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THE EFFECTS OF UNDERWATER BLAST ON DIVERS

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The Effects of Underwater Blast on Divers

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SUMMARY PAGE

THE PROBLEM

Underwater blast effects on divers received a great deal of attention up to the 1970s, and several investigators in the United States and the United Kingdom contributed to this work. Most of this research focused on the potentially lethal effects of the blast and used those to estimate safe diving distances. Several models were developed to make these estimates. The data used to drive the models were mostly conducted at shallow depths and with relatively small charges.

METHOD

A review of all information on underwater blast and their affect in divers was undertaken by the authors.

FINDINGS

There have been some more recent incidents which suggest that the current models of underwater blast may be incomplete and that additional data may be needed. Furthermore, there has been no systematic comparison of the various models. This review of underwater blast provides a brief background on the physical acoustics for underwater blast, summarizes the literature on the bioeffects for divers, and compares model results. The final chapter provides the author's views on necessary research to meet gaps in the models as well as describe the best application of our current knowledge to a guidance for underwater blast.

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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. This work was carried out under Work Unit #63706N M0099.001-5901, "The Effects of Underwater Blast on Divers." This report was approved for publication on 08 February 2001, and designated as NSMRL Report #1218.

1.0 Introduction

This report has been prepared jointly by the Naval Submarine Medical Research Laboratory, New London and the UK Defence Evaluation Research Agency. Supporting information has also been provided by Paul Smith acting as consultant to NSMRL, Dr. Jeremy Nedwell of Subacoustech Ltd and Surgeon Lieutenant Commander Mark Glover of the Institute of Naval Medicine.

Underwater blast effects on divers received a great deal of attention up to the 1970’s and several investigators in the United States and the United Kingdom contributed to this work. Most of this research focused on the potentially lethal effects of the blast and used those to estimate safe diving distances. Several models were developed to make these estimates. The data used to drive the models were mostly conducted at shallow depths and with relatively small charges.

There have been some more recent incidents, which suggest that the current models of underwater blast may be incomplete and that additional data may be needed. Furthermore, there has been no systematic comparison of the various models. This review of underwater blast provides a brief background on the physical acoustics for underwater blast, summarizes the literature on the bioeffects for divers, and compares model results. The final chapter provides the author’s views on necessary research to meet gaps in the models as well as describe the best application of our current knowledge to a guidance for underwater blast.

Previous reviews have frequently used in-air blast to describe the bioeffects associated with underwater blast. However, the body reacts very differently in water to pressure waves. It is therefore difficult to relate injuries in air to those in water, and hence this report uses primarily the conclusions of experimental work on blast conducted in water. Furthermore, underwater blast was generally treated as a unitary physical stimulus. That is, underwater blast was seen as a specific impulsive waveform and the bioeffects were related to that waveform regardless of distance from the source. As the physical acoustics section makes clear, the underwater blast waveform changes significantly over distance in a fashion very different than for a continuous wave signal. In effect, there are two primary types of sound stimuli for an underwater blast. Close to the explosion, there is a very rapid, high pressure wavefront, at greater distances the waveform more closely approximates a low frequency continuous waveform. Therefore, the bioeffects discussion is split into two parts. The first covers the traditional literature along with some new information regarding impulsive waveform effects. The second section summarizes results from some very recent work on the effects of low frequency sound on divers. The discussion is also expanded to consider the recreational diver. This is necessary because of the current impetus on the environmental effects of underwater sound. The implications of having to consider the environmental aspects of underwater blast are described in the final chapter, where future research directions and lessons learned for current guidance are discussed.

2.0 Physical Principles

2.1 Basic parameters.

2.1.1 Any process that causes a non-uniform pressure field generates sound. The acoustic pressure of the sound is related to the rate of change of displacement of the medium by the source. When the rate of change is small, the acoustic pressure is low, and the resulting pressure wave radiates without change to its basic waveform, other than being delayed by propagation and reduced in amplitude by spreading and attenuation. Due to the considerable amplitude range over which acoustic measurements are made, from threshold hearing levels in air of the order of micro-Pascals (μPa) to explosive measurements where the peak pressure may reach 100 MPa, acoustic measurements are usually related to a logarithmic scale (in decibels or dB). The Sound Pressure Level (SPL) is defined by;

$$SPL = 20 \log_{10} \frac{P}{P_{ref}} \qquad (1)$$

Where P is the acoustic pressure in Pascals (Pa) and P_{ref} is the reference pressure that relates the decibel scale to absolute units. For underwater acoustic measurements the convention is to use a reference pressure P_{ref} of 1 μPa. This reference has been used throughout this document.

2.1.2 In order to provide an objective and quantitative assessment of degree of any effect of underwater sound, and the range over which it is likely to have that effect, it is necessary to understand three parameters. These are:

- The *Source Level* (i.e. level of sound) generated by the source, the

- *Transmission Loss*, that is, the rate at which sound from the source is attenuated as it propagates, and the

- *Effect Threshold*, that is, the level of sound at which a particular effect such as death, injury, or avoidance occurs.

The first two parameters allow the sound level at all points in the water to be specified. An understanding of all three parameters allows an estimate of the range within which there will be an effect.

2.1.3 **Categories of effect.** The effects of underwater sound depend on the level of exposure, and for humans and marine animals may be divided into three categories, of

- *primary*, or life threatening physical injury, including death and severe physical injury;
- *secondary*, or non-life threatening physical injury, and in particular auditory damage; and

- *tertiary* injury, due to behavioral effects.

Each of these effects will have an associated Effect Threshold, which will in general depend on both the level and frequency range of the incident sound. Traditionally, the primary injury effects have been of greatest interest due to the military interest in the level of blast that was required to incapacitate a diver. Virtually all of the military research conducted to date addresses this issue. However, the interest now lies in defining the level of blast at which injury threshold occurs, since this is related to setting safe operating conditions for military divers during peacetime operations, and determining the psychological effects of a distant underwater blast on members of the public. It is this psychological effect that will define acceptable levels of exposure for recreational divers and swimmers.

2.1.4 **Models for estimating hazardous ranges.** The usual method of modelling the level is from the expression:

$$SPL = SL - N \log(R) - \alpha R,$$

Where SL is the Source Level dB re.1μPa at 1 meter, R is the range from the source, and N and α are coefficients relating to geometric spreading of the sound and absorption of the sound respectively. High values of N and α relate to rapid attenuation of the sound. Where values of N and α are low, the sound energy will propagate out to long range. For ranges of less than 10 km, the linear attenuation term α can in general be ignored; values of N in the order of 20, corresponding to spherical spreading of the sound according to the inverse square law, are often assumed. More complex propagation models may incorporate thermal effects, sound speed profiles and, bottom and surface reflection coefficients.

2.2 Parameters for measuring impulsive waves.

2.2.1 Explosively generated pressure waves are merely an extreme example of underwater sound. Sound sources of this type are characterized by having a very short duration, but with extremely high pressures and a wide frequency bandwidth. The three parameters that have typically been used to describe the severity of impulsive sources are peak pressure, particle velocity and impulse.

2.2.2 **Peak Pressure.** The peak pressure of a shock wave is the maximum level of overpressure, that is, the pressure above the local ambient pressure caused by the shock wave. Conventionally, this is usually considered to be in the initial peak of the waveform. This quantity is related to the transient deformation of tissues in the diver and hence, there is physical reason to believe that it may be related to effects such as stunning.

2.2.3 **Particle velocity.** The particle velocity of a shock wave is the instantaneous velocity of a particle of water as the shock wave passes. In air, the particle velocity is high as a result of its compressibility, leading to high transient air flows called "blast wind". Water is relatively incompressible and hence the particle velocities are much lower. Pressure and particle velocity are related in a plane wave or spherical wave at large distance by:

$$P = \rho c V \qquad (1)$$

Where V is the particle velocity, ρ is the density of water and *c* the speed of sound. It should be noted that the particle velocity is not the same as the speed of sound.

2.2.4 **Impulse.** The impulse is defined as the integral over all time of the pressure, that is:

$$I = \int_0^\infty P(t)\delta t \qquad (2)$$

Where I is the impulse in Pascal-seconds (Pa-s), P(t) is the acoustic pressure (Pa) and t is time. Expressed in this way the impulse might be considered to be the average level of the blast wave pressure multiplied by its duration. Physical considerations; however, indicate that in fact the impulse defined in this way will always be zero, since after the main blast front there is a period of relaxation in which the overpressure becomes negative. This introduces an equal and opposite contribution to the integral from that of the main pressure peak. Conventionally the impulse is estimated from the first peak of the blast wave, with the subsequent arrivals or relaxation being ignored. Expressed in this way, the impulse may be considered to be a measure of the low-frequency energy of the blast wave. Since pulmonary effects predominantly occur at low frequencies, the level of impulse may be expected to correlate reasonably well with the severity of these effects.

2.2.5 The term “impulse” is used to describe a wide range of underwater sound events. The term has been mainly used to describe the pressure pulses caused by the detonation of high explosives underwater, but the term may be applied to any event of limited duration. The terminology causes some confusion as the “impulse” is also used as a technical parameter for defining the strength of the event. In the interest of preventing confusion the term *impulsive wave* is used here to mean a pressure wave of short duration and typically high pressure; the term *impulse* is retained as a parameter of the strength of the wave.

2.2.6 The main interest in underwater blast has been in the primary effects of impulsive pressure waves caused by the detonation of high explosive sources. This is because freely-suspended explosives were used to investigate the effects of underwater blast on personnel. There was a need to relate the severity of the wave to the effects that it caused, but a simple measure of the strength of the wave, usually its peak pressure, was sufficient to categorize the effects of the wave. The use of a simple measure works well in this instance because the waveforms from freely-suspended high explosives are repeatable, and well defined in their characteristics. In particular, the spectrum is broad, flat and consistent for a wide range of charge types, ranges and sizes.

2.2.7 As the interest in the underwater environment has increased, there has been a raised awareness of the secondary and tertiary effects of underwater impulsive waves, ranging from auditory injury to subtle behavioral effects. The description of impulsive waves simply in terms of their peak pressure is not adequate for these purposes. The range of sources that may have an effect is much greater than historically was the case. The impulsive waves generated by these other sources may have very different spectral characteristics from that for high explosives. Where a high proportion of the energy of the wave is at frequencies to which the animal or human is sensitive, the effect may be much greater than a simple measure such as the peak pressure would imply.

2.3 Underwater Explosions.

2.3.1 Although underwater and airborne blast are similar in a nature, there are fundamental differences in the impact that the blast wave has in the different media. Water is approximately 800 times denser than air and some 10,000 times less compressible. For equal charge weights, blast waves in water generate much higher acoustic pressures than those in air, but have a considerably smaller particle velocity during propagation. Bubble pulses further complicate the picture in water and significantly enhance the low frequency energy of the blast wave.

2.3.2 When an explosion is initiated in a mass of explosive material, a pressure wave propagates into the surrounding medium. In all explosives this pressure wave results from the conversion of the solid explosive material into gaseous reaction products. The way in which the conversion process occurs, and the form of the accompanying pressure wave, depend on the category of explosive.

2.3.3 **High Explosives.** "High" explosives like TNT and other nitro-glycerine based explosives have a rapid detonation process. A violent chemical reaction, following in the wake of the shock front propagating through the explosive, turns the solid of the explosive into incandescent gaseous reaction products at extremely high pressure. The velocity of detonation of high explosives is about 5,000 to 10,000 m/s, and a shock wave that propagates in all directions is produced in the medium.

2.3.3.1 When a freely suspended charge is exploded underwater, the initial mass of explosive rapidly expands to produce a large volume of superheated gas. The boundary of the gas bubble radiates out supersonically creating a wave disturbance that is transmitted to the surrounding water by the accelerating interface between the explosive gas bubble and the water. The wave in the vicinity of the explosive does not propagate in an identical manner to small amplitude acoustic waves. The leading edge of the blast front, generated by the accelerating boundary of the gas bubble, rises in a very short time and hence contains much of the high frequency energy. The region of the wave that is at high pressure travels through the water at a greater speed than the main body of the blast wave and consequently the wave propagates as a non-linear wave which changes its form during propagation. The leading edge of the wave steepens to form a shock, and the tail of the wave becomes extended.

2.3.3.2 At large distances from the source the propagation of the pressure wave usually approximates to that of other sound waves. However, the high frequency energy is absorbed and scattered, and the waveform becomes extended in time. It is therefore common that the pressure wave from an explosive at a distant point is dominated by low frequency components, and is perceived as a "rumble".

2.3.3.3 **Water displacement.** The rise time associated with the underwater blast wave is so short it occupies only a few millimeters of the waterspace as it propagates. The whole of the passage of the blast front may occupy less than a meter (Assuming a 0.1ms duration blast front propagating at 1500ms^{-1}). The displacement of the water is very small (typically a few millimeters), and hence particle velocity is low. Except for the very near field of the source, the blast wind that is associated with air blast does not occur. Due to the density of water, projectiles are rapidly decelerated and are not a significant factor in underwater blast.

2.3.3.4 **Bubble Pulses.** The rapid expansion of hot gases associated with an underwater explosion force back the surrounding mass of water. The momentum of the water immediately surrounding the bubble causes the gas bubble to expand beyond equalization pressure (ambient hydrostatic pressure). Hence, at its maximum radius the pressure within the gas bubble is lower than that of the surrounding water and the bubble starts to re-compress. The momentum of the water mass forces the gas bubble past equilibrium once again, this time into compression. Hence, the momentum imparted to the surrounding water in the very near field of the gas bubble produces a series of secondary pressure waves that gradually decay toward static ambient pressure.

2.3.3.5 Whereas the initial wavefront contains much of the high frequency energy of the blast wave, and consequently has a much higher acoustic pressure, the secondary pulses produce a longer duration waveform with significant low frequency energy components. This low frequency energy has the potential to cause injury at long range.

2.3.3.6 **Blast waves at distance.** An underwater blast measured at short range is characterized by a very rapid rise in pressure to the peak pressure value, followed by an exponential decay. Due to the dominance of high frequency energy associated with the rapid rise in pressure, a diver exposed to a small charge at short range will perceive this exposure as a sharp “crack”. The limiting criteria in this case is likely to be related to the peak pressure.

2.3.3.7 As the acoustic pressure wave radiates out away from the blast center the form of the pressure wave changes. The very high pressure components that contribute to the initial blast front are attenuated more rapidly than the low frequencies. The peak pressure will, therefore, decay at a greater rate than that predicted by the inverse power law until the wave has travelled a very large distance (Cole, 1965). As it propagates the wave becomes “smeared” in the time domain and the high frequency energy is disproportionately reduced in amplitude. Consequently, underwater explosions at long range are more closely characterised as a short duration, low frequency wave. A diver will perceive this as a dull “thud” due to the dominance of the low frequency components. The limiting physiological criteria that applies in this case is unlikely to be consistent with that for a comparable exposure at short range.

2.3.4 **Underwater TNT Explosions in rock.** Pressure waves are substantially modified when underwater blasting involves the use of charges buried in boreholes to fragment rock prior to dredging. Peak pressure is reduced substantially, to approximately 5 percent of that for freely suspended charges, and the impulse to approximately 30 percent. No bubble pulses occur. However, the duration of the shock wave is increased tenfold over that for an equivalent freely suspended charge, typically to 1-2 ms. The rise time of the wave is also greatly extended to the order of a millisecond. The resulting blast wave is therefore likely to contain more of the low frequency energy components that have the potential to cause pulmonary injury.

2.3.5 **Propellants.** With other explosives, such as black powder, the explosion process is one of deflagration, or burning, rather than detonation. Consequently the process occurs at a much lower velocity of approximately 5 $m \cdot s^{-1}$ and gives rise to a relatively low, broad pressure peak. Although the pressure from propellants is comparatively low and they are usually thought of as being “safe”, the pressure wave is of much greater duration than that for high explosives.

2.3.5.1 A common use of deflagrating explosives is as the propellant used in bolt guns. Bolt guns are used to support underwater engineering tasks and operate by detonating a small explosive charge in the end of a barrel that is occluded by a bolt. This forces the bolt out of the barrel and into a target at high speed The pressure waves produced by the underwater explosion typically have a rapid initial rise to a peak pressure that may be of the order of 100 kPa. This is followed by a well-damped low frequency oscillation. The noise spectra is dominated by a broad peak in level over a low frequency range from 10 Hz to 100 Hz (Parvin, 1999).

2.3.6 **Impulsive pressure waves from seismic sources.** Virtually all seismic surveys are conducted using airguns as the acoustic source. The various types of airgun function in the same manner. A container of high-pressure air is released suddenly into the surrounding water producing an air-filled cavity. The resulting air bubble pulsates rapidly several times producing an acoustical signal that is proportional to the rate of change of volume of the bubble. The waveform is usually characterized as a damped sinusoid. The fundamental frequency of the waveform depends largely on the maximum volume of the bubble and the ambient pressure of the surrounding water. The level of the signal achieved depends primarily on the energy contained in the compressed air prior to discharge and hence, great efforts have been made to increase the volume and pressure of the initial gas charge.

2.3.6.1 Typically, the output for a single airgun in the 0 to 120 Hz frequency range is at a level of 226 dB SPL at 1 m. Where an array of sources is used the Source Level may approach 248 dB SPL (Malme et al., 1986). The peak sound pressure is roughly proportional to the airgun chamber volume and can vary from 1.4 to 15 MPa. Airgun sources typically have a frequency bandwidth of approximately 40 Hz, centered at 120 Hz, and hence have an effective “Q” of 3.

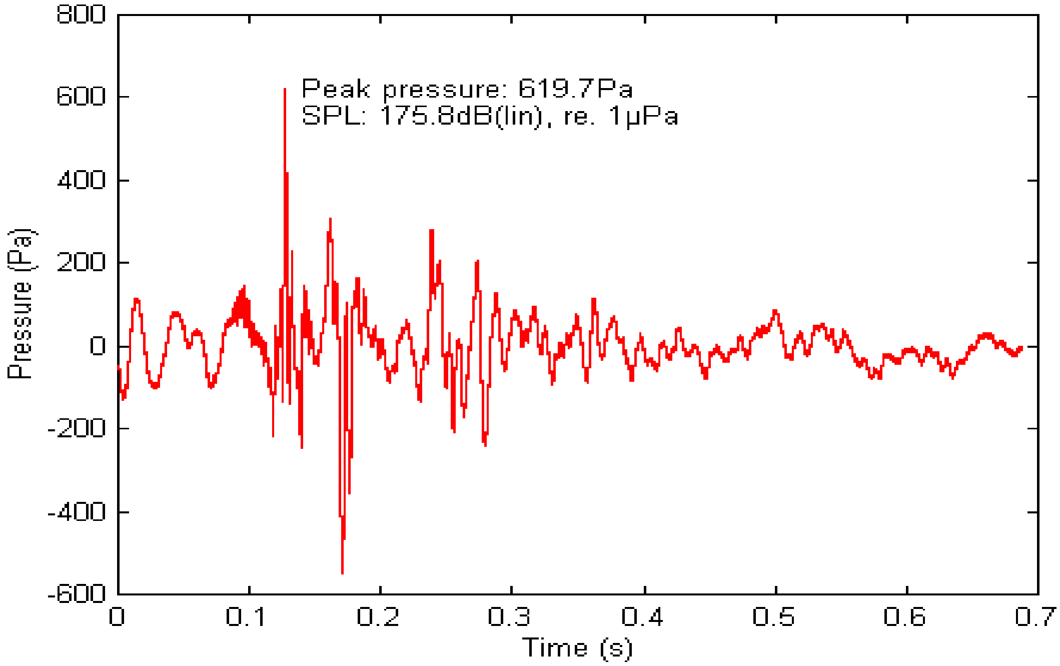

Figure 2-1. A typical noise time history during discharge of an airgun sound source, measured at a range of 3000m (Nedwell, 1999).

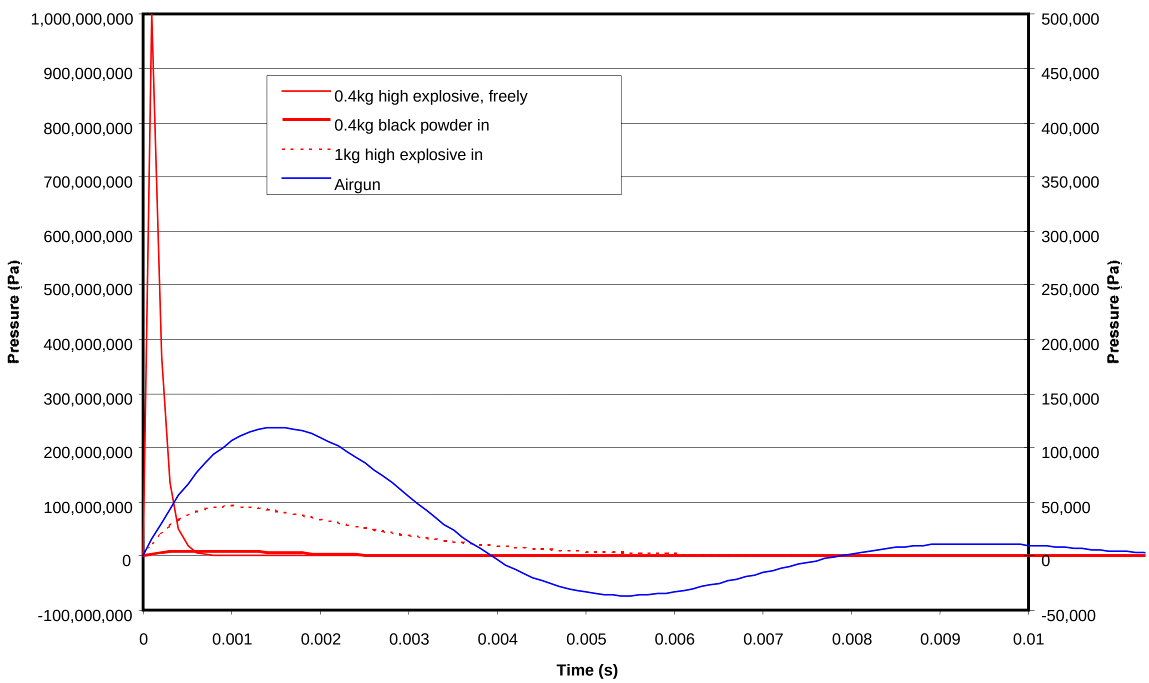

Figure 2-2. Idealized underwater blast waveforms for high explosive, deflagrating explosive and airgun sources.

2.4 Factors influencing underwater impulse measurement.

2.4.1 **Physical Parameters.** Section 2.3 of this report provides a formal definition of impulse, and indicates the difficulties in applying the formal definition as a physical measure of the blast wave. In order to quantify impulse from a sound pressure time history the effective duration of the impulse noise has traditionally been estimated. These estimates are based on the rise and decay of the pressure from its initial peak value to some proportion of the peak pressure that occurs some time later (Typically 10% or 20 dB). By this type of definition an impulse magnitude can be calculated and compared to the physical effects of the blast wave. Typically, this might involve lethality or injury. The following definitions are provided by Hamernik and Hsueh (1991) and are related to the waveforms illustrated in figure 2-3.

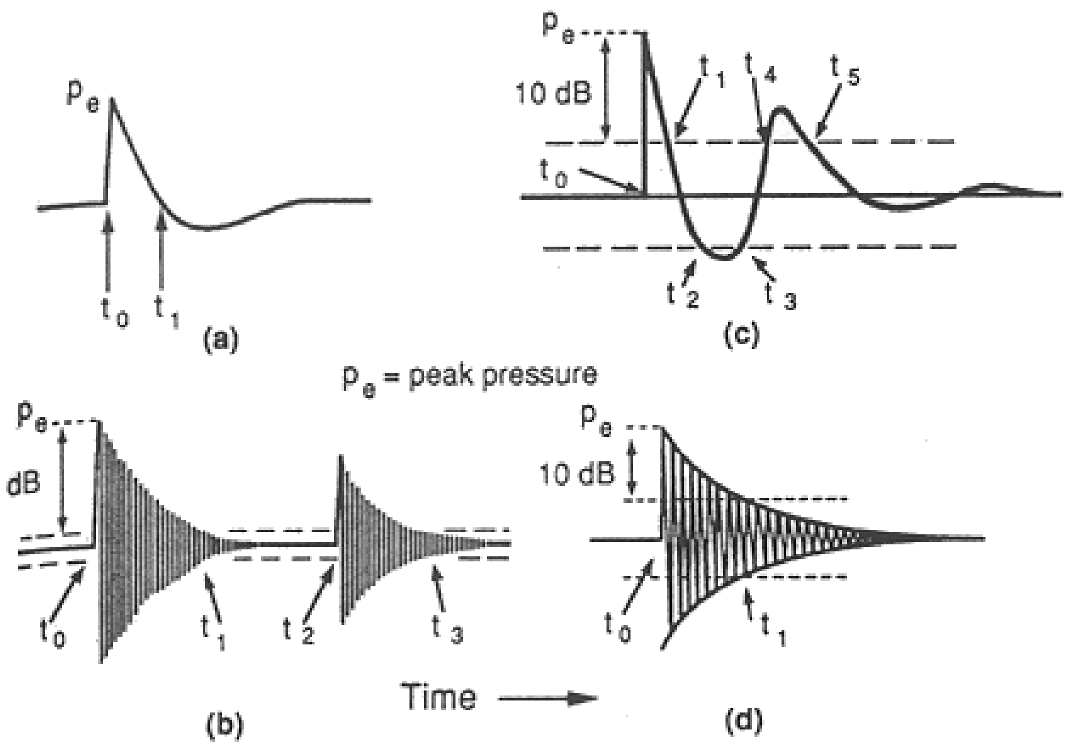

Figure 2-3. Schematic drawings of several simple impulse waveforms that illustrate the various temporal points which are used to determine the (a) *A* duration, (b) *B* duration, (c) *C* duration and (d) *D* duration of an impulse (after Hamernik, 1991).

(a) *A* duration = $(t_1 – t_0)$ (Coles et al., 1968).
(b) *B* duration = $(t_1 – t_0) + (t_3 – t_2)$. (Coles et al., 1968).
(c) *C* duration = $(t_1 – t_0) + (t_3 – t_2) + (t_5 – t_4) + \dots$ (Pfander et al., 1980).
(d) *D* duration = $(t_1 – t_0)$ (Smoorenburg, 1982).

2.4.2 In most cases the underwater blast records that are available do not specify the method by which impulse duration has been estimated. Similarly, measures of peak pressure have been made without reference to the sampling rate of the equipment involved, and for the early historic blast records the pressure was estimated from the blast scaling laws. Consequently, when reviewing the bioeffects of underwater blast waves in section 3 of this report, it is not always possible to directly compare the physical measures quoted in the studies. An immediate requirement for any future program of research into the impact of underwater blast on divers is to define these parameters so that study results can be directly compared.

2.4.3 **Impact on a diver.** An illustration of a typical underwater blast wave incident upon a diver operating an underwater bolt gun is shown in figure 2-4. The propellant employed by the bolt gun is a form of deflagrating explosive. This example indicates that when the gun is fired there is a rapid rise in the acoustic pressure, reaching a peak pressure of 80,000 Pa (218 dB re.1μPa) in less than a millisecond. The acoustic pressure pulse then decays over a period of approximately 10ms, before generating a negative pressure pulse as the explosive gas bubble reaches its minimum size. For the remainder of the time series the acoustic pressure oscillates about the mean pressure with a time period of approximately 10ms, the amplitude eventually decaying back to ambient pressure.

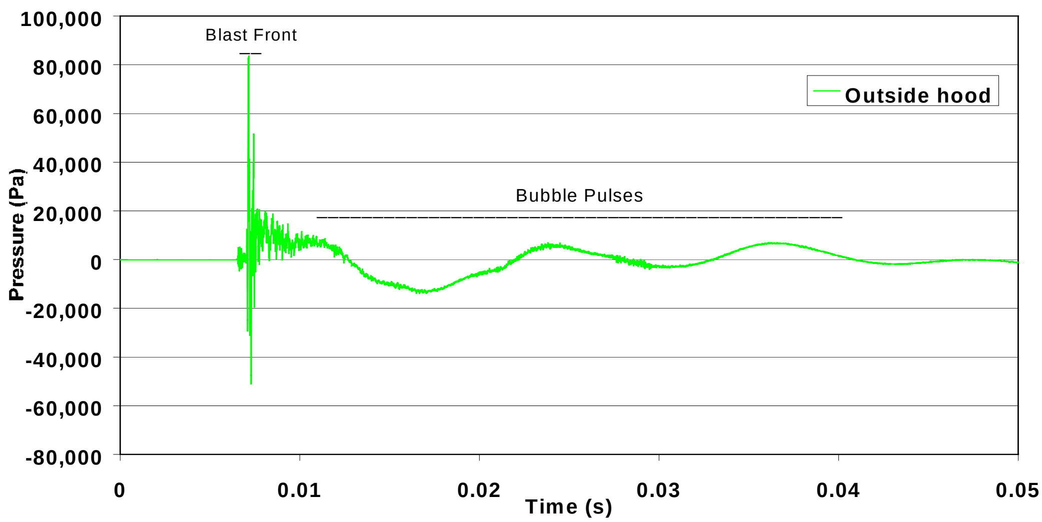

Figure 2-4. The time history of a typical acoustic pressure wave incident upon a diver operating an underwater bolt gun into a concrete block (Parvin, 1999).

2.4.4 The underwater blast waveform that is incident upon the diver's head and body (as shown in Figure 2-5) is very different from that illustrated in figure 2-4. A foam neoprene diving hood, diving suit and the face-mask worn by a diver strongly attenuates incident sound at frequencies above 500 Hz. The initial peak pressure is not, therefore, transmitted to the diver's head and body. The low frequency components, particularly those within the secondary bubble pulses, are transmitted to the diver unattenuated

(Figure 2-5 illustrates the corresponding blast waveform measured inside of the diver's foam neoprene diving hood at the ear position).

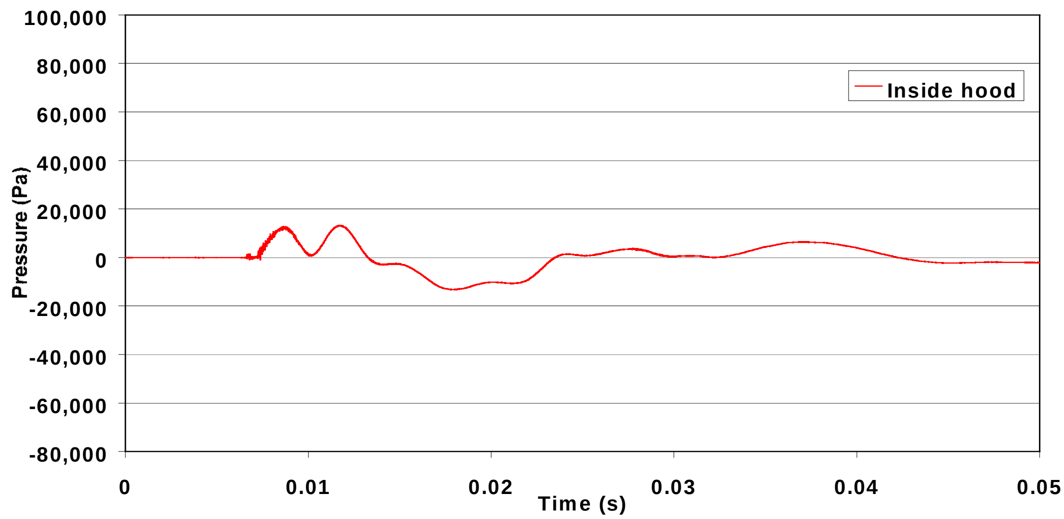

Figure 2-5. The time history of a typical acoustic pressure wave measured inside of a diver's foam neoprene diving hood whilst operating an underwater bolt gun into a concrete block (Parvin, 1999).

2.4.5 Much of the historic data relating to the effects of underwater blast on divers is based on exposure of divers in standard diving dress, where the diver's helmet is made of tinned copper. The transmission of acoustic energy across the water-copper-air boundaries will be an inefficient process, with much of the incident sound energy being reflected. Measurements of sound transmission across a modern fiberglass diving helmet have indicated that between 50 dB and 60 dB of protection to the divers hearing is provided over the frequency range from 1kHz to 6 kHz (Nedwell, 1989). The sound energy that is transmitted into the diving helmet will effect the divers "dry ear" in the same manner, and largely to the same degree, as a conventional airborne noise exposure. The subjective comments from historic "dry ear" underwater blast exposures may not, therefore, provide an accurate assessment of the effects of peak pressure on a Self Contained Underwater Breathing Apparatus (SCUBA) diver.

2.4.6 **Reflections from the surface and seabed.** A diver in shallow water, or a surface swimmer, will receive not only the direct blast wave from a source, but also the reflected waves from the surface, seabed and any surrounding structures.

2.4.6.1 **Surface reflections.** Due to large acoustic impedance mismatch between air and water ($\rho c_{water} = 1.5 \times 10^6$ Pa·s·m^{-1} whereas $\rho c_{air} = 415$ Pa·s·m^{-1}), as the acoustic waves approach the water surface the acoustic pressure falls rapidly to zero, is inverted at the boundary, and is reflected as an inverted wave with negative pressure. Christian and Gaspin (1974) describe the superposition of the direct wave with the surface reflected wave that arrives a short time later. The theory indicates that the peak pressure will be consistent with the direct wave incident at the diver, but that the duration of the waveform will be considerably reduced (See figure 2-6). As the duration of the waveform is related to the impulse and low frequency energy components, it follows that divers exposed to a specific charge weight will receive the same level of peak pressure, but that the level of impulse exposure will be reduced for the shallow water case. Hence, much of the advice given to divers likely to be exposed to underwater impulse is "the shallower the safer" (Christian and Gaspin, 1974) (Marine Technology Directorate, 1996).

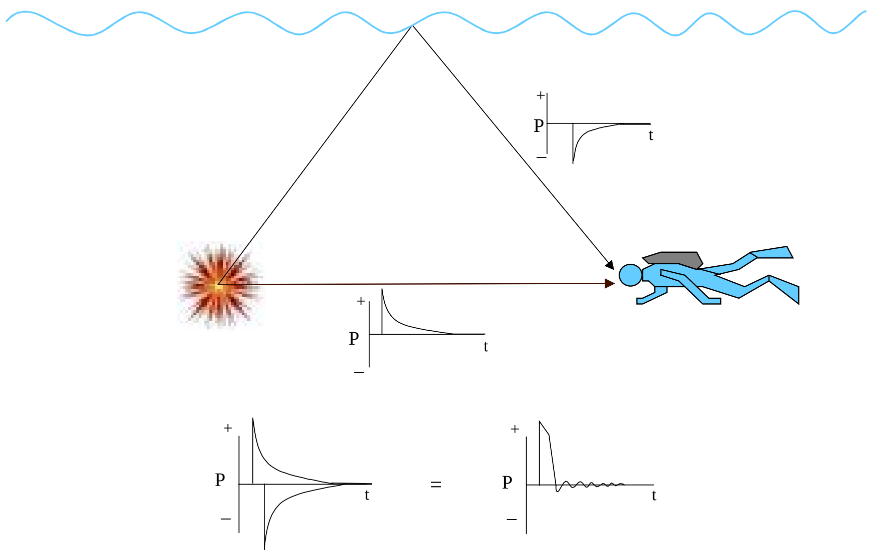

Figure 2-6. The superposition of the direct and surface reflected blast waves incident upon a shallow water diver.

2.4.6.2 **Bottom reflections.** Where a diver is exposed to underwater blast in shallow water there may be an additional contribution to the impulse exposure from the reflection of the blast wave from the seabed. The degree to which this contributes will depend upon the type of seabed. Soft mud and sediments will have a low bottom reflection coefficient and so any reflected wave will be substantially attenuated. By comparison a hard rock seabed will reflect much of the incident sound and can have a significant contribution to the impulse exposure of the diver, particularly where the diver is close to the seabed and the direct and seabed reflected waves propagate a similar distance. A pressure wave that is reflected from the seabed is not inverted and so contributes to the overall impulse exposure of the diver. A similar form of reflection occurs where the diver is close to other underwater structures such as harbor walls or a ship's hull, and multiple reflections will occur where a diver is exposed to an underwater sound wave in an enclosure.

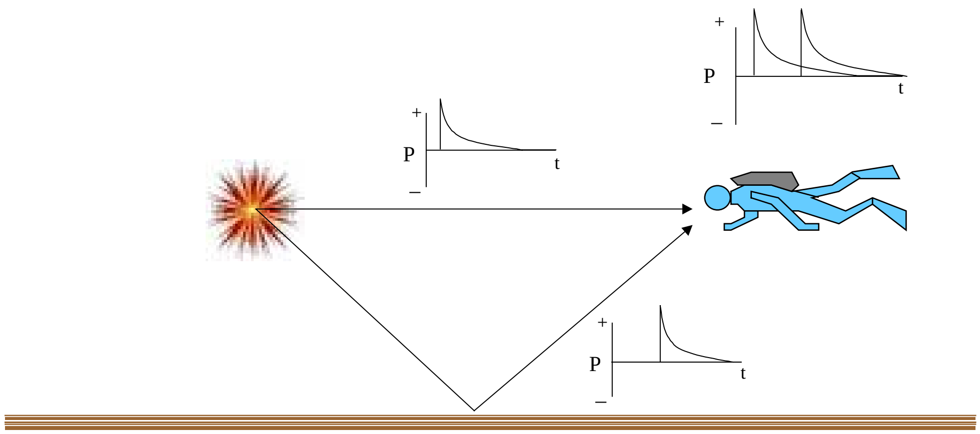

Figure 2-7. The superposition of the direct and bottom reflected blast waves incident upon a shallow water diver.

3.0 Types of Injury

3.1 Introduction

This section discusses types of injury to be expected from underwater blast along with some discussion of potential mechanisms of injury. The medical effects of underwater blast have been taken from a recent review by Sg Lt Cdr Mark Glover of the Institute of Naval Medicine (Glover, 1998) and the low frequency effects of sound from a research summary by Cudahy et al., (1999).

As described in the physical parameters sections, most experimentation involves ranges such that the primary component of the blast has been peak pressure. With the advent of environmental scrutiny, it is necessary to discuss the further range effects, which are more closely allied to low frequency sound effects. Recently, there has been a series of experiments regarding the effects of underwater low frequency sound on military and recreational divers. Those data will be used to indicate the potential types of responses at longer ranges from the blast. The injury section will also be expanded beyond physiological effects to address psychological effects, as psychological effects are most likely to be the controlling factor in any guidance proposed for broad range application to divers.

3.2 Blast Front Effects

The best available information on underwater blast injuries to human subjects dates from the 1940s and 1950s, where equipment suitable for measuring underwater pressure waves was either unavailable or rudimentary. As a result, the majority of the experimental programs did not include reliable measurements of parameters of the shock wave. In addition to these experiments, a considerable body of information is available as a result of accidental exposure to blast, but of course due to the circumstances no record of the pressure wave parameters is available.

3.3 Historical Reports

In World War II it was noticed that detonations yielding the same energy were more deadly in water than in air (Hoff and Greenbaum, 1954). This is presumably due to the complex blast waveform, lower attenuation of shock wave energy and more efficient conduction of blast energy into the tissues in water.

Damage by underwater blast will only extend up to the level of immersion. All the wetted area will be subject to the same peak pressure, but the wave will terminate later in those areas furthest from the surface for the same reasons as discussed above. The time-integral for the pressure will, therefore, fall to almost zero at the surface. Wakeley (1945) suggested that this non-uniform application of pressure might lead to a greater tendency for cells to burst and for all the tissues to be squeezed upwards.

Tissues of the body are of similar density to water and, as a result, pressure waves will tend to pass through, rather than reflect off. Tissues, like water, are relatively incompressible but gas within the body is easily and instantaneously compressed. Thus, damage will tend to be concentrated at gas/tissue interfaces where the differential in compressibility is greatest. Lungs, gas-filled viscera, sinuses and ears are all susceptible. Lungs and intestines are the prime targets (Committee on Amphibious Operations 1952), although the air spaces in the head render them and the adjacent central nervous system vulnerable to damage if the head is underwater (US Navy 1970). Wolf (1970) suggested that the CNS lesions that were occasionally seen were actually due to blood shifts or air emboli. Parts of the body that do not contain gas, such as muscle and bone, transmit the shock wave without disruption and are relatively spared (Committee on Amphibious Operations 1952).

Delayed death is usually due to pulmonary complications of oedema and severe hypoxia. Early symptoms of pulmonary blast injury may be as minor as retrosternal pain and dyspnoea. Clinical signs include tachypnoea, cyanosis and haemoptysis. On auscultation, rales and rhonchi can usually be heard, particularly at the bases, but chest symptoms are often slight in the early stages and the physical signs unremarkable. Severe pulmonary disruption and hemorrhage (perhaps with arterial gas embolism, too) will die immediately or within minutes. Respiratory failure can develop in the acute phase. Other cases will appear well, but deteriorate as much as 12-24 hours later (Gray and Coppell 1975), resolving after 36-48 hours.

Those exposed to underwater blast often recall a sudden severe abdominal pain, like a violent kick in the stomach. High velocity pressure waves may induce a stinging pain in the chest and head. Slower ones are felt as a solid thump in the chest and abdomen. Significant lung injury can occur with either. Injury in the area of the gall bladder, including hepatic tear can cause referred right shoulder pain. Transient paralysis in the lower limbs, testicular pain, nausea, vomiting and an urge to defecate are not uncommon.

3.3.1 Symptoms & Signs - Experiences of WW2

Cameron (1947b) reviewed injuries sustained by immersion blast victims to date in 1947. These are predominantly head out survivors of sinking ships. Life-jackets will lift the thorax further out of the water, so many within this study population will have relative sparing of the thorax and head. The clinical presentations described by Cameron are mirrored in many other accounts (Huller and Bazini 1970).

The abdominal symptoms and effects as well as the time course of injury are as described earlier. Unconsciousness was a rare occurrence; partial or complete paralysis of legs, lasting an hour or so, did occur and might have caused some victims to drown. No cerebral lesions were found but there was one case of sub-arachnoid hemorrhage. Right heart failure followed lung damage in some cases. Cameron reports fat embolism but no evidence of air embolism in these cases.

Experimental work on human subjects that may be considered to be suitable for the determination of standoff ranges underwater is extremely limited. The available experimental evidence in this category reduces to two main trials, the work by Wright et al., at the RNPL, and the Stump Neck, Maryland trials and their deep water sequel.

3.3.2 Experimental work on human subjects

This section will present the primary available data on human trials. The latter description of effects on various organ systems should be considered in the context of the results presented here. References are provided for more complete descriptions of the experiments.

3.3.2.1 The RNPL trials, 1941-1951

A comprehensive study of the effects of underwater blast in man was performed by the Royal Naval Physiological Laboratory (RNPL) during 1941 to 1951, and summarized by Bebb, et al., 1953. The program commenced with experiments conducted on animals in 1941 to 1943, and culminated in a large scale trial with human subjects in 1949. The divers wore hoods, which were designed to protect the head and hearing, but otherwise had minimal protection from the effects of blast. This work is unique, and in light of modern ethical constraints it is most unlikely that any similar experiment will be performed again. Significant symptoms of blast exposure were noted. In the context of standoff distances this work is mainly valuable in that it indicates levels of peak pressure and impulse that are the thresholds at which the diver becomes unable to complete his task.

As a preliminary to the large-scale trial, Dr. Wright of RNPL acted as subject in some trials of various hoods. At the highest levels of exposure, the effects included the sensation of a violent blow, shaking, substernal pain, paralysis, concussion and aural damage. It is interesting to note that the effects were apparently more severe in the case of higher impulse energy, indicating that impulse may be a more important criterion of effect than peak over-pressure. At the lowest levels of exposure the sensation was predominantly one of a loud bang. It was also observed that at deeper depths, the effects were more severe.

In the main large program, 60 controlled exposures of divers to underwater blast at two depths of 3.05 meters and 15.3 meters were undertaken. The results are reported in Wright et al., 1950. The range from diver to charge was progressively reduced to 33.5 meters from a 0.57 kg charge, and 65.5 meters from an 11.3kg charge. At these ranges, significant indications of primary injury were observed.

One shortcoming of the information is that only one charge depth, of 9.1 meters, was used, and hence it is not possible to assess what influence this might have had on the results. In view of the significant differences in the effect of the blast noted for the divers at different depths, it must be considered possible that the depth of the charge could have a similarly large effect.

3.3.2.2 **Stump Neck trials, 1942**

In 1942 tests were performed to determine the level of underwater blast at which divers could continue to work underwater; the results have been reported in Christian & Gaspin, 1974. Seven divers dived in two trials, with charges of 0.45 to 4.5 kg of TNT being fired underwater, on a river bottom at 5.5 to 6.1 meters of water depth, with the diver working on the bottom. It should be noted that the divers were in US Navy standard diving suits, using surface supplied air, and hence, while the noted effects of the shock waves on the body may be expected to be similar to those for a SCUBA diver, effects on hearing will be modified by the presence of the air helmet.

The effects ranged from "ping" sounds to pressure squeezes on the body, but no other significant effects were noted. None of the effects were bothersome.

3.3.2.3 **USS WASSUC trials, 1942**

The trials conducted at “Stump Neck” were subsequently moved to deep water. Divers were submerged off the stern of the USS WASSUC in water of 26 meters depth. The divers were dressed in thermal clothes and in standard diving equipment, on a diving stage at 6.1 meters depth. Charges of 25 kg of nitramon at 12.2 meters depth were fired at a range of 480 meters, and 136 kg of TNT at 18.3 meters depth at a range of 1234 meters. The divers reported sensations of muffled thuds or rumbling. No sensation of pressure was noted, but each described vibration of the stage as though its lines had been struck; none of the sensations were unpleasant.

In respect of secondary injury, it may be commented that, while symptoms of hearing damage were reported, it was not a main interest of the experiments and no useful data were presented.

3.3.2.4 **Audible Recall Device, 1987**

Diver trials of an underwater explosive recall device were conducted in 1987 at the Naval Coastal Systems Station by the Navy Experimental Diving Unit (Sterba, 1987b). The device detonates an explosive charge at 11 foot depth. Five divers were tested at 7 meters from the explosion, which yielded a peak pressure of 5.85 psi (40.3 Kpa) or an impulse of 2.17 psi-msec (14.96 Pa-sec.). The focus of the testing was hearing and fragmentation risk. Divers reported the explosion as very loud, but did not have any temporary threshold shift (TTS). Fragmentation was a hazard and a modified device which reduced the fragmentation to acceptable levels was developed and tested. The safe standoff distance for this device was determined to be 6 meters, based on the 1987 testing (Sterba, 1987b).

3.3.2.5 **Deflagrating explosives: Underwater bolt guns.**

In the course of some underwater operations divers are required to operate hand held underwater bolt guns. These devices have an explosive propellant and consequently the divers operating them are exposed to significant levels of blast. This type of measurement is valuable in that deflagrating explosives tend to have a lower peak pressure than high explosives, but have a high impulse.

The potential for hearing damage due to a Ramset Stud Gun was investigated in 1987 (Sterba, 1987a). The gun produced an impulse of 10.76 psi-msec (74.19 Pa-sec). Several different patterns of shots were studied and it was found that none of the patterns produced TTS. The maximum continuous use of the gun was 40 successive shots because more shots resulted in thumb injuries. Two of the five divers tested reported tinnitus immediately following the 40-shot sequence, but did not have any TTS. The tinnitus resolved within one hour.

Measurements were taken in July 1993 of the noise exposure of divers operating a Cox's Bolt Gun and a Tornado Stud Gun (Parvin, 1999). The tools were operated by the diver and fired into a workpiece resting on a lake bed. Measurements were taken of the waterborne blast at the diver's right ear. During firing of the Cox's Bolt Gun the incident peak pressure reached 350,000 Pa, with a corresponding impulse of 500 Pa-s. The measures for the Tornado Stud Gun were marginally higher. The divers operating these tools found the experience “unpleasant” and consequently conducted further firings with the guns at arms length.

The UK Defence Evaluation and Research Agency have recently completed a further study of the noise exposure to divers operating underwater bolt guns (Parvin, 1999). In this instance the propellant charge was at lower levels than those used in the Cox’s Bolt Gun and Tornado Stud Gun. Incident peak pressures at the diver of 100,000 Pa were recorded. The divers were not unduly concerned with these exposures and felt that neither the impulsive noise level, nor the blast wave would prevent them from completing their task using the tool. This study has, however, indicated the shortfall in current guidance relating to underwater noise exposure of this type.

3.4 Pulmonary Injuries

Several animal models have been used to study blast. Much work in underwater blast has used sheep and has focused on thoracic injury. One potential limitation of this approach is that the sheep's rumen, a gas filled viscus and therefore theoretically very sensitive to blast injury, occupies a significantly larger proportion of its abdomen, compared with the stomach of a human.

A study by Fletcher, et al., (1976), was aimed at modeling the response of the thoraco-abdominal system to underwater blast. Experiments were conducted using fish, rats and sheep, balloons, and excised organs, including sheep lungs. Measurements of the level of the shock wave were made, and the existence of a pulmonary resonance demonstrated. Theoretical analysis of the results suggested that the severity of lung hemorrhage in divers in SCUBA equipment would be constant for a diver receiving an impulse proportional to the square root of the hydrostatic pressure at his depth. It should be noted, however, that the available experimental evidence clearly indicates that the deeper the subject, the greater the effect of the blast.

Nevison et al., (1971) and Mason et al., (1971) used Doppler techniques to monitor the carotid arteries of dogs exposed to blast in air. Emboli were seen in large numbers in the first hour post-exposure with bursts of high counts in time with respiration. These emboli were believed to be of gaseous origin. Benzinger (1950) and Rössle (1950) both record findings of arterial air emboli in coronary and cerebral vessels at post-mortem examination of a number of air-blast exposed animals and humans. The absence of bubbles in the venous system leads them to assume that the bubbles are introduced in the lungs. Emboli were found in most of a series of immersion blasted experimental animals which died soon after exposure. Those that survived were sacrificed and had no evidence of gas emboli

Carlton et al., (1945) exposed dogs to intermittent bronchial pressures of 35-50 mmHg for up to 15 mins at 28 cycles per min. Single "blasts" of 70-110 mmHg were administered to another group. These "overpressures" resulted in varying pulmonary barotrauma with Arterial Gas Embolism (AGE). Coughing precipitated death in some subjects and AGE was suspected as the cause.

Pulmonary hemorrhage is the most frequent blast related injury found in humans and animals. As described by several authors (Chiffelle, 1966, Greaves et al., 1943; Rössle 1950; Theis 1943, Williams, 1943; Zuckerman, 1940, and Clemedson, 1956), the damage concentrates at the interface between alveolar tissue and bronchovascular structures. This suggests that the damage is caused by shearing action between the gas-filled spaces and tissue constraining the spaces as various thoracic structures accelerate at different rates (Clemedson and Granstrom 1950). Rib markings occur where the force of the blast has impinged on the lungs via the softer intercostal spaces.

In summary, pulmonary damage can be:

a. Acute:
   - (i) trivial to massive alveolar disruption and consequent hemorrhage
   - (ii) pneumothorax, pneumomediastinum
   - (iii) arterial gas embolism

b. Delayed:
   - (i) trivial to multiple small pulmonary emboli
   - (ii) pulmonary oedema consequent on pulmonary damage

Note that most of these will result in a varying degree of respiratory insufficiency in either the acute or delayed phases.

3.4.1 Non-Pulmonary Effects of Lung Injury

Lung damage is accompanied by effects in other systems. The terminal event in overwhelming lung injuries is suffocation due to airway obstruction by hemorrhage. In lesser, but nonetheless fatal, injuries death is more often due to circulatory failure, air embolism (Benzinger 1950) or complications such as bronchopneumonia (Clemedson 1956). Hamlin (1943) also describes associated nervous system pathology ranging from headache to depressed reflexes and sensorial changes.

3.5 Gastrointestinal Injury

Wolf (1970) attributes intestinal susceptibility to the gas filled areas and the relatively non-muscular walls. Thus, the basic mechanism is similar to that for pulmonary injury. Damage is generally restricted to lower abdomen (Wakeley, 1945) usually with little or no damage to liver, spleen, kidneys and bladder (Hoff and Greenbaum, 1943). Most of the effects in the gastrointestinal tract are related to either the immediate or delayed results of hemorrhage. Although gas-filled space effects predominate, damage to abdominal organs that do not contain air has also been reported. Hemorrhage has been seen in liver, kidney, spleen, pancreas, adrenals and testes (Cameron et al., 1943 & 44, Chiffelle, 1966, Clemedson, 1948 & 49, Fridell and Ecklund, 1943, Goligher et al., 1943, Huller and Bazini, 1970, Hirsch and Bazini, 1959, Richmond et al., 1961 & 73, Williams, 1943, Zuckerman, 1940). This would agree with reports of pain in these areas reported in human data. Fluid filled viscera are, in the main, spared although urinary bladder injuries have been reported in both air (Chiffelle, 1966, Zuckerman, 1940) and immersion blast Yaguda, 1945).

3.6 Central Nervous System

Benzinger (1950) notes focal cerebral signs in both air-blasted and head-out immersion-blasted animals. Most of the nervous system dysfunction that follows blast is attributed to air emboli of pulmonary origin. There is some work that suggests a direct CNS effect. Meningeal tears and bleeds into and around central nervous system tissue have been demonstrated, although the relative contributions of pure blast and gross movement cannot be assessed (Bebb and Wright, 1954). Säljö et al., (1994), believe they have shown that there is abnormal uptake by and leakage out of nerve and glial cells with an intact blood-brain barrier in air-blast exposed rats.

At short ranges, divers report sensations consistent with concussive effects. These are most likely peak pressure effects. At greater ranges, central nervous systems effects are expected to be more similar to the impact of low frequency sound and related to sheer stress caused by a fluctuating pressure wave.

3.7 Nose and Throat

The paranasal sinuses are air-filled but are rarely mentioned as sites of blast trauma. This is probably because most immersion blast has been studied with heads above the water, sinus injury is unlikely to threaten life and, as Wolfe (1970) observes, the structures are encased in bone which will protect from distortion. Rössle (1950) exposed a sheep to air blast using 0.25 kg of TNT at 15 m distance and demonstrated significant hemorrhage within the upper respiratory passages extending to the paranasal sinuses. Bebb and Wright (1954), while evaluating protective materials exposed sheep to 1.25 lb charges. At 15 feet distance (peak pressure 911 psi, impulse 0.138 psi-sec) with no cover or a flexible rubber hood 3 out of 5 animals had depressed fractures of the sinuses. At 25 feet (507 psi, 0.082 psi-sec) there were no sinus injuries. Nedwell and Parvin (1993) report that divers exposed to low frequency (100 Hz) sound at a level of 160 dB re.1μPa experienced a sensation of vibration in the region of the sinuses. Blast waves typically have high energy components over this frequency range.

3.8 Ear

The auditory system can be a limiting factor in exposure to underwater blast, but damage to the auditory system is more likely to be a long-term effect from exposure to multiple blasts. It would be expected that blast would induce damage to the ear and have the potential for creating a hearing loss. Direct experiments for in-water estimates of hearing loss due to impulsive noise, much less blast, are virtually non-existent. Thus it becomes necessary to extrapolate from in-air data. As will be seen, this carries its own set of problems, but there is the advantage of considerable data on in-air blast. The effects described below are mostly from the in-air animal literature. Where there is evidence regarding these effects from blast studies on humans, that data is presented. However, the paucity of underwater blast data severely limits extrapolation.

3.8.1 Middle Ear Effects

The tympanic membrane is possibly one of the easiest structures in which to imagine how a rapid external change in pressure might bring about damage, as an extreme form of the barotrauma frequently seen in diving. In reality, however, middle ear injury from underwater blast is rarely mentioned in the literature. Richmond et al., (1973) describe tympanic membrane rupture and ossicular disruption in dogs close to small charges underwater. The injury was usually confined to the ear facing towards the blast and the proportion of the membrane area ruptured, as might be expected, decreased as distance increased.

Human data (Bebb et al., 1981) agrees with this observation. The person must be close to the blast to have physical damage to the middle ear mechanism. Garth (1994) reviews ear injuries in air-blast. Hamernik (1984a) also reviews how physical components of air blast relate to permanent hearing loss. While there will, no doubt, be differences in blast components responsible for damage, the basic principles of injury and the types of injury for the inner ear are expected to be similar in underwater blast. This may not be as true for the portion of the ear exposed to water.

3.8 .1.1 **Blast waves and their transmission to the ear**

Laboratory animals, cadaveric ears and models have been used to investigate the biophysical interactions of pressure waves with the ear. The nature and severity of damage are influenced by peak overpressure, duration of positive pressure (James et al., 1982) and orientation of the ear canal to the blast wave.

Using a scale model to investigate sound pressure distribution on the tympanic membrane, Stinson (1985) found areas with as much as 20 dB of attenuation. Although the continuous noise used is not the same as a blast wave, this still shows how a wave traveling down the external auditory canal may be modified. Wax might influence the extent of damage. If it occludes the canal it might attenuate the blast, but if impacted on the drum it may act like a 'ramrod' and cause ossicular disruption (Hirsch, 1968). Similar blasts can, therefore, produce injuries of quite different magnitude. Chinchillas exposed to repeated 166 dB re 20µPa impulse stimuli developed altered tympanic compliance, returning to normal within two weeks (Eames et al., 1975). However, inter-species differences (Roberto et al., 1989) make application to humans unreliable.

In summary, tympanic membrane damage observed includes:

a. injection of blood vessels
b. subepithelial hemorrhages
c. small split like perforations (often parallel to the fibers of the lamina propria)
d. multiple or total perforation

3.8.2 **Hearing Loss**

It is well known that excessive levels of noise in air may cause deafness, and legislation exists to control the effects of noise both as a pollutant and as a source of industrial injury. Hearing damage may also occur underwater, both as the result of a single traumatic exposure, such as that from blast, and as a result of repetitive exposures to sound, with a small and irreversible loss occurring as a result of each exposure. There are important differences between in-air noise exposure of industrial workers and in-water noise exposure for SCUBA, bandmask, and helmeted divers.

There are well-established criteria that are used to judge the hazard from airborne noise. For the US Navy the continuous noise exposure limit is 84dB(A) re 20 µPa (110 dB re 1 µPa) for an eight hour period. For each halving of the duration of exposure an increase in level of 4 dB is permitted. Peaks in excess of 145 dB re 20 µPa (171 dB re 1 µPa) are also hazardous. In the context of exposure to underwater impulsive sound, it is very unlikely that the criterion for continuous sound will be significant. However, in view of the high source levels associated with impulsive sources of sound, the peak action level is likely to be of significance. For explosive sources, the source sound level may be as high as 280 dB re 1 µPa. In the case of divers using SCUBA equipment, the sound is attenuated by the inefficiency of the human ear in hearing underwater and the diver’s wet suit hood. In the case of divers wearing helmets, the sound is attenuated in passing from the water into the helmet.

3.8.2.1 **"Wet Ear" exposure**

When the ear is wet and receives sound via the water, the hearing process is modified as a result. The sensitivity of the ear changes from that of the ear in air, and hence the criteria used in atmospheric air do not apply to the underwater case. This has been an area of interest for some time, and measurements have been conducted by a number of investigators (Hamilton, 1957, Al-Masri et al., 1992). While there is a considerable difference in the reported results, a recent and significant experimental program reported by Parvin and Nedwell (1995) made extensive measurements of hearing threshold in air and in water from 20 Hz to 20 kHz.

Whereas hearing in air is most sensitive at about 2 kHz, in water the results indicate it is most sensitive at about 800 Hz. At all frequencies the sensitivity of underwater hearing is significantly lower than in air. The difference is smallest at the lowest frequencies measured, on the order of 20 dB, and increases to about 70 dB at 8 kHz. The implication of this result is a significant degree of attenuation to the effects on hearing of underwater impulsive sound.

Divers generally wear a foam neoprene hood over their heads to prevent heat loss. In effect the diver is wearing a hearing protector, which may further increase protection against the effects of sound. In studies which have examined the potential degree of protection (Smith 1988; Montague and Strickland, 1961; Hollien and Feinstein, 1975; Parvin and Nedwell 1995; Parvin et al., 2000), the thickness of the hood seems to have little effect. In general, high frequencies (above 500 Hz) are attenuated up to 25 dB and lower frequencies are attenuated hardly at all. Even combining these effects to produce an attenuation of 20 to 95 dB still results in very high peak pressure levels close to the sound. For the 280 dB source level given earlier, spherical spreading would still require on the order of 30 km before it would decrease to the peak criterion level of 171 dB re 1 μPa.

3.8.2.2 **Divers wearing helmets**

The ear is in the hyperbaric air of the helmet for divers wearing helmets and hence hearing occurs by the same process as hearing in atmospheric air. The criteria that are used in atmospheric air may be used to predict hazard from hyperbaric noise in a helmet, provided that it is possible to estimate or measure the level of sound at the diver's ear. This could be done if it is known how much attenuation is provided to the sound passing into the diving helmet. Unfortunately, there is little detailed information concerning the transmission of blast into diving helmets, and the measurement problem, due to the small space in the helmet, is formidable. Estimates of attenuation by the helmet range from 13 dB to up to 70 dB at frequencies above 500 Hz (Carderock report, 1995, Nedwell, 1989). Thus divers wearing helmets can still be exposed to considerable peak pressures from underwater blast and would need considerable stand-off distances for safety.

3.8.2.3 **Temporary Effects**

Profound sensorineural hearing loss and tinnitus immediately follow in-air explosions. These are usually short lived with hearing returning within a few hours. Sometimes improvement is gradual, and a few have permanent hearing loss. Teter et al., (1970) described four different characteristic audiometric configurations. Commonest is high tone sensorineural loss. It does not share the 4 kHz dip with noise induced hearing loss, suggesting a different mechanism of injury.

Persistent vertigo following blast injury is uncommon. Pratt et al., (1985) performed brain stem audiometry on 37 human blast survivors and found no central effects.

3.8.2.4 **Permanent hearing loss**

Hamernik et al., (1984b) exposed chinchillas to repeated 160 dB (190 dB re 1 μPa) impulses in air and found a great deal of cochlear damage and permanent hearing loss. Akiyoshi et al., (1966) found less cochlear damage in guinea pigs exposed to a large blast, which disrupted the middle ear, than in those exposed to smaller bursts. Tympanic membrane perforation and ossicular disruption might, therefore, protect the cochlea. Hamernik et al., (1984a) and Eames et al., (1975) reported similar findings using multiple shock waves. Disruption of the conducting mechanism will reduce energy transmission to the cochlea during subsequent shock waves. Kerr and Byrne (1975), however, found no evidence of this phenomenon in their series of human blast victims, though none had ossicular damage.

3.9 **Musculoskeletal**

'Solid' tissues, such as bone, muscle and fat, can tolerate very high shock wave pressures without significant injury. Experimental exposures of a limb to the 7 MPa (1000 psi) shock wave from a small charge at close range results in a strong stinging sensation, but no damage. The shock wave travels through the water and traverses the limb without impediment. Close to the explosive source, however; there is violent trauma to the rib-cage, chest and abdominal contents, and limb fractures. Involvement in the turbulence associated with the bubble pulse results in gross injury, including major lacerations and avulsion of tissues and limbs.

3.10 **Psychological Effects**

Psychological effects have the potential to be the limiting factor in developing guidance for underwater blast in the environmental arena. At low levels of exposure, insufficient to cause hearing damage, sound may still produce significant behavioral effects that could lead to injury. Sudden exposure of a diver to sound may cause the diver to be startled. The diver may react by panicking and rapidly surfacing, with the risk of decompression injury or death, or by spitting out his diving valve, with the attendant risk of drowning. The risk of behavioral effects may be mitigated where divers are aware that they may be exposed to sudden loud noises, and hence startle is of most significance with regard to recreational divers.

There are no existing guidelines as to acceptable levels of underwater blast noise in respect of startle. Some recent evidence that may be applied to the bubble effects portion of the blast waveform is described in the next section.

3.11 Bubble Pulses

The blast studies described to this point have focused largely on effects due to the early part or blast front of the pressure wave. The latter part of the blast wave or the bubble pulses, can actually carry more energy and are much more characteristic of the blast wave at significant distances, on the order of a kilometer or even less, from the site of the blast. This occurs due to the propagation characteristics of a blast waveform through water. This section gives a brief summary of recent results based on studies of the bioeffects of low frequency sound. A more comprehensive treatment can be found in Cudahy et al., 1999. These bioeffects are more likely to serve as estimates for injury at longer distances from the blast than the blast front data. This section also describes measures of the psychological response to sound, an area that will serve as a significant factor in setting exposure limits for recreational divers. [Note: All SPL's in this section are re 1 μPa.]

A key element for interpreting these data and relating it to an underwater blast is the criteria for defining the impulsive waveforms. As will be discussed later (Section 5.1.1) particular selections of waveform parameters covered permit easy extrapolation of the low-frequency sound bioeffects to generating guidance for divers. Of course it would need to be verified that the criteria were correct in selecting these parameters critical to psychological or physiological impact. It could easily be the case that the criteria would be different for predicting the two types of insult.

3.12 Bioeffects of Low Frequency Underwater Sound in Animals

3.12.1 Physiological effects and damage thresholds in different organ systems following low frequency sound exposures: animal data.

The animal species tested included rats, mice and guinea pigs. Larger animal models were not tested because it was felt that the small animal results could be extrapolated to humans. Most tissue damage resulting from LFS exposures is predicted to occur at the resonance frequency of the various organ systems because the greatest amount of tissue displacement for a given SPL occurs at this frequency. Furthermore, large displacements in the lung could cause damage to adjacent organ systems. Preliminary research (Rogers, et al., 1996) suggested that there might be a human lung resonance at around 130 Hz. Given the importance of the lung to a human diver, much of the animal research was directed toward defining the damage thresholds of the lung and surrounding tissues at the lung resonant frequency.

In order to identify correctly damage risk thresholds for various organ systems resulting from LFS exposures in animal preparations, it is important to isolate those effects that are due to aspects of the experimental procedures that are unrelated to the sound exposures. This isolation includes controlling for the effects of immersion *per se* and any surgery and anesthesia required to keep the animals on a ventilator. In the studies listed below, assessment of damage risk thresholds and performance changes in animals exposed to LFS were thus compared with a control group of animals that underwent sham exposures (i.e., submersion in the G40 calibrator without the presence of sound). In addition, studies had a control group of animals that were not submerged but were anesthetized and prepared for testing in the same manner as the experimental group.

It should be noted that while the frequency content of the signals tested is within the range of interest for underwater blast, the duration of the signals considerably exceeds that of the typical blast waveform. Thus, any estimates of damage risk threshold in these experiments should be conservative relative to the damage risk threshold for underwater blast. Damage risk thresholds were always measured at lung resonance frequency and above lung resonance frequency so that any effects observed were not contaminated by damage to the lungs and hence, reflected a generalized debilitation of the animal rather than injury to the specific organ system under investigation.

3.12.2 **Lung Resonance**

Using an acoustic scattering technique to measure the lung resonance frequency in mice and rats, Dalecki (1998) found that the lung resonance frequency (f_o) in Hz varied as a function of body mass (w) in grams according to the following relationship:

$$f_o=742w^{-0.25}$$

These data indicate that the resonance frequency of the lung varies with body mass in close accordance with the quarter-power scaling described recently by West et al., (1997). According to the above formula the resonance frequency of the lungs for a 70 kg (154 lb) person is predicted to be approximately 45 Hz. This model's prediction compares favorably with the observed lung resonance frequencies of divers found in the human experiments described later.

Results of LFS exposures at lung resonance indicate that there is no observable lung damage in guinea pigs at SPLs up to 170 dB. Data on LFS exposures at lung resonance frequency in mice show that the threshold for both lung and liver hemorrhage occurs at about 184 dB (Dalecki, 1998) and increases rapidly as intensity is increased. Preliminary data indicate that the threshold for lung hemorrhage at the lung resonance frequency in rats is somewhat higher than in mice. The resonance curve itself is relatively narrow and lung damage is reduced rapidly as the target frequency deviates from the resonance frequency.

3.12.3 Vestibular Effects

Measurable performance decrements in vestibular function were observed in guinea pigs using 160 dB SPL signals at the lung resonance frequency and 190 dB SPL signals at 500 Hz (Jackson and Kopke, 1998). No decrements in performance were found for an additional group run at 150 dB SPL. These results suggest that subtle changes in vestibular functioning may occur following LFS exposures as low as 160 dB at lung resonance frequency (Jackson and Kopke, 1998).

3.12.4 Cognitive Effects

McIntosh (1998) examined central nervous system effects including neuromotor, memory, learning, and brain cell histology. Neurological, motor and cognitive effects were evaluated 48 hours, 1 week and 2 weeks post-sound exposure. He found that there was no evidence of concussive effects in rats exposed to 150 Hz (close to their rat population lung resonance frequency) signals at 180 dB SPL. A 250 Hz signal of 192 dB SPL produced a mild impairment in learning performance. A 250 Hz, 150 dB signal produced no effects on neuromotor or cognitive performance. Histological analysis showed no significant cellular effects in the hippocampus or cerebellum.

3.12.5 Summary of animal experiments

The animal experiments appear to support a damage risk threshold of about 160 dB SPL for 5-minute continuous signals. It is clear that no effects were ever observed for 5-minute signals at 150 dB SPL. The continuous signals tested in the animal studies were much longer than signals produced by underwater blast, which are on the order of msec. This would suggest that signals below 160 dB SPL using short duration signals would be safe physiologically. The human experiments were conducted to determine if effects could be elicited at these lower intensities.

3.13 Low Frequency Underwater Sound Exposures in Humans

3.13.1 UK Diver Noise Exposure Test (15 Hz to 1500 Hz).

During 1993 and 1994 the UK Defence Evaluation Research Agency conducted several series of low frequency noise exposures (Nedwell and Parvin, 1993, Parvin and Nedwell, 1994, Parvin, 1998). All of the test involved exposure of divers to underwater sound at a level of 160 dB re.1μPa. The initial study was conducted in a small water tank (3mx2mx2m deep). The results indicated a human lung resonance at a frequency of 25 Hz, and a vibration within the diver's mask at a frequency of approximately 100 Hz that was attributed to a resonance of the sinuses. In the subsequent hyperbaric phase of the trial these resonances shifted up in frequency. At a depth of 30m, the waterborne sound produced a sensation of vibration within the chest over the frequency range from 52 Hz to 110 Hz, and a buzzing sensation within the head over the frequency range from 52 Hz to 500 Hz. Nedwell and Parvin suggested that the Minnaert theory of gas bubbles in water (1933) could be applied to the air containing structures of the body to indicate resonance frequency. This would also suggest that the resonant frequency would increase as the square root of absolute pressure. The final series of tests extended these findings to open water conditions.

3.13.2 US Diver Noise Exposure Tests.

In order to simulate the free field acoustic characteristics in the laboratory environment, particular attention was directed toward choosing appropriate underwater testing facilities and methodological techniques for the sound exposures. Most of the human trials were conducted at the Space and Naval Warfare Systems Center Transducer Evaluation Center (TRANSDEC) in Point Loma, CA. TRANSDEC is a specially designed anechoic acoustic testing pool that has contoured sides and sound traps designed to reduce boundary effects and thereby simulate the acoustic transmission properties of an infinite expanse of water.

All subjects held a civilian SCUBA diving certification and were medically cleared for diving by a US Navy diving medical officer. The subjects' ages ranged from 20 - 44 yrs, with diving experiences ranging between 2 weeks and 25 years. The median number of dives completed by all participants prior to conducting the sound experiments was between 25 and 30. The proportion of men to women (2:1) in the subject populations corresponds closely with that of the active diving population listed in the Divers Alert Network (DAN) insurance database.

3.13.3 Vibration Detection

Auditory thresholds were measured for divers within the frequency range of 100 – 500 Hz and ranged from approximately 100 dB SPL at 100 Hz to 90 dB at 500 Hz. At SPLs above the underwater hearing threshold, SCUBA divers begin to detect vibration in various body parts. The most likely body areas for detection of vibration are those that contain air filled cavities such as the lungs, abdomen and head. Lower levels of vibration were reported in the arms, hands and mask. At a given SPL, vibration will be detected first at the lower frequencies (i.e., 100 Hz). At 130 dB SPL nearly all subjects reported detecting vibration for 100 Hz sound exposures. However, as the frequency of the LFS is increased from 100 to 500 Hz, the probability of detecting vibration in any body part decreases with increasing frequency (Fothergill et al., 1998A). These data indicate that the threshold for detection of vibration during exposure to LFS is frequency dependent, and, for most subjects, lies below 130 dB SPL for frequencies below 500 Hz.

3.13.4 Neuropsychological and Vestibular Effects

Immediately prior to and immediately following one of the dive studies (Sims et al., 1998A), the subjects performed an extensive battery of tests designed to assess if the LFS exposures affected neuropsychological and vestibular functioning. The neuropsychological functioning was measured with the Automated Neuropsychological Assessment Metric (ANAM), which was administered prior to and immediately following the second of two 60 min dives in which multiple underwater sound exposures were administered. This test provides assessment of mood state, arousal, reaction time, attention, concentration, learning and memory, mathematical reasoning, and spatial processing. Statistical analysis of pre-dive and post-dive ANAM scores revealed no adverse effects of cognitive processing following LFS underwater exposures.

None of the tests of neuropsychological functioning showed a significant decrement in performance as a result of the LFS exposures. Recreational sport divers did not report acute or delayed vestibular symptoms. Post study mean equilibrium performance tests were unchanged or improved in all divers compared to pre-dive baseline. Post-study mean dynamic visual acuity and occulomotor performance tests were unchanged in all divers compared to pre-dive baseline (Clark et al., 1998).

3.13.5 Cardiac Effects

Studies of the effects of LFS on cardiac control in humans have so far only examined changes in heart rate (HR) (Sims et al., 1997, 1998A). Current findings indicate that HR decreases approximately 10% during the presence of LFS (Fothergill et al., 1998B). The interpretation of these results is that LFS provokes a temporary decrease in HR that is consistent with a normal non-habituating orienting response to sound (Fothergill et al., 1998B).

3.13.6 Vascular Effects

Assessment of the possible vascular effects of LFS in immersed individuals was conducted based upon observed effects in humans and animals reported in the current literature and extrapolation of this direct evidence to conditions encountered during exposure to LFA sonar using theoretical considerations (Gerth and Thalmann, 1998). The conclusions of this literature review suggest that it is very unlikely that exposure to LFA emissions at SPLs up to 182 dB will induce vascular damage or increase the risk of a pre-existing cerebral aneurysm to rupture relative to the risk during normal everyday physical activity (Gerth and Thalmann, 1998).

3.13.7 Lung Resonance

Human diving experiments have directly measured lung resonance frequency in an acoustically treated wet pot located within a hyperbaric chamber. Results indicate that the human lung resonance frequency is approximately 40 Hz at the surface and increases as a function of depth to 80 Hz at 120 FSW. Although no empirical data is available on the minimum SPL required to induce lung damage at lung resonance frequency, present models of the human lung predict that the greatest amount of tissue strain with LFS will occur in the central airways at frequencies between 30 and 40 Hz (Jackson, 1998). If tissue damage in the lung is caused by excessive tissue deformation then these model predictions would indicate that the greatest chance for damage to the lung tissue would occur for LFS exposures at frequencies close to the observed lung resonance frequency.

3.13.8 **Aversion**

At SPLs above 130 dB, aversion to LFS increases in direct relation to the increase in SPL. However, the subjective level of aversion at a given SPL and frequency is highly variable between individuals. At an SPL of 140 dB, none of the subjects exceeded an aversion rating of "Very Severe" for the frequency range 100 - 500 Hz. At the highest SPL tested (157 dB) there was a 19% chance that the subjective level of aversion to LFS would exceed "Very Severe" (Fothergill et al., 1998A). According to the experimental design of the study by Fothergill et al., (1998A) any individual who gave an aversion rating greater than "Very Severe" for a given sound presentation was not subjected to further sound exposures for that frequency and signal type. Figure 3.1 shows the percentage of sound exposures at each SPL tested that were not presented due to the subjects' aversion ratings exceeding "Very Severe". The line drawn through the points in Fig 3.1 was fitted using a cubic spline function. This figure shows that an increasing incidence of high levels of aversion to LFS occurred once the SPL exceeded 148 dB.

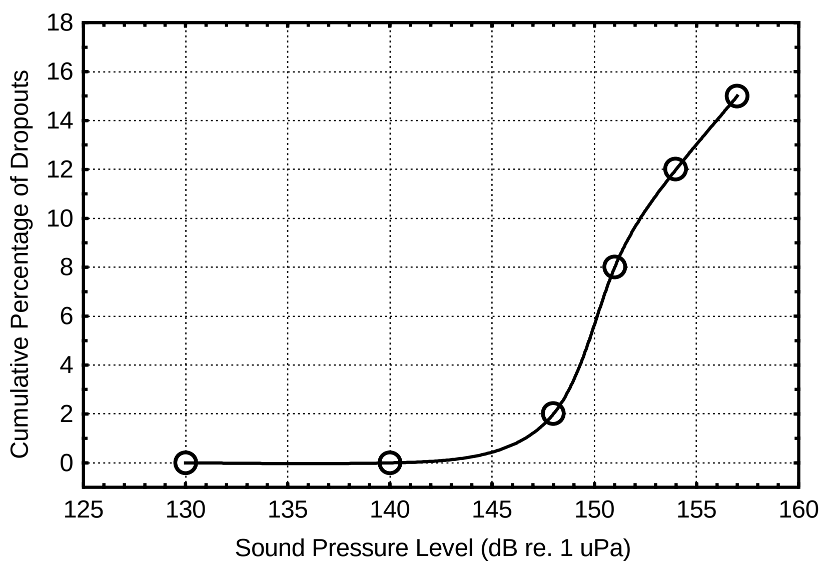

Figure 3.1: Cumulative percentage of sound exposures not presented to subjects at each SPL tested as a result of aversion ratings to previously presented LFS stimuli exceeding "Very Severe" (Fothergill et al., 1998A).

Although there were no differences in the reported level of aversion between the different signals presented (pure tone, 30 Hz hyperbolic sweeps up and down) there were significant differences in aversion ratings among the frequencies tested. Results showed that aversion to LFS varied according to a 'V' shaped function between 100 and 500 Hz, with the most and least aversive frequencies occurring at 100 Hz and 250 Hz, respectively (Fothergill et al., 1998A). This same pattern of response was also shown for perceived loudness levels for LFS between 100 and 500 Hz (Sims and Fothergill, 1999).

The effect of duration of the LFS sound exposures on aversion was tested with the most aversive frequency (100 Hz) at a SPL of 136 dB (Sims et al., 1997). The duration of the sound exposures lasted between 7 and 28 s with at least a 50% duty cycle between consecutive sound exposures. The increase in sound duration from 7 to 28 s did not significantly affect the aversion ratings which were on average midway between “Very Slight” and “Slight”.

3.13.9 Summary of human research

In summarizing the above research on the effects of LFS in humans, it is clear that behavioral and psychological reactions to LFS are the major limiting factors for LFS exposures up to 157 dB and within the 100 – 500 Hz frequency band. Of particular concern is the level of aversion induced by LFS since this will possibly determine the level of enjoyment or amount of time spent underwater by a recreational diver during the presence of LFS. Aversion to LFS exposures is likely a function of both the perceived loudness of the sound and the level of vibration felt during the sound exposure. However, post-test debriefings indicated that twice as many subjects rated the loudness aspect of the sound as more annoying than the vibration aspect of LFS. Despite occasional extreme ratings for aversion, loudness and vibration, which for some individuals exceeded “Extremely Severe” for the 157 dB exposures, none of the sound exposures resulted in an uncontrolled or unsafe ascent to the surface (Sims and Fothergill, 1999).

During a post-test debriefing, 21% of subjects indicated that they would abort a dive if they were exposed to these sounds (SPLs up to 157 dB) during an open water dive. Unfortunately, it was not possible to discriminate the precise SPL and frequency of LFS at which they would have aborted their dive (Sims and Fothergill, 1999).

Summary of Research Findings

It is clear from the human and animal research that there are no observable effects of LFS on the major organ systems at SPLs below 160 dB. At SPLs above 160 dB the first system that will most likely show a decrement as a result of the LFS exposure is the vestibular system. However, at SPLs of 160 dB continuous LFS sound exposures of 5 min or more are required before significant decrements in vestibular performance are observed. When rats and mice are exposed to LFS at lung resonant frequency, significant lung and liver hemorrhage does not occur until SPLs exceed 170 dB. Considerably higher SPLs are required to induce lung and liver hemorrhage if the LFS exposure deviates significantly from the lung resonant frequency. As the lung resonance frequency of humans falls well below 100 Hz, the threshold for damage of lung and liver tissue during LFS exposures will be much higher than that shown for rodents.

The primary effects of LFS on the recreational diver at SPLs below 160 dB are limited to psychophysical sensations of loudness and vibration. The perception of loudness and vibration during LFS exposures seem to be the primary components that contribute to the diver’s level of aversion to LFS. As the level of aversion to LFS will likely determine the level of enjoyment or amount of time spent under water by a recreational diver during the presence of LFS, it would be prudent and justifiable to use this measure as the lowest limiting system in the development of the guidance for LFS exposures in recreational divers.

4.0 Underwater Blast Injury Models

4.1 Introduction

4.1.1 This section of the report reviews the models that have been proposed for determining the limiting physiological criteria and stand-off ranges from underwater blast. Some of the early models are based on the shallow water blast exposure of animals and divers to underwater TNT charges. The empirical models that were developed as a consequence of these studies incorporate blast propagation within them. The more recent studies have attempted to identify an injury threshold for either peak pressure or impulse. Stand-off range is then determined using sound propagation models.

4.2 Lethal Range

4.2.1 Bebb and Wright (1947,1951,1952a,1953) made extensive use of animal models to determine the effects of underwater blast. As a result of a series of underwater blast exposures over short range, a formula to estimate the lethal range from an underwater charge of known weight was proposed. It is based on the conclusion that a peak pressure of 12,000 kPa and an impulse of 700 Pa-s would be lethal to a diver, as would a wave of 4300 kPa peak pressure with an impulse of 4900 Pa-s. For charges of between 1 lb (0.45 kg) and approximately 300 lb (136 kg) of TNT, the lethal range D in feet, from a charge of M lb., fired underwater is regarded as being within a distance

$$D = 7 M^{0.5} \qquad (1)$$

If this formula is expressed using the International System of units (SI), then the lethal range R_L in meters for a charge of weight W in kg is given by,

$$R_L = 3.17 W^{0.5} \qquad (2)$$

4.2.2 The US Navy Diving Manual (1970) contains guidance on the exposure of divers to underwater blast. This is based on the studies of Bebb and Wright, and also on the trials aboard USS Wassuc and at Stump Neck (Naval Ordnance Laboratory, 1942). The guidance is based on peak pressure alone to describe the severity of the effect from an underwater blast. The peak pressure P (psi) for TNT exposive is derived from the relationship,

$$P = \frac{13\,000\ M^{0.33}}{D} \qquad (3)$$

where M is the mass of the charge in pounds and D is the distance in feet. The injury potential from an underwater TNT blast is outlined in table 4-1.

Peak Pressure (psi)	Peak Pressure (kPa)	Effect
>2000	>13800	Death Certain
500 - 2000	3450 - 13800	Likely to cause death or severe injury
50 - 500	345 - 3450	Likely to cause injury
< 50	<345	Unlikely to cause injury.

Table 4-1. Injury potential of an underwater TNT blast (US Navy Diving Manual, 1970).

Therefore, assuming the effect of the blast is lethal as the peak pressure exposure increases above 2000 psi (13800 kPa). Equation 3 can be re-written in the SI system of units where the stand-off range to avoid lethal effects is given by

$$R = 3.17\ W^{0.33} \qquad (4)$$

4.2.3 Yelverton et al., (1973,1976) used terrestrial mammals immersed in shallow water, to establish models for the potential lethal effects of underwater blast. The studies are referred to by Richardson (1995) in converting the expressions for fish mortality into those that are representative of larger sea mammals. The expressions relate the impulse I (Pa-S) of the underwater blast that would produce a mortality probability and "no-injury" exposure, for a body weight W (kg). It is suggested that these expressions can be extended to a submerged diver or swimmer where,

50 % mortality $$\log_e (I_{50}) = 5.01 + 0.3857 \log_e W \qquad (5)$$

1% mortality $$\log_e (I_1) = 4.55 + 0.3857 \log_e W \qquad (6)$$

Assuming a diver of mass 80 kg then these expressions suggest a diver impulse that will produce a 50% mortality I_{50} = 812 Pa-s and a 1% mortality I_1 = 516 Pa-s.

4.3 Physical Injury / Deterrent Range

4.3.1 The previous section of this report on biomedical effects of underwater blast outlined the series of diver noise exposure tests that were conducted in the UK by Wright et al., (1951). Table 4-2 presents the comments from Wright following the blast exposures that he undertook at comparatively short ranges from the source. The final series of exposures indicate that Wright went within the region at which some violent and disabilitating effects of the blast were recorded. (It should be noted that the peak pressure and impulse levels were estimated from the blast scaling laws available at the time. They are not as a result of actual measures of the physical parameters.)

4.3.2 In the subsequent trial that occurred at Spithead, Portsmouth, divers were exposed to underwater blast at a considerably greater range than that which Wright underwent (See Table 4-3). The results indicate that shallow water exposure to a 5 lb (2.27 Kg) charge at a range of 411m produced a "slight squeeze" and a sound like a "dull bang" or "rumble".

There are no indications that any of the divers were unduly concerned by exposure to the charge at this range, or any signs of physical injury in the subsequent medical examination. However, the divers in this study underwent numerous exposures to underwater blast and so were somewhat accustomed to the effects. The divers involved in the Spithead study were eventually exposed to a 25 lb (11.3 kg) charge at a distance of 65.6m. At this point the trial was terminated as a significant number of the divers were developing a "wheeziness" in the chest.

Range		Sensations	Estimated Shock Levels			
feet	meters	Subjective comment	P psi	P MPa	I psi-msec	I Pa-S
110	33.5	Sound of intense bang.	160	1.1	75	516
100	30.5	Intense bang. Mild blow on chest	175	1.2	85	585
90	27.4	Severe blow on chest	195	1.3	95	654
80	24.4	Blow on head and torso. Body shaken. Brief paralysis of arms and legs	220	1.5	105	720
75	22.9	Violent blow. Brief paralysis of limbs. Substernal pain for 1/2 to 1 hour.	240	1.65	110	760
70	21.3	Violent blow. Temporary paralysis of limbs. Substernal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	260	1.8	115	790

Table 4-2. Subjective comment from a diver exposed to a 5lb (2.27kg) charge of TNT (Wright et al., 1950)

Range (meters)	Diver depth (meters)	Impulse (Pa-S)	Peak Pressure (kPa)	Subjective Comments (Assessed from comments of up to six divers for each underwater blast)
411	3.05	50	83.6	Small impact, waist squeeze, push. Sound like bang, crack rumble.
411	15.25	50	83.6	Jolt, vibrated through body, hardly felt a thing. Heard dull bang, like Chinese cracker.
183	3.05	103	209	Slight impact, slight vibration - lower half of body. Quite a loud bang, sharp and sudden bang.
183	15.25	103	209	Shudder all over, felt blast - shove from waist upwards. Louder than I expected, two pretty loud bangs.
122	3.05	134	311	Vibration of whole body, slight sharp squeeze all over, fairly powerful thump in belly. Sharp loud explosion, low rumble, fairly loud bang - two distinct echoes.
122	15.3	134	311	Shook whole body, squeeze all over, blow on front of chest and top of head, pressure in ears. Loud explosion, double very loud rumbling bang, loud muffled bang.

Table 4-3. Summary of results from exposure of divers to a 5 lb (2.27 Kg) charge in shallow water (Wright et al., 1950).

4.3.3 Based on the exposures that took place at Spithead and on the preceeding exposures that Wright underwent at Horsea Lake, an equation for estimating the deterrent range for a "well motivated assault swimmer" was postulated, where the deterrent distance D in feet could be estimated from,

$$D = 40\ M^{0.5}, \qquad (7)$$

and where M is the weight of the charge in pounds. If Wright's formula is expressed using SI units, then the deterrent range R_D in meters for a charge of weight W in kg is given by,

$$R_D = 18.1\ W^{0.5} \qquad (8)$$

4.3.4 Bebb and Wright's conclusions, and the formulae that they developed are based on the shallow water exposure of divers. The authors warn of the dangers of extrapolating the peak pressures and impulses that these relationships derive to other circumstances. The deterrent range for a surface swimmer could easily be halved without any adverse effect. However, with the diver and the charge at a deeper depth unexpectedly severe effects may be experienced at 3 to 4 times the deterrent range.

4.3.5 The US Navy Diving Manual states that as the peak pressure increases above 3450 kPa there is an increasing risk of severe injury, leading to lethal effects as the peak pressure approaches 13800 kPa. Re-writing equation 3 in the SI system of units for a peak pressure of 3450 kPa indicates a stand-off range for a charge of mass W kg where,

$$R = 10.8\ W^{0.33} \qquad (9)$$

4.3.6 Richardson (1995) also quotes an expression for the underwater impulse that will produce a 0% mortality for fish and marine mammals where,

$$\log_e (I_0) = 3.68 + 0.3857 \log_e W \qquad (10)$$

for a diver of mass 80 kg this indicates a value for I_0 = 215 Pa-s.

4.4 <u>Non-injury range</u>

4.4.1 Tests with submerged animals, primarily sheep, indicated that there was no incidence of physical injury provided that the impulse did not exceed 5.5 psi-milliseconds (38 PaS) or a peak pressure of 125 psi (9.05 x 10^5 Pa or 239 dB re.1µPa) (Yelverton et al., 1973; Richmond et al., 1973). A "safe" level for human swimmers of 2 psi-msec (14 PaS) was proposed. In addition to this impulse level, Christian and Gaspin (1974) also included a maximum peak overpressure of 50 psi (345 kPa or 231 dB re.1µPa). The figure of 50 psi for a non-injury peak pressure is quoted in the US Navy Diving Manual (1970). This level of peak pressure is comparable with the impulsive noise incident upon a diver operating some of the noisier underwater bolt guns (Parvin, 1994). It is an extremely loud noise even to a diver wearing head protection. Hence, although the data suggests that this level of peak pressure will not cause direct injury, it is too high a level of exposure for a recreational diver.

4.4.2 The criteria proposed by Christian and Gaspin (1974) and also Gaspin, (1983) were used to calculate "safe zones" for military swimmers and divers. When these blast exposure limits are compared with the exposures undertaken by the divers in the spithead study (Wright et al., 1950) they initially appear to be fairly conservative estimates. However, the experimental studies and subsequent modeling of blast injury ranges undertaken by Christian and Gaspin were all conducted at very shallow depth (Surface to 10m depth). Christian and Gaspin were quick to point out that the level of impulse delivered to a distant point is a function of the geometry. Nedwell (1988) (Marine Technology Directorate, 1996) developed an expression that can be used to determine diver stand-off for any combination of diver and charge depth. The expression is of the form,

$$R = 22.5\ W^{0.2}\ d^{0.33}\ h^{0.33} \qquad (11)$$

where W is the weight of TNT charge in kilograms, d is the diver's depth and h is the charge depth in meters. This expression has been adopted in British Standard BS 5607, "Code of practice for safe use of explosives in the construction industry" (British Standards Institute, 1988), as a method for estimating the minimum stand-off distance for divers and swimmers from underwater blast. It is based on the range at which no direct physical injury should occur. The expression highlights the importance of diver and charge depth in assessing the effects of underwater blast on divers. Doubling the diver depth would increase the stand-off range by a factor of $\sqrt[3]{2}$ or 1.26 whereas doubling the charge weight W would increase the stand-off range by a factor of 1.15.

4.5 Use of existing models to assess stand-off range from TNT charges

4.5.1 The models set out in this section of the report have been used in Table 4-4 to estimate stand-off range for divers for charge weights from 0.1 kg to 100 kg. The impulse models of Richardson (1995) (I_{50}, I_1 and I_0) and of Christian and Gaspin provide effect thresholds at the diver. For these cases the source impulse and propagation with range have been estimated using the models of Aarons (1954) for propagation in the non-linear region, and that of Rogers (1977) in the far field linear region. It has been assumed that both the diver and source are at a depth of 10m. Similarly, the expression proposed by Nedwell (1988), makes allowance for both source and diver depth, and so for consistency, values of 10m depth have also been used here.

4.5.2 The first two models of Table 4-4 indicate the range at which the blast from an underwater TNT explosion is expected to produce a 100% mortality rate. As well as being dimensionally incorrect (implying that the constant has dimensions and is a function of the specific test parameters), the models fundementally disagree on the dependance of stand-off range with charge weight. The Bebb expression uses a square root relationship, whereas the US Navy Diving Manual uses a cube root and is solely based on peak pressure. Consequently, for a 1 kg charge the models are in agreement, but larger charges produce greater variance in the calculated stand-off range. For a 100 kg TNT charge the models vary by over 100%.

4.5.3 The data indicate that a 1kg charge would produce 100% lethality for a diver inside a range of 3m, a 50% lethality at 7m, decreasing to a 1% lethality at 12m. The physical injury models indicate that the blast wave from the 1 kg charge is likely to cause injury to a range of approximately 20m (Taking Bebb and Wright's expression at 18.1m and I_0 at 31m). Using a peak pressure of 3450 kPa (US Navy Diving Manual value for death or severe injury) generates a stand-off range of 10.8m, which is well within the range at which the Richardson impulse models indicate a significant mortality.

4.5.4 The stand-off range data for the physical injury models can also be compared with the subjective comments from the underwater blast exposures of Wright (See table 4-1). At a range of 33m from a 2.27 kg TNT charge Wright reported an "intense bang", but with no obvious signs of physical injury. The effects became progressively severe with the diver experiencing "brief paralysis of the arms and legs" at a range of 24m, and the onset of physical injury at 21m. As expected, as it is based on these results, the Bebb and Wright model is in good agreement with these findings indicating the onset of physical injury at 18m for 1 kg charge and 57m for a 10kg charge. The impulse model of Richardson for 0% mortality produces a conservative stand-off range, but it should be noted that this model applies equally to deep water where the impulse duration will not be reduced.

	Charge Weight			
	0.1 kg	**1 kg**	**10kg**	**100 kg**
Lethal Range				
1. $R_L=3.17W^{0.5}$ (Bebb and Wright)	1m	3.17m	10m	31.7m
2. $R=3.17W^{033}$ based on P>13800 kPa. (US Navy Diving manual).	1.47m	3.17m	6.8m	14.7m
3. I_{50} = 812 Pa-s (50% mortality for 80kg mammal, Richardson)	1.3m	7.3m	36.7m	123m
4. I_1= 516 Pa-s (1% mortality for 80kg mammal, Richardson)	2.3m	12.1m	59.8m	165m
Physical injury / Deterrent range				
5. $R_D=18.1W^{0.5}$ (Bebb and Wight)	5.7m	18.1m	57m	181m
6. $R=10.8W^{033}$ based on P<3450 kPa. (US Navy Diving manual).	5.0m	10.8m	23.3m	50.1m
7. I_0 = 215 Pa-s (no mortality for 80kg mammal, Richardson)	6.4	31.2	133	272
Non-injury range				
8. $R=83.2W^{033}$ based on P<345 kPa. (US Navy Diving manual).	38.6	83.2	179	386
9. I = 14 Pa-s (Christian and Gaspin,)	112	389	710	1113
10. $R=22.5W^{0.2}d^{0.33}h^{0.33}$ (Nedwell)	61.1	96.7	153	243

Table 4-4. Comparison of diver stand-off distance (in meters) for underwater TNT charges.

4.5.5 The non-injury models indicate that the peak pressure, and hence the loudness of the 1 kg TNT blast has fallen to an acceptable level for an aware military or commercial construction diver at a range of either 83.2m (US Navy Diving Manual) or 96.7m (Nedwell, 1988). The non-injury impulse criteria used by Christian and Gaspin (14 Pa-s) produces a much longer stand-off range at 389m.

4.5.6 The data contained within Table 4-4 indicates that the underwater blast models are in good agreement where the charge weight is small, and the effect threshold is related to lethality or physical injury. The models do not extrapolate well for larger charges. At longer range those models that are based on peak pressure produce much shorter stand-off distance for each of the effect thresholds. As outlined in section 2 of this report, due to the greater rate of absorption of high frequency energy components of the blast wave as it propagates, the peak pressure amplitude is rapidly reduced. Consequently, at longer range it is likely that the low frequency components of the blast wave will produce the limiting physiological criteria. Dependance on peak pressure in this instance may indicate an insufficient stand-off from whole body vibration effects.

4.5.7 None of the models that are currently available address the impact of a distant underwater blast wave on a recreational diver or swimmer. Use can be made of the existing knowledge of underwater hearing threshold to estimate the perceived loudness of a blast wave, but no measures have been conducted to support an exposure limit for this case.

5.0 Research Needs

5.1 Research Gaps and Needs

It is not possible to use the results of the experimental programs reported in the preceding sections to predict a suitable standoff range from a given charge directly, in view of the limited range of experimental conditions, charge weights and geometry. The limited and uncertain measurement information adds to difficulty. Furthermore, the type of data collected is such that it can be used only to relate to physical harm to the diver or prevent the diver from completing a task. There is no data on the psychological impact of underwater blast on the recreational diver, nor at what level the diver may abort the dive due to the blast. For military applications, they may however be used to find the level of blast at which given effects occur, and hence to establish acceptable levels of blast exposure. Given a suitable model that can predict the blast level from a charge as a function of physical parameters, it is a simple matter to predict an acceptable standoff distance. Based on the foregoing review, a case where sufficient information exists to determine a guidance is for small charges at short range. This guidance is discussed in section 5.2.1.

5.1.1 Selection of Parameters Critical for Bioeffects

A key element in developing a research program leading to guidance in underwater blast exposure is to define the parameters that characterise the blast wave. Impulse duration has been estimated using a number of different methodologies, and the correct measurement of peak pressure for any transient event relies on the analysis being conducted with a sufficient sample rate. In addition, the frequency components within the impulse wave are vital in understanding both the physical and psychological impact of the blast wave. To ensure a common approach across any future studies these parameters need to be clearly defined at the outset.

5.1.2 Exposure to large charges at long range

Table 4-4 indicates that there is a considerable variation in the predicted stand-off range for large charge weights. Those models that are based on peak pressure produce considerably shorter stand-off ranges than those based on impulse for all of the effect thresholds. Section 2 of this report discussed the transition in the blast wave that occurs as it propagates away from the source. At long range the waveform will approximate more to that of a short duration, low frequency waveform than a steep-sided peak pressure wavefront. Consequently, the duration of the wave is likely to be as significant as the pressure amplitude. As the waveform is transformed during propagation the resulting injury mechanisms within the body are almost certain to change. At present there is a poor understanding of the effect thresholds and injury mechanisms for both peak pressure and impulse, and so the point at which this transition occurs cannot be predicted. Indeed, it would be better if there were some common physical parameter of the blast wave and its impact with the body that incorporated both the peak pressure and impulse. This could then be used to predict injury throughout the propagation of the blast.

The concern regarding exposure to explosive charges at long range is that this is the situation that will occur during ship shock trials, ordnance disposal or seismic activity. Military, commercial or recreational diving may occur simultaneously, with the potential for an aversion reaction at considerable distances from the source.

5.1.3 **Depth**

It is also worth considering that none of the animal or diver blast exposure studies have been conducted in deep water. In the study at Spithead, some of the divers were exposed to blast at a depth of 15.3m. This is the deepest controlled underwater blast exposure data. Nedwell's (1988) expression incorporates both the source and diver depth and indicates that stand-off range should be increased with depth. The expression suggests that the depth factor has a greater influence on the predicted stand-off range than the charge weight. Mine-warfare divers are currently able to operate to a depth of 80m, with stretch potential to greater depth. Guidance on exposure of divers to an underwater impulsive source must, therefore, address the depth issue. At present the Nedwell expression is untested and there has been no controlled exposure of divers to underwater blast waves at a depth greater than 15.3m. The majority of the modeling of underwater blast waves on divers has involved shallow water applications.

5.1.4 **Multiple Reflecting Surfaces**

As indicated at the beginning of this chapter, guidance can be done for only a limited set of conditions, especially with regard to geometry and depth. A recent incident illustrates the need to have an underwater blast noise standard for enclosed spaces (Clarke, 1998). The Russians have developed an underwater rifle. They desired to show off this rifle at a conference being held at the Navy Experimental Diving Unit (NEDU) and SEALs were tasked to demonstrate the rifle in operation within a test pool. When the rifle was brought into the test pool and fired the SEALs reported effects that suggested they were experiencing whole body reactions to the test firings. The reactions were severe enough that the SEALs were concerned about being permanently injured. It was speculated that the rifles produced what was in effect an underwater blast noise impulse and this was dangerous in the enclosed space of the test pool. The Naval Submarine Medical Research Laboratory (NSMRL) was consulted and informed NEDU that there was no official instruction covering the effects of blast-produced sound on divers in an enclosed space. It was requested that some measurements be made and these would be compared to the literature that was available to NSMRL for some guidance. The test was set up but at the Russian's request was not conducted. Rather than cancel the demonstration it was decided that the rifles would be fired in a less desirable relatively open ocean area near NEDU (per NSMRL and NEDU recommendation) and this was done without incident.

This case illustrates the need for a requirement to develop a databased guidance regarding blast noise in enclosed spaces. The currently available guidance (Christian and Gaspin, 1974; Gaspin, 1983) specifically excludes enclosed spaces or multiple reflecting surfaces.

5.1.5 Other types of underwater impulse exposure

All of the current underwater blast exposure models either directly relate to exposure to an underwater TNT charge, or are physiological limits based on the exposure of animals or divers to a freely suspended TNT charge. Section 2 of this report highlighted the considerable range in amplitude and duration of the blast waves that are produced by underwater explosives and impulsive sources. Currently, there is very little data on either animal or human exposure to other types of underwater impulsive source, and no guidance in place by which to assess acceptable exposure.

Shielded mild detonating cord (SMDC) is used in a number of models of both commercial and military helicopter. For the British Royal Navy, in the event of ditching the helicopter windows are removed by this severance cord, allowing the crew to escape the cockpit. The United States Navy has a similar approach except that a hatch is created by the detonating cord in the floor of the cockpit. The pilot is expected to initiate the detonation after the helicopter has turned over in the water and the cockpit has filled with water.

The UK Ministry of Defence is in the process of procuring a Weapons Attack Helicopter that will have the capability of operating from an amphibious assault ship. DERA has been tasked with assessing the impact on the UK helicopter aircrew of operation of the severance cord in the event that the helicopter has ditched, rolled in the sea, and the cockpit is flooded. Measurement of the physical parameters from underwater severance cord were conducted (Parvin, 2000), however, other than the open water blast models, there is no criteria by which to assess impact on the aircrew.

During underwater demolition or ship’s husbandry tasks divers routinely operate underwater bolt (stud) guns. These devices use a deflagrating explosive to propel a hardened steel bolt through wood, concrete or steel plate. The diver operating the bolt gun is very close to the explosive source (approximately 0.3m) and is therefore exposed to high incident peak pressure. The analysis of impulse exposure to divers operating this type of bolt gun has highlighted the problems of implementing an impulse noise limit (Parvin, 1999). The impulse duration was defined in this study as the period from the initial peak pressure of the blast waveform until the amplitude of the subsequent pressure variation had decayed to 10% of this original value (Ministry of Defence, DEFSTAN 00-

27/1, 1985). Where the incident wave at the diver is used the duration is short (of the order of 10ms) and the impulse is low (See figure 2-4). This is not, however, the waveform that impacts the diver's head or body as the diving suit and hood attenuate the initial peak pressure of the waveform. Consequently, although the waveform that impacts the diver is of considerably lower amplitude than the incident wave (See figure 2-5), the time period for the wave to decay to 10% of its initial value is now substantially longer. The calculated impulse for this exposure considerably exceeds the non-injury criteria of 14 Pa-s proposed by Christian and Gaspin (1974). The analysis suggests that by removing the initial peak pressure of the blast wave the impulse has increased. This is clearly not the case, and there must be some minimum pressure variation below which the contribution to the impulse exposure can be neglected. Indeed, impulse may not be an issue at all for this type of exposure and guidance may be based solely on the peak pressure amplitude.

Employers of divers have a responsibility to ensure the safety of personnel working for them, and any diving supervisor must be satisfied that the divers to be deployed in the water are not being exposed to undue risk. Seismic operations in support of the oil and gas industry produce impulsive waveforms that may impact both military and commercial diving operations. The only data by which to assess these impacts is by application of the models and exposures for freely suspended TNT charges.

5.1.6 Repetitive exposure

The degree to which repetitive exposure has an impact on guidance for impulsive noise exposure will depend upon the injury mechanism involved. In this respect the current animal exposures are too severe and do not address the onset of injury and effect thresholds. The divers involved in the Spithead study (Wright, 1950) were exposed to a number of charges at long range, and although unconcerned regarding the level of noise, the trial was eventually terminated when a number of the divers developed a "wheeziness" in the chest. Divers operating underwater bolt (stud) guns will undergo a repetitive insult to the auditory system. Individual measures of incident noise have been conducted, but there has been no supporting audiometric data or physiological measures to determine any effect of repetitive exposure. Both commercial divers in the oil and gas industry, and military divers may be exposed to the low frequency impulsive wave from seismic exploration. By the nature of these operations divers, even at some considerable range, will undergo repetitive exposure. Guidance on impulsive noise exposure must therefore consider not only the amplitude and duration of the blast wave, but the number of exposures that a diver may undergo in the course of a diving operation.

5.1.7 Psychological Impact of Blast Wavefront on Recreational Divers

While it is hoped that recreational (or commercial) divers would be sufficiently far away that they would not be subjected to the very short duration impulsive blast wavefront, the lack of data regarding the diver response to this scenario creates a serious deficiency in being able to examine damage claims in these circumstances. Such wavefronts could be encountered not only for underwater blast, but also from impact of heavy non-explosive objects hitting the surface of the water. It is also the case that sonar systems using impulsive technology are being developed which may also create such a wavefront. As an example, the UK Ministry of Defence is currently conducting an environmental assessment for a sonobuoy that employ an explosive source. There is currently no proven guidance by which to assess the impact of this type of source on either military divers or recreational divers.

It should be noted that it is extremely difficult to simulate the psychological situational conditions of an open water dive in a laboratory environment. The behavioral reactions to LFS were likely tempered somewhat by informed consent and the additional safety precautions in place and available to the subject in case assistance was needed during the experiments (Sims et al., 1998A). Despite this fact, many subjects were noticeably nervous immediately prior to conducting the underwater sound exposures. This nervousness was confirmed by their state anxiety scores which were significantly higher pre-dive than post-dive, and by their resting respiratory rate and heart rate which were significantly elevated at the beginning of the dive compared to at the end of the dive. These suggest that in spite of the difficulties inherent in such a study, it can be done and the LFS work would provide a suitable model for examining psychological effects. The situational simulation, combined with appropriate test signals, could provide critical data for setting guidance for recreational and commercial divers exposed to underwater blast.

There may be a method by which the data for low frequency may be extrapolated to generate a guidance for distances at which the blast waveform has become an impulsive waveform. The approach would be to adjust the intensity criterion for psychological response using an equal energy rule. The current guidance for low frequency sounds between 100 and 500 Hz is 145 dB SPL (Cudahy et al., 1999). The evidence indicates that aversion ratings, which form the basis for the guidance limit, are unaffected by duration down to 7 seconds. If the typical underwater blast impulsive waveform is on the order of 7 milliseconds or greater, then the equal energy limit would be 175 dB SPL. This could be validated by determining the aversion for signals that reflect a blast waveform at long distances.

5.1.8 **Summary**

Current models and proposed limits are based on relatively few diver and animal exposures to small explosive charges at close range. The empirical based models therefore provide consistent stand-off ranges for these limited conditions. The models produce inconsistent results when extrapolated to large charges at long range. The models are based exclusively on exposure to underwater TNT charges hence, although the impact criteria may be applicable to other types of underwater impulsive source (i.e., deflagrating explosives, detonating cord and seismic airguns), their use has not been tested or proven for these cases. What is needed is a common effect criterion at the diver, whether this is based on peak pressure, impulse, or some other physical parameter, that can be related to physiological injury or psychological impact.

The increased awareness of environmental issues and the requirement on the Navy to ensure its trials and operations are not having adverse impact dictate that this is perhaps the most important area to address. Currently, there is no proven criterion by which to assess the impact of an underwater blast wave on a recreational diver or swimmer. A blast wave will propagate for hundreds and even thousands of kilometers before it has decayed to a level at which it has fallen below sea state noise. Clearly at some level the blast wave will be so innocuous as not to produce an aversion reaction in an unaware diver or swimmer. Without data on the psychological reaction of unaware divers to low level impulse exposure there is no basis for estimating an acceptable exposure level. The shortfall in this respect may impact future equipment procurement, military trials and commercial oil and gas exploration activities.

5.2 Applications

5.2.1 Setting guidance

Animal studies are clearly a necessary step in setting guidance for potentially lethal situations such as underwater blast. Their main strength lies in setting damage risk thresholds and setting absolute limits for people such as military personnel who may have to expose themselves to higher risk because of operational needs. In the context of standoff distances for military divers, the harmful level of blast is usually of more interest, i.e., the level at which an actual but minimal level of injury occurs; this can be addressed by animal experiments.

Animal experiments are relatively easy to conduct, and yield valuable insight into damage processes and lethal levels of exposure. However, the results are difficult to interpret in the context of acceptable levels of blast, and have been mainly of value in determining lethal levels of exposure. The major deficiency of animal studies lies in setting limits for situations where there is a need to know the behavioral response limits. This becomes of special importance when asked to develop guidance for groups such as recreational divers who are not motivated to accept high risk. In fact, the guiding rules for setting guidance for this population is to use minimal risk guidelines.

5.2.2 Exposure to small charges at short range

The review of empirically based blast models and the stand-off ranges that they produce in Table 4-4 indicates that there is some consistency in the predicted stand-off range where the effective charge is small (on the order of 1 kg TNT), and the effect is severe (lethal range or injury range). For these cases the diver will be in relatively close proximity to the charge and it is likely that injury will be related to the peak pressure of the blast wave. The models do not, however, extrapolate well for larger charges, or where the effect of the blast wave must be less severe. This will almost certainly be the case for peacetime diving operations. Furthermore, the models are based on very few trials, and all of these were conducted in shallow water. Of more value is an effect threshold level that can then be applied for an explosive source and diver location at any point in the water space. In this respect the peak pressure guidance within the US Navy diving manual, and the model for non-injurious levels of blast proposed by Nedwell (1988) are of more value than the models of Bebb and Wright. The US Navy diving manual states a value of 3.45 MPa as the effect threshold at which the blast wave is "likely to cause death or severe injury". This compares with the estimates of 1.8 MPa for the point at which Wright experienced some disabling effects during underwater blast exposures at Horea Lake, Portsmouth. There may be some value in re-modeling the Wright exposures using modern blast propagation models to obtain more accurate estimates of the parameters of the blast that Wright underwent.

Even for small charges the models do not predict a consistent stand-off range based on a "non-injury" criteria. The US Navy diving manual and the peak pressure based model of Nedwell are in good agreement irrespective of charge weight, but neither of these criteria compare well with the non-injury impulse of 14 Pa-s proposed by Christian and Gaspin. In order to set guidance on a non-injury range there must be a good understanding of organs within the body that are the most sensitive to the blast wave. For peacetime activity, and for the case where divers are required to operate in relatively close proximity to small explosive charges, the limiting physical parameter is likely to be peak pressure, and the onset of injury, particularly for repetitive exposure, is likely to be related to the auditory system.

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