

THE SAFETY OF DIVER EXPOSURE TO ULTRASONIC IMAGING SONARS

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Abstract: *To achieve image-quality resolution, imaging sonars operate in the ultrasonic regime at frequencies on the order of 300 kHz up to 1.5 MHz. Although there are no known instances of harm or adverse effects caused by imaging sonars to divers, it is known from diagnostic ultrasound that human exposure to ultrasonic energy can be harmful. The risks identified in diagnostic ultrasound have apparently never been examined for imaging sonars. The risks posed by a diver hand-held imaging sonar are examined here in light of the metrics used in diagnostic ultrasound, especially the thermal and mechanical indices (TI and MI respectively). One imaging sonar in particular is assessed. Its ultrasonic field was characterized by direct measurement under anechoic conditions at the Defence R&D Canada Acoustic Calibration Facility and MI and TI were conservatively applied to assess the risk of harm to divers who may be exposed to the ultrasonic beam of the sonar during dive operations. This report reviews the exposure characteristics of ultrasonic fields and their connection to metrics commonly used by sonar engineers, the indices of diagnostic ultrasound, the experimental setup and results, and the implications for safe standoff and exposure time. The methodology can be applied to other ultrasonic sonar makes, models and technologies for imaging sonars and diver detection sonars.*

Keywords: *Imaging Sonar, Diver Handheld Sonar, Ultrasonic Safety, Diver Ultrasonic Safety*

1. INTRODUCTION

Imaging sonars provide visual-style real-time imaging of an underwater scene. They operate in the ultrasonic regime, at frequencies on the order of 300 kHz up to 1.5 MHz, depending on the imaging technology used. The high frequencies are required to achieve relatively high acoustic resolution of a scene (typically less than 1° beam resolution) in a compact, light-weight low power sonar transducer. They are among highest frequencies used by sonars. There are no known cases of harm or sensation of effect caused to divers by imaging sonars. From medical diagnostic ultrasound, however, it is known that exposure to ultrasonic energy can be harmful. The ultrasonic risks of diver exposure have never been examined. Existing sonar safety recommendations focus on hearing and underwater blasts (references [1] to [5]), which do not apply to ultrasonic sonars.

The purpose here is to summarize the assessment [6,7] of the ultrasonic safety for the Teledyne Blueview P450-45 series imaging sonar in Fig. (1), which features in a version of the diver hand-held sonar package made by Shark Marine Technologies (not shown) that is currently deployed for operational use by the Canadian Fleet Diving Unit. The method used for that sonar could be applied to other classes of imaging sonars.



Fig. 1: The Teledyne BlueView P450-45 sonar head [8]. Two mounting positions were used for anechoic ultrasonic field measurements: horizontal mounting (left) for far-field measurements (beyond 2 m from the sonar face), and vertical mounting (right) for near-field.. The sonar beam direction (axis) is indicated by the arrow.

The P450-45 sonar operates in the 300 kHz to 600 kHz frequency band. Two similar blazed (echelon) arrays are collocated in the sonar head, covering the right and left horizontal fields of view, roughly 22.5° to either side of the sonar axis. The patented technology splits the broad frequency spectrum into angular beams of different frequency. Overlapping 500 kHz beams from both arrays are directed along the axis of the sonar, and 300 kHz beams are directed toward the outer edge of sonar coverage. The ultrasonic metrics deal mainly with the ability of the field to heat and disrupt the biomaterial through which the ultrasound propagates. The sound field metrics used here are taken from the sonar [9,10] and ultrasonic literature in references [11] to [16].

2. ULTRASONIC THERMAL INDEX

Ultrasonic waves are potentially harmful through the heating delivered to biomaterial, which depends on the intensity of the ultrasonic sound waves, on the absorption of that energy by the biomaterial, and on the time duration of exposure. The risk of harm is

correlated with the intensity of the ultrasonic waves, particularly with the spatial-peak temporal-average intensity I_{SPTA} . Safety guidelines in ultrasonic diagnostics set maximum limits on the Thermal Index (TI) defined [11, 19-25] as the energy E of the ultrasonic waves delivered to a location in the body, divided by the energy E_{1° that, under the same test conditions, would raise the temperature of bone or tissue by 1°C .

Diagnostic ultrasound uses three different classes of thermal indices [12, 19] for soft tissue, bone, and cranial bone, based on different thermal model absorption and specific heat for each. Since any part of a diver may be exposed to the sonar beam under uncontrolled conditions, a new model of heating was required. The general method of thermal modelling was developed for diagnostic ultrasound in [11, 15] was adapted in [26] to diver exposure under uncontrolled exposure conditions, with the result that

$$TI < \frac{I_{SPPA}}{I_{SPPA_{1^\circ\text{C}}}}, \text{ in which } I_{SPPA_{1^\circ\text{C}}} = \frac{1}{(\ln 10)f_{\text{MHz}}\tau f_{\text{ping}}\Delta t} \frac{W}{\text{cm}^2} \quad (1)$$

in which I_{SPPA} is the spatial-peak pulse-average acoustic intensity of the sonar in W/cm^2 (i.e., highest intensity measured in the ultrasound beam averaged over the *time duration of the pulse*), $I_{SPPA_{1^\circ\text{C}}}$ is the I_{SPPA} conservatively estimated in [26] to raise the biomaterial of the diver by 1°C , f_{MHz} is the ultrasonic frequency expressed in MHz, τ is the pulse length in seconds, f_{ping} is the ping frequency in Hz, and Δt is the exposure time of the diver in seconds. Example values of $I_{SPPA_{1^\circ\text{C}}}$ are given in Table (1). Here $I_{SPPA_{1^\circ\text{C}}}$ errs on the safe side inasmuch it assumes that the diver biomaterial is particularly susceptible to heating—a combination of the high ultrasonic energy capture (the attenuation) of bone together with high temperature sensitivity (low heat capacity) of fat—and it assumes that the diver is motionless in a stationary sonar beam, without a dive suit or equipment, while nevertheless undergoing no cooling (neither diffusion or perfusion of heat). These assumptions suffice if, as we shall see, the resulting conservative safety recommendations to not significantly impact the operational use of the sonar.

Representative Sonar Type	Center Frequency	Pulse Length	Ping Rate	$I_{SPPA_{1^\circ\text{C}}} (\text{W}/\text{cm}^2)$		
	f_{MHz} (MHz)	τ (s)	f_p (Hz)	$\Delta t = 60 \text{ s}$	$\Delta t = 300 \text{ s}$	$\Delta t = 600 \text{ s}$
Acoustic Lens Imaging Sonar [27]	1.10	0.0005	15	0.877	0.175	0.088
Blazed Array Imaging Sonar [8]	0.500	0.001	20	0.724	0.145	0.072
Diver Detection Sonar [28]	0.070	0.040	0.5	0.517	0.103	0.052

Table 1: Example $I_{SPPA_{1^\circ\text{C}}}$ conservatively estimated three ultrasonic sonars in [26]. The blazed array sonar is the P450-45 sonar assessed in this work.

3. ULTRASONIC MECHANICAL INDEX

Ultrasonic waves are potentially harmful through the mechanical effects that they may have, which include (1) macrostreaming (induced flow) in vessels filled with a moderately

absorbing liquid due to the transfer of momentum from the propagating wave to the liquid, and (2) harmful energy released in the collapse of transient gas bubbles by means of cavitation, causing capillary haemorrhaging in soft tissues [13, 15, 31]. The risk of mechanical harm is correlated with the *mechanical index* [12, 13, 18]

$$MI = \frac{p_{peak_MPa}^-}{\sqrt{f_{MHz}}} \quad (2)$$

in which $p_{peak_MPa}^-$ is the peak rarefaction (under) pressure expressed in MPa. For divers, there is a risk of bubble formation in the blood during decompression. The mechanical bioeffects of ultrasound generally increase with the presence of bubbles and air cavities [29].

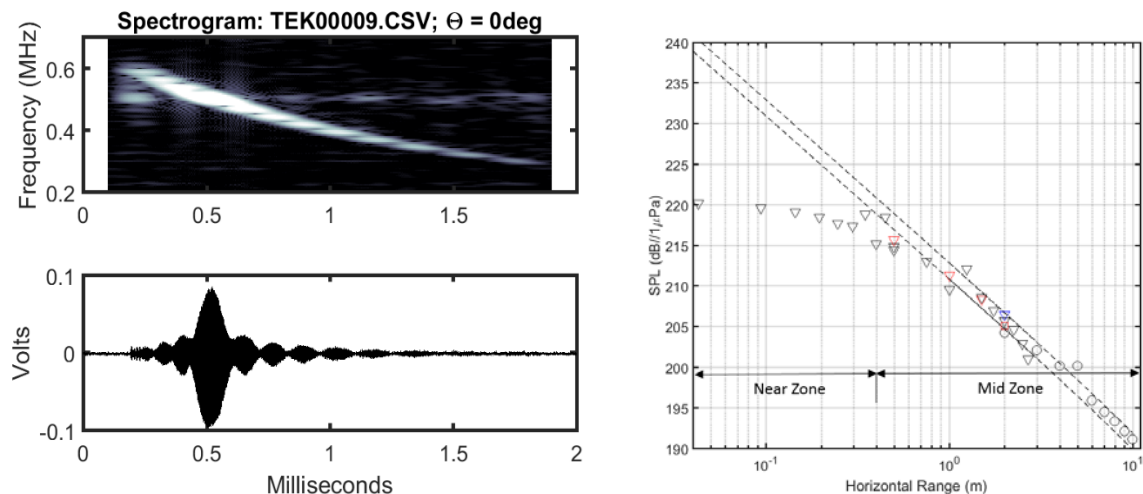


Fig. 2: (Left) example spectrogram and time series 4 m on axis of the sonar in relative units. (Right) Measurements of sound pressure level (SPL) on the axis of the sonar.

4. ULTRASONIC SAFETY RECOMMENDATIONS

Leading safety recommendations for diagnostic ultrasound are summarized in references [12, 19, 20, 21, 24, 25]. The Canadian Ministry of Health [19] safety recommendations will be used here, namely:

Thermal Index $TI \leq 1.5$

Mechanical Index $MI \leq 1.9$ generally
 $MI \leq 0.5$ when gas bodies present

Spatial-Peak Temporal-Average Intensity $I_{SPTA} \leq 720 \text{ mW/cm}^2$ (highest intensity measured in the ultrasound beam averaged over the pulse repetition period)

Spatial-Peak Pulse-Average Intensity $I_{SPPA} \leq 190 \text{ W/cm}^2$ (highest intensity measured in the ultrasound beam averaged over the time duration of the pulse)

5. RESULTS

Space does not permit a detailed account of measurement method and results. The full report [6] should be consulted for details. Fig. (2) illustrates the kind of time domain wave forms that were measured and the sound pressure level (SPL, dB re $1\mu\text{Pa}$) measured along the axis of the sonar. The resulting safe exposure time and distances (the main result of the work) are summarized in Fig. (3) in terms of the thermal and mechanical indices computed from the measured data.

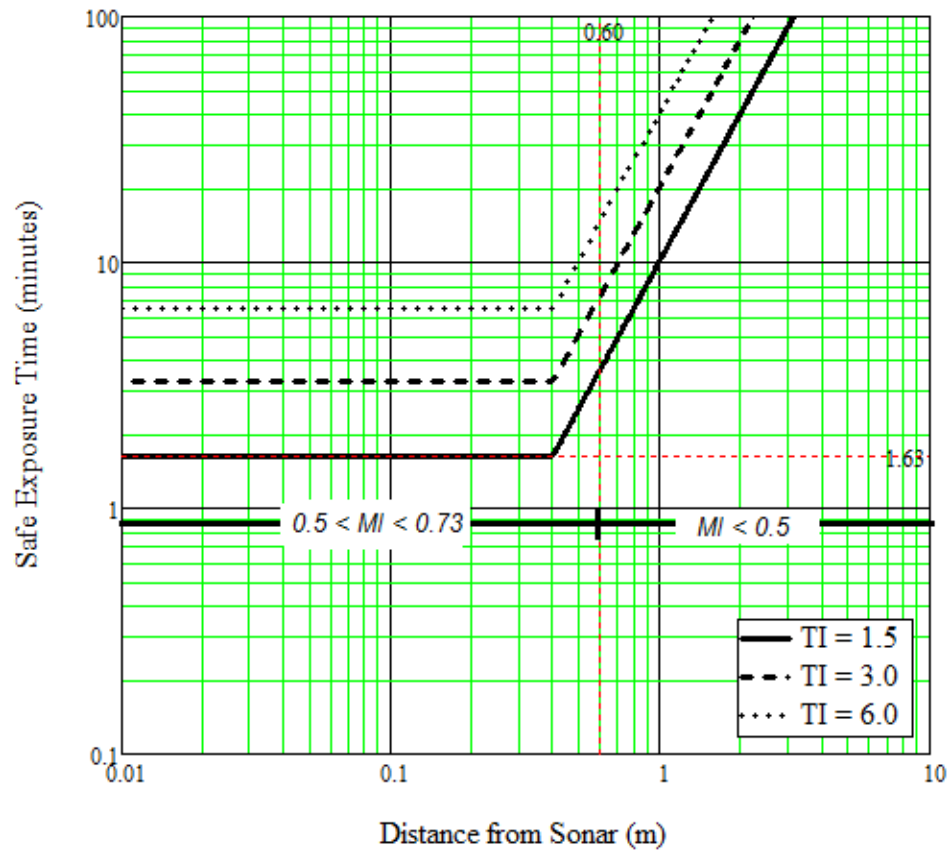


Fig. 3: The safe exposure time and distance, conservatively estimated, for a diver on the axis of the P450-45 sonar.

6. CONCLUSIONS AND RECOMMENDATIONS

The main result is Fig. (3). It shows that:

1. The strongest ultrasonic exposures occur along the axis of the sonar beam, with higher exposures closer to the sonar face.
2. At *all* distances from the sonar, the ultrasonic effects fall within the safety recommendations for mechanical effects (mechanical index $MI < 1.9$), and for thermal effects under continuous exposure of 1.63 minutes or less (thermal index $TI < 1.5$).
3. At distances *greater* than 1 m from the sonar, the thermal effects for exposure times up to 10 minutes fall within the safety recommendations (thermal index $TI < 1.5$).

4. In the event of bubble formation in the diver body during decompression, at distances *greater* than 0.60 m from the sonar, the ultrasonic mechanical effects fall within the safety recommendations ($MI < 0.5$).

The thermal effects of the ultrasonic field produced by the P450-45 leads to the maximum exposure times as a function of distance for $TI = 1.5$ in Fig. (3):

5. The exposure is highest close to the sonar face, at distances less than 40 cm, where a conservative estimate of the maximum safe exposure time for $TI = 1.5$ is $\Delta t = 1.63$ minutes.
6. The exposure decreases quickly with increasing distances R from the sonar face, with $(R, \Delta t) = (1 \text{ m}, 10 \text{ min})$ and $(2 \text{ m}, 40 \text{ min})$ for instance.

The safety assessment is considered to be conservative (erring on the side of caution) inasmuch as:

7. The safe exposure regime ($TI < 1.5$) was taken from medical diagnostic ultrasound applied to the particularly sensitive developing fetus during pregnancy.
8. The model [26] of the power required to raise temperature 1°C assumes relatively large attenuation (highest energy capture) for bone and relatively low heat capacity (highest temperature sensitivity) for fat, with no need then (as in diagnostic ultrasound) to consider where the ultrasonic illumination falls and passes through the body.
9. Significant mitigating factors against thermal effects were ignored, namely: the protection against ultrasonic waves provided by a diver's suit and other equipment; cooling of the diver by immersion in water; and the time variation, and hence reduced average exposures, that can generally be expected owing to the motion of both the hand-held ultrasonic sonar beam and of the exposed diver.

Additional points to be made in conclusion are:

10. Very close proximity of a diver to the face of the sonar will certainly ruin the sonar image of a more distant scene. No scene imaging or navigation could be carried out with a diver within 1 m of the sonar face, for instance. The P450-45 sonar furthermore cannot create an image of scenes closer than about 2 m. Maintaining a safe standoff of distance of 1 m therefore does not interfere with imaging operations.
11. The intense part of the P450-45 sonar beam is much smaller than the field of view of the sonar. The cross-sectional diameter of the intense portion of the sonar beam is given by the effective diameter d_{eff} . At a distance of 10 m, for instance, the effective diameter of the sonar beam is 93 cm, corresponding to $\pm 2.6^\circ$ beam width.
12. The eye is known to be vulnerable to ultrasonic exposure. Direct exposure of the eye was not considered to be a safety risk for divers properly wearing a diver's mask. Divers should be cautioned to avoid direct exposure of the eyes to the sonar beam close to the sonar.
13. One could take steps to remove the conservative assumptions used here in the thermal index, but there is no need to do so if the present constraints on exposure level and time do not interfere with dive operations with a sonar. If the conservative safety limits do interfere with diver operations, then the safety limits should be revisited and adjusted, taking into account of the mitigating that cooling by water temperature difference and flow will have, as well as the protection that a wet suit or dry suit provide.

14. The exposure of divers who may be pregnant is not recommended owing to the higher vulnerability of the fetus.
15. Fresh water is less attenuating of ultrasound than seawater. Slightly stronger fields are expected in freshwater, but these effects will be negligibly small over the small distances, close to the sonar face, where the ultrasonic field poses its risk.
16. Ultrasonic fields can be reflected from hard flat surfaces, redirecting the beam, reflecting back toward the diver using the sonar for instance. Divers should be made aware of the possibility of redirection of the sonar beam by reflection.
17. These safety recommendations are conservative and are not expected to limit sonar operations in any significant way.

The quantitative analysis could be applied to other ultrasonic sonars that divers may face, other imaging sonars, diver detection sonars, sidescan sonars, or multibeam sonars.

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