TOWARD EXPOSURE LIMITS TO LOW FREQUENCY UNDERWATER SOUND: METHODOLOGICAL CONSIDERATIONS FOR HUMAN TESTING

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INTRODUCTION

Low frequency underwater sound (LFS) is a concern in the marine environment because of its long propagation distances, its contribution to sound pollution and its potential for adverse biological effects. There are multiple sources of LFS: super tankers, military sonar, oceanographic research systems, oil exploration, drilling platforms, underwater construction and blasting, earthquakes, as well as whale songs. As part of an environmental impact statement for low frequency active sonar, the U.S. Navy is conducting studies investigating the effects of LFS on marine mammals and human divers. The goal of these studies is to determine the limits for acceptable exposures to low frequency active sonar.

The preliminary U.S. Navy human exposure guidelines for LFS **(160-320** Hz) state that exposures should not exceed **160 dB** re. **1** µPa **(1).** The cumulative sound exposure duration should not exceed 15 min over a 24-hour period **and** a continuous exposure should not exceed 100 s with a duty cycle no greater than 50%. Currently there is no restriction on dive depth during the sound exposure. A limited number of studies performed on military-trained divers suggest that no physical damage occurs within the exposure guidelines **(2,3).** However, when approaching the upper boundaries of the guidance, military divers tended to approach their limit of subjective tolerance to LFS **(2,4).** Since all previous studies were performed on a highly selected population of well-trained, healthy military divers, the preliminary guidance needs to be adapted for the recreational diving population. In particular, the guidance should account for the possible psychological reactions that may occur following an unexpected LFS exposure in a recreational diver. Such an exposure might startle the diver and result in an inappropriate, rapid ascent to the surface. ***An*** uncontrolled ascent increases the likelihood of arterial gas embolism (AGE), pulmonary over-inflation syndrome, decompression illness (DCI) and drowning ***(5).*** We are currently investigating the psychological effects of LFS in recreational divers. This paper addresses some of the methodological issues involved in conducting underwater sound exposures on divers to ensure subject safety and data integrity **and** reliability.

Sound Variables

The transmission of sound in water is largely unimpeded by the human body since most tissues have the same density as sea water. However, when LFS travels through air-filled body cavities (e.g., lung, sinus and bowel) the change in impedance between body tissues and the air cavities increases the influence of sound on these bodily structures. Listed below are the primary variables required to define underwater sound exposures and their influence on physiological and psychological reactions.

Sound Pressure Level (SPL). The pressure of underwater sound is usually expressed in decibels (dB) referenced to 1 μPa. To compare SPL measured in air (normally referenced to 20 μPa) with that measured in water, it is necessary to add ***26* dB *(20* log *20)*** to the 20 μPa referenced value. Regardless of fkequency, experiments in humans and animals, as well as theoretical models, suggest that damage thresholds for sensitive organs (e.g., lung, bowel) occur above **190 dB *(6).*** Temporary threshold shifts in hearing have been demonstrated at 170 dB **(7).**

Frequency. LFS includes frequencies below 1 kHz, which coincides with the resonant frequencies of various organ systems (e.g., lung, Pacinian corpuscle, bowel) **(6).** Frequency impacts the perception of vibration (8) and loudness **(9).**

Signal type. There are many signal types (e.g., pure tones, sweeps, warbles). Some signal types such **as** complex tones produce audible beats at lower fkequencies than the constituent pure tones. Depending on their bandwidth and pulse repetition frequency, sweep tones increase the likelihood of matching the resonant fkequency of a body structure. **Our** findings suggest that **7** second hyperbolic sweeps **(30** Hz bandwidth) result in similar psychological aversion to pure tones of the same duration (8).

Duration. Short sound durations at high **SPLs** are important for damage thresholds of gas-filled voids **(6).** Mathematical models **of** bubble growth implicate long sound durations at high SPLs in the generation of rectified diffusion in supersaturated tissue, theoretically increasing the risk of **DCI** (10). Long sound durations, even at low SPLs, can cause damage to certain organs such as the ear (7). Duration is also important for subjective tolerance limits **(1).**

Near **vs.** far field. To simulate the acoustic conditions in the ocean environment, the diver should be placed in the far field so that the acoustic wavefront will be uniform oyer the diver's body. For LFS, the far field can be defined as beginning at a distance from the sound source equal to twice the maximum dimension of the projecting transducer. Any distances closer than the above calculation is defined as the near field.

Duty cycle. It is defined as the percentage of time that sound is present in a repeating interval (e.g., if a 30-s sound repeats after a 30-s pause, then the duty cycle is **50%.** We are unaware of studies that have investigated the effects of duty cycle on physiological responses and psychological reactions to **LFS.**

Dive Site Selection **for Low** Freauencv Sound Exneriments

The choice of dive site used for conducting LFS experiments has considerable implications for data fidelity. An ideal dive site should have a well-controlled environment with easy dive access, anechoic properties and minimal background noise. To avoid any unwanted masking effects on physiological parameters, background noise should be at least 20 dB below the SPL of the frequency of interest. Sources of background noise in artificial pools that should be minimized include pool pumps, nearby vehicle traffic or construction work and 60 **Hz** power line hum. To obtain uniform SPLs at the diver, it is important to minimize the effects of standing waves that cause spatial deviations in SPL over the sound field. Standing waves are created when sound reflects fiom surfaces such as pool walls, the bottom and the air-water interface. Most pools and tanks are reverberant environments that preclude their use in LFS experiments. However, there are specially designed anechoic underwater sound testing facilities (e.g., TRANSDEC; Point Loma, CA) that have contoured sides and sound traps that simulate an infinite expanse of water. While deep blue water dive sites provide better anechoic conditions than most artificial pools, their main disadvantages are loss of a controlled environment and an increased complexity of scientific and dive support. Furthermore, open water LFS studies require calculating the transmission loss of sound to ensure that sound beyond the dive site does not have significant impact on the environment.

Diver Safety

The choice of dive depth for experiments on LFS needs to balance issues of sound field integrity (as stated above) and diver safety. When conducting LFS experiments with divers of varying experience, we have found that a dive depth of 1 m maximizes diver safety. At this depth the spatial deviation in SPL over the diver's body is less than 1.3 dB for frequencies between 100 and 500 Hz (8). Suspending a diver at a depth of 1 m essentially eliminates the possibility of barotrauma and DCI caused by an uncontrolled ascent. If dives exceed a 1-m depth, a medical recompression chamber should be immediately available **for** treatment of AGE or DCI. To prevent uncontrolled ascents caused by reactions to the sound, divers should be provided with a means for immediate termination of the sound exposures upon reaching thresholds of pain or tolerance. Voltage cut-off circuits can also be used for automatically shutting off the power to the sound transducer should **SPLs** exceed predetermined limits.

Electrical safety is a significant concern when conducting diving experiments, particularly when using high-power underwater sound transducers that may introduce current leakage into the surrounding water. Means for ameliorating the danger of electrocution include using surge protectors and current leakage cut-off switches, isolating the source transducer and grounding electrical equipment to eliminate ground loops.

CONCLUSIONS

The acoustical parameters of LFS might independently affect physiological and psychological responses and must be clearly defined. Obtaining valid scientific data for development of LFS exposure limits requires understanding the impact of the dive site on the sound field. Suggestions for ensuring subject safety are provided that take into account the inherent risk of the diving environment, as well as, the potential aversive nature and possible physiological effects of LFS.

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ACKNOWLEDGMENTS

Supported by the Chief of Naval Operations N-874. Views expressed in this report are the authors and do not reflect official policy or position of the Department of the Navy, DoD, or U.S. Government.