT) in pounds
D = Distance between diver and explosion in ft.

Shock wave reflects when it encounters an interface of two different acoustic impedances. Upon encountering a less acoustic impedance, such as water-air interface, it reflects and becomes a tensile wave that immediately reduces pressure at a point. This phenomenon is known as surface cut-off. In contrast, reflection off a larger acoustic impedance such as the ocean bottom produces a compressive wave that immediately increases the pressure at a point (see Figure 2).

Behind the shock wave propagation, the released gaseous products expand rapidly due to the high temperature and pressure. This continues to the point when the pressure outside the bubble exceeds the pressure within the bubble, resulting in a change from the expansion phase to contraction phase. The contraction continues until the bubble cannot contract any more due to the compressibility of the gases within. This is followed by a reversal to the expansion phase, resulting in the first bubble pulse. This alternating expansion-contraction phenomenon continues until the bubble is released through the water surface, generating several bubble pulses along the way up. These secondary pressure waves generated are of reduced amplitude compared to the initial shock wave but of longer duration, lasting up to a few seconds. This phenomenon is illustrated in Figure 3.

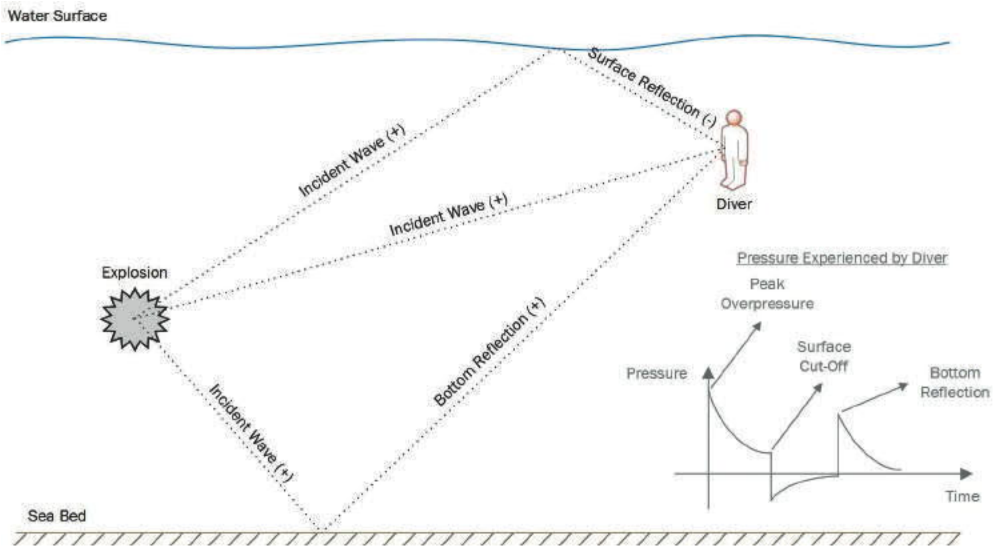

Figure 2. Reflected pressure waves

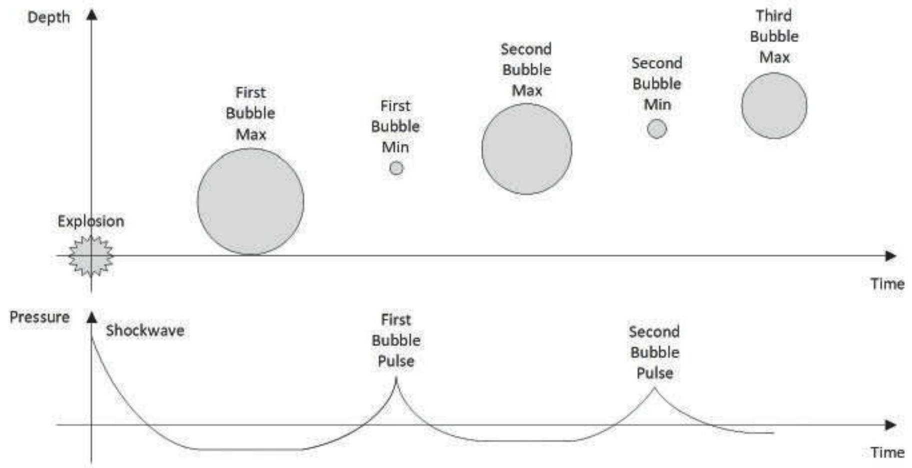

Figure 3. Bubble pulsation effects

It was observed that published safety criteria and studies focused on investigating the hazardous effects associated with the shock wave parameters on humans, namely peak overpressure and impulse.

PUBLISHED SAFETY CRITERIA

The differences in safety criteria recommended for divers are summarised in Table 1.

Reference Literature	Peak Overpressure (psi)	Impulse (psi.msec)
US Navy Diving Manual Revision 7 (Naval Sea Systems Command [NSSC], 2016)	< 50 psi	Not Mentioned
Swimmer Safe Standoffs from Underwater Explosions (Christian & Gaspin, 1974)	≤ 50 psi	≤ 2 psi.msec
Far-field Underwater Blast Injuries Produced by Small Charges (Richmond, Yelverton & Fletcher, 1973)	≤ 100 psi	≤ 3 psi.msec
O'Keeffe and Young (Lewis, 1996)	≤ 100 psi	≤ 2 psi.msec
US Navy EODB 60A-1-1-37 (US Navy, n.d.)	≤ 100 psi	≤ 2 psi.msec

Table 1. Non-injury limits for peak overpressure and impulse values

PAST UNDERWATER EXPLOSION STUDIES

A review of past studies was done to better understand the impact of these parameters on divers. Of particular interest was the research by Lovelace Foundation for Medical Education & Research (Yelverton, Richmond, Fletcher & Jones, 1973). A series of trials with several animals (comprising sheep, dogs and monkeys) was conducted with the intent of establishing safe ranges for swimmers. During which, an underwater blast criterion for aquatic mammals, with 5 psi.msec considered as the safe level was developed as well (see Table 2). Pressure-time measurements were taken to determine the exposure they were subjected to during the explosion experiments. In particular, there was no eardrum rupture at an impulse of 12.4 psi.msec (9.1% of eardrums ruptured for test subjects tested at 19.0 psi.msec to 19.2 psi.msec while 36.4% of eardrums ruptured for test subjects at 20.4 psi.msec to 23.5 psi.msec). This would mean that there is a good margin of safety for the 5 psi.msec blast criteria for aquatic mammals.

Impulse (psi.msec)	Effect
40	No Mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should be able to recover on their own.
20	High incidence of slight blast injuries including eardrum rupture. Animals should be able to recover on their own.
10	Low incidence of trivial blast injuries. No eardrum rupture.
5	Safe level. No injuries.

Table 2. Underwater blast criteria for underwater mammals

In order to provide additional data on the impact of impulse on divers, a series of trials with a swimmer in water was conducted (Richmond, 1977; Richmond, n.d.). During the test facility trial, it was reported that impulse levels of 1.9 to 3.0 psi.msec were tolerable and did not produce any discomfort. At impulse levels above 3 psi.msec, a transient stinging sensation over the front surface of the body was evident but tolerable. During the open water tests, it was reported that the swimmer, when exposed to impulse levels of approximately 2 psi.msec, experienced slight sensations at the lower abdomen or pelvic region but not discomfort. It was also observed that at peak overpressure ranges above 112 psi and at impulse levels 0.9 to 2 psi.msec, the swimmer began to experience slight thump in the lower abdomen or pelvic region. Lastly, the acceptability of sound levels from an underwater blast near an impulse level of 2 psi.msec was also investigated. It was reported that no ringing in the ears or discomfort was experienced by the swimmer who wore the upper half of a wet suit at an impulse exposure of 2.1 psi.msec with a corresponding peak overpressure of 71 psi.

A series of trials involving divers was conducted in the UK, off the coast at Spithead, Portsmouth (Cudahy & Parvin, 2001). At peak overpressure of 12.1 psi and impulse of 7.3 psi.msec, the divers reported hearing a bang, as well as feeling jolts and vibrations through the body. As the exposure increased to 30.3 psi and 14.9 psi.msec, the divers heard a loud bang and shuddered all over. As the exposure increased further to 45.1 psi and 19.4 psi.msec, the divers reported hearing a very loud rumbling bang, their whole bodies shook and were squeezed all over. They also felt a blow on the front of the chest and head as well as pressure in the ears.

The most comprehensive series of trials involving humans was conducted by the Royal Naval Physiological Laboratory to investigate the impact of underwater blast on humans (Christian & Gaspin, 1974). The divers wore hoods to prevent direct blast exposure to the ears and were exposed to relatively high levels of peak overpressure and impulse levels, which should not be considered acceptable for general applications. At an estimated exposure of 85 psi and 29 psi.msec, the diver experienced a loud bang and slight pressure on the torso but no discomfort. At an estimated exposure of 120-150 psi to 35-45 psi.msec, the diver felt a bang on the head but no discomfort to the ears or torso. Notably, it was observed that at an estimated exposure of 300 psi and 76 psi.msec, the diver experienced a severe blow to the head and torso, and his body was violently shaken but there was no substernal pain.

With reference to several published studies (Cudahy & Parvin, 2001; Christian & Gaspin, 1974; Yelverton, Richmond, Fletcher & Jones, 1973; Richmond, 1977; Richmond, n.d.; Parvin, Nedwell & Harland, 2007), the results of both human and animal trials are compiled and summarised in Figure 4.

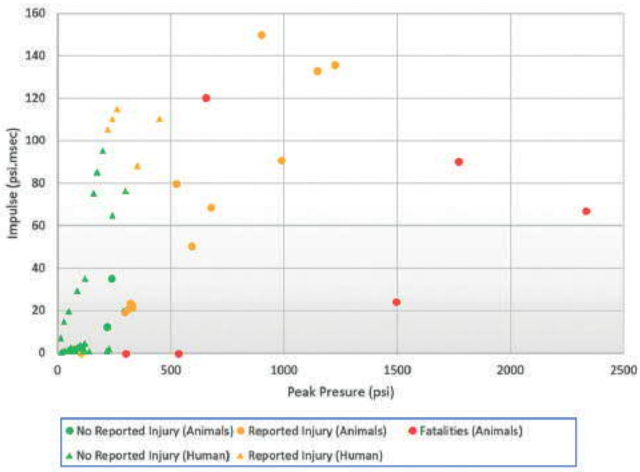

Figure 4. Summary of key past trials

There were no reported injuries to humans at the range of 100 psi and 3 psi.msec in the published studies. Hence, limiting the exposure to less than 50 psi and 2 psi.msec appear to be adequately safe, though it is to be noted that the studies did not cover the effects of repeated exposures or long-term effects.

REFERENCES ON DEFINING INJURIES

Apart from safety limits, several references aimed to define the injury criteria. The US Navy Diving Manual Revision 7 (NSSC, 2016) states that a peak overpressure wave of 500 psi is sufficient to cause serious injury to the lungs and intestinal tract (and even fatal injury under certain circumstances) while one greater than 2000 psi will result in death. A quantitative model was developed by Goertner (Cavanagh, 2000) to estimate injury to marine animals. This has been used in assessments and could serve as a reference for risk estimates for underwater explosions. The baseline thresholds of the Goertner model, where M is the mass of subject animal in kilograms, are as follows:

Onset of slight lung haemorrhage	$I = 19.0\ (M/42)^{1/3}$ psi.msec	(2)
Onset of extensive lung haemorrhage (1% mortality)	$I_{1\%} = 42.0\ (M/34)^{1/3}$ psi.msec	(3)
Extensive lung haemorrhage (50% mortality)	$I_{50\%} = 83.4\ (M/43)^{1/3}$ psi.msec	(4)

These equations relate impulse tolerance to animal weight – a marine animal of higher body weight will be able to tolerate impulse more as compared to one of lower body weight. An example can be found in Table 3.

Extent of Injury	60 kg Body Mass	80 kg Body Mass
Onset of slight lung haemorrhage	21.4 psi.msec	23.6 psi.msec
Onset of extensive lung haemorrhage (1% mortality)	50.8 psi.msec	55.9 psi.msec
Extensive lung haemorrhage (50% mortality)	93.2 psi.msec	102.6 psi.msec

Table 3. Comparison of injuries from impulse perspective

CONCLUSION

While there are variances in the safety criteria recommended by different researchers, 50 psi for peak overpressure and 2 psi.msec for impulse appear to be the most suitable for the purpose of safety. Nevertheless, there were no reported injuries in some of the aforementioned studies at higher exposures. It was also observed that the studies did not address the effects of repeated exposures or long-term effects. Thus, a safety factor could have been applied to cater for potential unknowns associated with underwater explosions. With a better understanding on the safety considerations and potential injuries associated with underwater blasts, more appropriate safety precautionary measures for training and operations can be established.

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REFERENCES

Cavanagh, R. C. (2000). *Criteria and thresholds for adverse effects of underwater noise on marine animals* (Report No. AFRL-HE-WP-TR-2000-0092). Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a395599.pdf

Christian, E. A., & & Gaspin, J. B. (1974). *Swimmer safe standoffs from underwater explosions* (NSAP Project No. PHP-11-73). Retrieved from https://babel.hathitrust.org/cgi/pt?id=uc1.31822009066242&view=1up&seq=1

Cudahy, E., & Parvin, S. (2001). *The effects of underwater blast on divers* (NSMRL Report No. 1218). Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a404719.pdf

Lewis, J. A. (1996). *Effect of underwater explosions on life in the sea* (Report No. DSTO-GD-0080). Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a315490.pdf

Naval Sea Systems Command. (2016). *U.S. Navy diving manual* (revision 7). Retrieved from https://www.navsea.navy.mil/Portals/103/Documents/SUPSALV/Diving/US%20DIVING%20MANUAL_REV7.pdf?ver=2017-01-11-102354-393

Parvin, S. J., Nedwell, J. R., & Harland, E. (2007). *Lethal and physical injury of marine mammals, and requirements for passive acoustic monitoring* (Subacoustech Report No. 565R0212). Retrieved from https://tethys.pnnl.gov/sites/default/files/publications/Subacoustech_2007.pdf

Richmond, D. R. (1977). *Underwater shock facility and explosion levels evaluated by a swimmer.* Retrieved from https://mabs.tcnet.ch/data/documents/05-36.pdf

Richmond, D. R. (n.d.). *Safe distances from underwater explosions.* Lovelace Foundation for Medical Education & Research.

Richmond, D. R., Yelverton, J. T., & Fletcher, E. R. (1973). *Far-field underwater-blast injuries produced by small charges* (Report No. DNA 3081T). Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/763497.pdf

U.S. Navy. (n.d.). *EODB 60A-1-1-37.*

Wolf, N. M. (1970). *Underwater blast injury – A review of the literature* (NSMRL Report No. 646). Retrieved from https://archive.rubicon-foundation.org/xmlui/bitstream/handle/123456789/8688/NSMRL_646.pdf?sequence=1

Yelverton, J. T., Richmond, D. R., Fletcher, E. R., & Jones, R. K. (1973). *Safe distances from underwater explosions for mammals and birds* (Report No. DNA 3114T). Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/766952.pdf

BIOGRAPHY

SIM Gim Young is a Deputy Head (Systems Management). He oversees the readiness of the SAF Chemical, Biological, Radiological and Explosives equipment. He was previously involved in the safe storage and transportation of military exposives. He also ensured that in-service ammunition continue to meet the required safety, performance and quality standards throughout their life cycles. Gim Young graduated with a Bachelor of Engineering (Mechanical) from Nanyang Technological University (NTU) in 2008.

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