The Thermal Index for Assessing Diver Exposure Risk to Ultrasonic Sonars

Prepared by:
Ronald Kessel
Maritime Way Scientific Ltd. (MWS)
1420 Youville Drive
Ottawa, Ontario K1C 7B3

PWGSC Contract Number: W7707-4501478116
Technical Authority: Vincent Myers, Defence Scientist

Contract Report
DRDC-RDDC-2017-C088
March 2017

The Thermal Index for Assessing Diver Exposure Risk to Ultrasonic Sonars

Maritime Way Scientific Full Report
Prepared for:
Defence R&D Canada – Atlantic and the Canadian Fleet Diving Unit (FDU)
Halifax, Nova Scotia, Canada
Contract Project Authorities: Vincent Myers, DRDC - Atlantic
PWGSC Contract Number: W7707- 4501478116

Prepared by:
Ronald Kessel,
Chief Technical Officer,
Maritime Way Scientific Ltd. (MWS),
1420 Youville Drive,
Ontario, Ottawa, Canada K1C 7B3

MWS Project Number: 13-027.9

Date: 23-Mar-2017

Title & Project Identification Page

Company name and address	Maritime Way Scientific Ltd. 1420 Youville Drive, Unit 5A Ottawa, Ontario • K1C 7B3 Phone 613.841.0505 • Fax 613.590.7231
MWS Project Number	13-027.9
Contact Persons	Mr. Martin Taillefer Phone 613-841-0505 mtaillefer@maritimeway.ca Dr. Ronald Kessel Phone 613-841-0529 rkessel@maritimeway.ca
RFP Title:	The Thermal Index for Assessing Diver Exposure Risk to Ultrasonic Sonars
Abstract	Divers can be exposed to ultrasonic fields from hand-held imaging sonars (used to navigate and search in turbid waters, typically 300 KHz to 1.5 MHz) and from diver detection sonars (large area, underwater surveillance in maritime security, typically 70 KHz to 100 kHz). No reports of harm have been reported by divers exposed to these sonars or by the manufacturers of the sonars. Nevertheless, the question of ultrasonic exposure safety and recommendations regarding safe use have apparently never been addressed. One established ultrasonic safety metric is the *thermal index* (TI) used by the medical diagnostic community. Modern diagnostic equipment provides its operator with several versions of TI, depending on the diagnostic objectives and scanning methodology. TI can be applied in other applications provided that an appropriate model of ultrasonic heating can be developed for the exposure faced. A new heating model is especially required given the departures in diver sonar exposures from the controlled and very focused diagnostic conditions assumed in medicine require a different thermal model as the basis for TI. A very conservative thermal model for diver exposure to ultrasonic sonar is developed here for underwater exposure conditions that are largely uncontrolled, unpredictable, and incidental to other mission objectives. The resulting thermal index and its implications for safe sonar use are illustrated for two diver hand-held imaging sonars and for a diver detection sonar. The conservative recommendations are not expected to interfere with relatively free sonar use by divers.

Executive Summary

This project will make safety recommendations regarding the use of a particular diver hand-held imaging sonar deployed the Canadian Fleet Diving Unit, for use by its divers in turbid waters with low visibility.

One very well established ultrasonic safety metric is the thermal index (TI) used by the medical diagnostic community. Modern diagnostic equipment provides the operator with three different versions of TI, depending on the diagnostic objectives and ultrasonic scanning being used. TI can be applied in other applications, but departures from the very controlled and repeatable diagnostic conditions assumed in medicine require a different thermal model as the basis for TI.

A very conservative thermal model for diver exposure to ultrasonic sonar is developed here for underwater exposure conditions that are largely uncontrolled, unpredictable, and incidental to other mission objectives. The resulting thermal index and its implications for safe sonar use are illustrated for two diver hand-held imaging sonars and for a diver detection sonar. The conservative recommendations are not expected to interfere with relatively free sonar use by divers.

These results, and the results elsewhere for the mechanical index (MI), will be used to make specific recommendations to the CAN Fleet Diving Unit. The results will be of interest to the users and manufacturers of these sonars more generally.

Martin L. Taillefer, CD, M.Sc., B.Sc.
President & Managing Director
Maritime Way Scientific Ltd

Table of Contents

List of Figures

List of Tables

1 Introduction

The two main safety metrics developed by the medical community for exposure to ultrasonic waves in diagnostic ultrasound are the thermal index (TI) and mechanical index (MI) [1, 2, 3]. There is a requirement to apply both to the exposures that are delivered by the high-frequency sonars that military divers might face in the course of their work. In particular, under low visibility conditions, divers often use a hand-held, high-frequency sonar help locate objects, orient themselves, and for navigation. The risk under consideration, then, is the exposure to ultrasonic waves that other divers face if they are illuminated directly by the beam of the sonar, or by indirect reflections of the beam from highly reflective surfaces.

1.1 Objective:

The objective here is to bring the thermal index (TI) developed for risk assessment in diagnostic ultrasound to bear on the diver sonar situation.

Modern diagnostic ultrasound equipment, and hence much of the related literature, report three different classes of thermal indices to the operator of the equipment [1, 4]: TIS for soft tissue based on three different models of thermal effects arising from three different scanning modes; TIB for bone; and; TIC for cranial bone. Each of thermal index is based on a different model of illuminated scene, its vulnerability to heating, scanning mode, and transducer head, and the set covers most of cases routinely faced and carried out under very controlled, repeatable conditions in medical diagnostics. Significant departures from those conditions require a new model of heating for computing the thermal index. The modelling methodology for diagnostic ultrasound was developed at length in [5]. Here the method is adapted (apparently for the first time) to the largely uncontrolled conditions of exposure of divers to the ultrasonic beam of a sonar.

It must not be forgotten here that ultrasonic waves can have significant mechanical effects on the human body (cavitation), which are in no way addressed by the thermal measure, and which may have more restrictive safety recommendations for the exposure of divers to ultrasonic sonars that are not addressed here.

1.2 Thermal Index:

Ultrasonic waves are potentially harmful through the heating that the waves can deliver to soft tissue and bone, which depends on the intensity of the ultrasonic sound waves, on the absorption of that energy by the human body, and on the time duration of exposure. Guidelines for the safe use of ultrasonic waves in ultrasonic diagnostics set maximum limits on the Thermal Index (TI) defined [1, 2, 5] as the energy E_X of the ultrasonic waves delivered to a location in the body, divided by the energy E_{1^0} that, under the same test conditions, would raise the temperature of bone or tissue by 1 ^{o}C,

$$TI = \frac{E_X}{E_{1^0}}. \tag{1}$$

The greatest risk on diagnostic ultrasound is the risk to a fetus, particularly during the early stages of development in the first trimester. The high value of diagnostic ultrasound for care during pregnancy has motivated considerable research into the risks posed to the fetus, which is the human tissue and bone that is most vulnerable to harm to ultrasound. The National Council on Radiation Protection and

Measurements (NCRP, USA) advises that the risks of ultrasound diagnostics may offset the benefits of ultrasound exposures to the fetus when the temperature rise at the focal point of the ultrasound beam is calculated to be more than 3 degrees Celsius for ten minutes or more [6]. More generally, some diagnostic ultrasound machines can cause a temperature rises of 6 ^{o}C at the spot where they are continuously focused, which is generally avoided by movement of the ultrasound probe.

The following recommendations, made by the Canadian Ministry of Health [1] and the NCRP (USA) [5, 6], have been drawn out of the development of the thermal index:

1. If $TI \leq 1$, then do not withhold the ultrasonic exposure out of concern for its adverse thermal effects;
2. If $TI > 1$, then do not withhold the ultrasonic exposure out of concern for its adverse thermal effects if the dwell (exposure) time t, expressed in minutes, satisfies the maximum dwell-time condition:

$$t < 4^{6-TI} \tag{2}$$

3. If $TI > 1$ and the maximum dwell-time condition is violated, then use informed clinical judgement concerning the anticipated benefits and risks about the exposure.

These are the best established recommendations for risk to ultrasonic waves, and they would be conservative recommendations for the exposure of adult divers, even for those who may be pregnant, so they are adopted here.

The adult eye is also identified as being particularly vulnerable to ultrasonic waves owing to the relatively high absorption of the lens of the eye. A diver's mask provides good shielding from ultrasonic waves owing to the high acoustic impedance mismatch between water and the air gap created by the mask. Canadian safety recommendations [1] from the Ministry of Health in connection with diagnostic ultrasound is that the thermal index (TI) should be less than 1, much as above, but modelling of the thermal heating of components of the eye by ultrasound is not undertaken here, assuming, in effect, that the divers are wearing dive masks.

Localized temperature differences of 1 ^{o}C would generally be noticeable. The bio-effects of heating of adults by ultrasonic exposure are mainly those of hyperthermia (elevated body temperature [7]), which would presumably not ordinarily be an issue for a calm diver in relatively cold waters, though it may be a concern for divers under heavy exertion. The bio-effects are not considered here because the 1 ^{o}C safety recommendations followed here (reviewed above) are considered to be safe across a very wide spectrum of elevated body temperatures [7].

2 Ultrasonic Energy for 1 ^{o}C Temperature Rise:

As in the method of Chapt 3 and 4 in [5], assume that all of the energy lost by ultrasonic waves in one or another part of the human body is converted into heat. Then the heat production rate is

$$q_v = 2\alpha I \ \frac{\mathrm{W}}{\mathrm{cm}^3}, \tag{3}$$

in which I is the intensity of the sound in units of power per unit area (here we will use SI units W/cm^2), and α is the attenuation (relative loss) of the sound energy per unity length travelled in the body (Nepers/cm). Example values for α are reported in Fig. (3.1) of [5]. These are duplicated here in Fig. (1).

The assumption in (3) that all ultrasonic energy loss is lost into heat is a conservative assumption. It overestimates the heat energy generated for bone where other loss mechanisms of scattering and reflection are significant [8],

The momentary rate of temperature increase $\Delta T/\Delta t$ is the small change in temperature ΔT (in units of degrees Celsius, ^{0}C) divided the exposure time Δt (in units of seconds, s) required to produce that temperature change, in the limit as the exposure time becomes very short. The rate of momentary rate temperature increase in one or another part of the human body is equal to

$$\frac{\Delta T}{\Delta t} = \frac{q_v}{c_v} \quad \frac{{}^0\mathrm{C}}{\mathrm{s}} \tag{4}$$

where c_v is the *heat capacity* of the human tissue or bone being heated in units of energy per unit volume per degree temperature change (here in SI units of J/(cm^3 ^{0}C)). This rate of temperature increase applies conservatively, under the assumptions that there is *no* mechanism for cooling; i.e.,

1. no perfusion by the blood, and no cooling by outer seawater; and
2. no diffusion of heat away from the heated regions of the body.

(In equation (4.1) of [5], for instance, the first sets the thermal diffusivity κ to zero, and the second sets the perfusion time constant τ to be infinitely large, leaving only (4) above.) Example values for c_v are reported in Table (4.1) of [5]. These are duplicated here in Table (1).

Using equations (3) and (4), it can be shown that the rise in temperature ΔT over *extended* exposure times Δt will be

$$\Delta T = \frac{2\alpha}{c_v} I \Delta t. \tag{5}$$

Setting ΔT to be 1 ^{0}C and solving for $I\Delta t$ gives the incident energy density $E_{1\,{}^0C}$ required to raise the temperature by 1 ^{0}C of a thermally insulated 1 cm thick layer of 1 cm of biomaterial,

$$E_{1\,{}^0C} = \frac{c_v}{2\alpha} \quad \frac{\mathrm{J}}{\mathrm{cm}^2}. \tag{6}$$

And the thermal index TI, conservatively estimated for an exposure time Δt, is the ratio of the incident ultrasonic energy of actual exposure E to $E_{1\,{}^0C}$,

$$TI = \frac{E}{E_{1\,{}^0C}}. \tag{7}$$

2.1 Upper Bound on Attenuation α:

The highest TI will result for human tissues or bone that have the highest attenuation coefficient α. An upper bound was sought for α in the literature. Bone and fat generally have the highest attenuation. Attenuation is higher, moreover, at high ultrasonic frequencies than at low.

From Fig. (1) it can be seen that, for sonars with maximum frequency f_{max} less than 1 MHz, $f_{max} < 1$ MHz, the maximum attenuation α (excluding bone) occurs for tendons. Elsewhere (page 73 in [5]), the nominal attenuation for bone at 2 MHz is taken to be 3 Np/cm; hence 1.5 Np/cm at 1 MHz owing to the roughly linear dependence of attenuation on frequency. This is lower than the attenuation $2.303 = \ln(10)$ Np/cm (i.e., 20 dB/cm) at 1 MHz in the range reported for bone in [9]. The upper bound $\alpha' \leq \ln(10)$ Np/cm/MHz will be assumed here. Multiply this value by the frequency in MHz to prorate the upper bound for the human body to other frequencies,

$$\alpha \leq \alpha' f_{MHz} = \ln(10)\, f_{MHz} \ \text{Np/cm} \tag{8}$$

2.2 Lower Bound on Heat Capacity c_v:

The highest TI will result for human tissues or bone that have the lowest heat capacity c_v. A lower bound was sought for c_v in the literature. It is generally accepted that the average *specific heat* of the human body is 3470 J/(kg ^{0}C). Assuming the average density of the human body to be equal to that of water, 1000 kg/m^3, that gives an average heat capacity of $c_v = 3.74$ J/(cm^3 ^{0}C). More particularly, from Table (1) it can be seen that the minimum heat capacity $c_v = 2.0$ occurs for fat, whereby it is assumed here that

$$c_v \geq 2.0 \ \frac{\text{J}}{\text{cm}^3\ {}^0\text{C}}. \tag{9}$$

2.3 Upper Bound on the Thermal Index TI:

An upper bound TI by inserting the lower bound on $E_{1\,^0C}$ into (7). From the maximum attenuation (8) and the minimum heat capacity (9) it follows that, for any part of the human body[1],

$$E_{1\,^0C} > \frac{c_v}{2\alpha} = \frac{2.0}{2(\ln 10) f_{MHz}} = \frac{1}{(\ln 10) f_{MHz}} \ \frac{\text{J}}{\text{cm}^2} = \frac{434}{f_{MHz}} \ \frac{\text{mJ}}{\text{cm}^2}. \tag{10}$$

For example: If the chest area of a diver dive suit or equipment is very close to an ultrasonic sonar, intercepting the entire ultrasonic sonar beam, and the sonar beam is characterized by cross-sectional

[1] It may be noted that energy density $E_{1\,^0C}$ in mJ/cm^2 is used here rather than power W_{deg} in mW, as found equation (9) of [2] for instance. This is because it has been conservatively assumed that there are no cooling mechanisms, and the biomaterial therefore continues to increase its temperature linearly *without limit* as the exposure time increases.

area $A = 15$ cm X 3 cm = 45 cm^2, frequency $f_{MHz} = 0.500$ MHz, total acoustic average power of $W_A = 29000$ mW per pulse, pulse length $\tau = 0.001$ ms and pulse (ping) frequency $f_p = 20$ Hz, then the average incident acoustic energy in the exposure time Δt is $W_A\ \tau f_p \Delta t/A$ mW/cm^2, and the diver's temperature increase in the illuminated portion of the chest area is certain be *less* than 1 ^{o}C if $W_A \tau f_p\ \Delta t/A \leq E_{1\,^oC} < 434/0.5 = 868$ mJ/cm^2; which implies that the exposure time Δtshould be kept *less* than $\Delta t \leq AE_{1\,^oC}/\tau f_p W_A = 45 \times 868/(0.001 \times 10 \times 29000) = 67$ sec or about 1.1 minutes.

The lower bound (10) implies that TI for any part of the human body is bounded by

$$TI < (\ln 10) f_{MHz} E. \tag{11}$$

In order for TI to meet the safety recommendations of diagnostic ultrasound, it suffices for the right side of (11) to meet the safety recommendations of diagnostic ultrasound. If the right side violates the safety recommendations, then one must venture into further detail about the way particular parts of the human body are exposed, in order to check the risk of the more vulnerable body parts mode particularly. Ideally the exposure levels E of the sonar under assessment will be low enough that that additional work is not required.

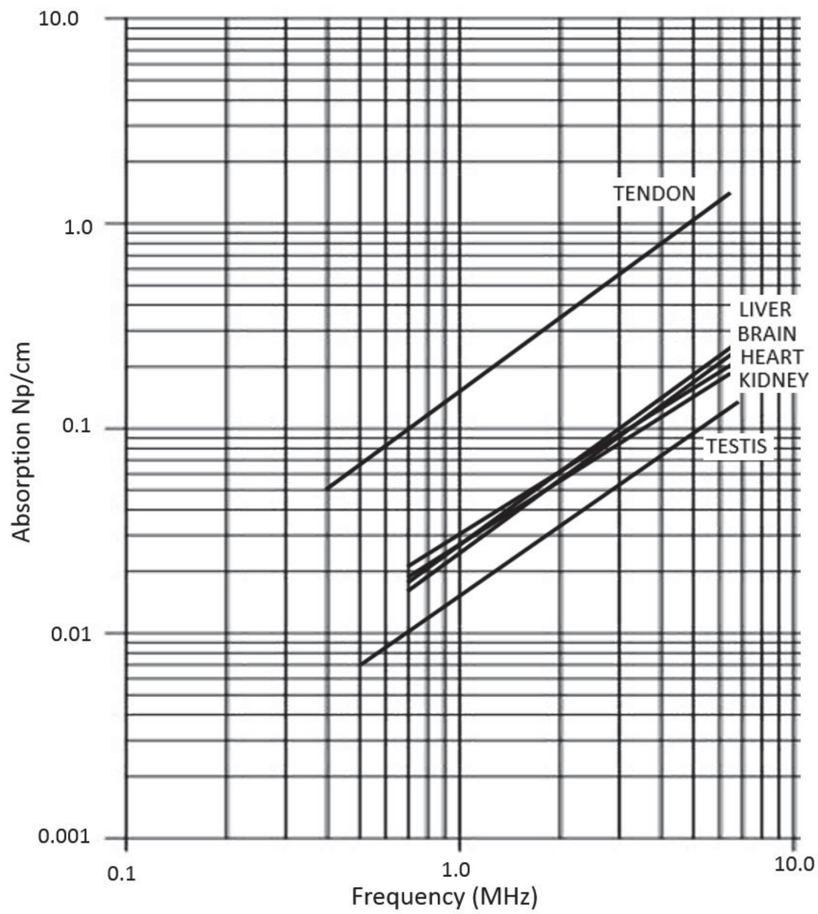

Figure 1 Absorption coefficients (Np/cm) for a variety of mammalian tissues (adapted from [5], attributed to Goss et l. 1979).

Table 1 Thermophysical constants (adapted from [5])

	Density	Thermal Conductivity	Heat Capacity per unit volume	Thermal Diffusivity
	g/cm^3	W/m °C	J/cm^3 °C	mm^2/s
Fat	0.85	0.19	2.0	0.095
Brain	1.05	0.52	3.9	0.13
Kidney	1.05	0.55	4.1	0.13
Muscle	1.05	0.55	3.7	0.15
Liver	1.05	0.57	3.8	0.15
Heart	1.06	0.59	3.9	0.15
Whole Blood	1.05	0.55	3.8	0.14
Water	1.00	0.63	4.2	0.15
Bone (cancellous)	1.3	0.58	2.1	0.28
Bone (cortical)	1.7	2.3	2.7	0.85

3 Exposure Level E from a Sonar:

Following [10], let the highest acoustic intensity measured at any point in the sonar's ultrasonic beam, when averaged over the time duration pulse τ (the spatial-peak pulse-average of the ultrasonic field) be I_{SPPA}. And finally, let the ping-rate of the sonar be f_P in Hz (not MHz). Then the average of I_{SPPA} over a long exposure time to the sonar—namely, the spatial-peak temporal-average intensity I_{SPTA} as in [10]—is given by

$$I_{SPTA} = I_{SPPA}\,\tau\, f_P \quad \frac{\mathrm{W}}{\mathrm{cm}^2}, \tag{12}$$

and the exposure to incident energy over an extended time period Δt is given by

$$E = I_{SPTA}\,\Delta t = I_{SPPA}\,\tau\, f_P \Delta t \quad \frac{\mathrm{J}}{\mathrm{cm}^2}. \tag{13}$$

Using (13), the thermal index for the exposure is therefore bounded by

$$TI < \frac{E}{E_{1\,^\circ C}} = I_{SPPA}\,\tau\, f_P (\ln 10) f_{MHz} \Delta t = \frac{I_{SPPA}}{I_{SPPA\_1^\circ C}}, \tag{14}$$

in which

$$I_{SPPA\_1^\circ C} = \frac{1}{(\ln 10) f_{MHz} \tau\, f_P \Delta t} \quad \frac{\mathrm{W}}{\mathrm{cm}^2}. \tag{15}$$

Example $I_{SPPA\_1^\circ C}$ are computed in Table (2) for exposure times $\Delta t = 60, 300,$ and 600 s.

Table 2 Example values of $I_{SPPA\_1°C}$ for existing kinds of ultrasonic sonars to which divers may be exposed.

Representative Sonar Type	Center Frequency f_{MHz} (MHz)	Pulse Length τ (s)	Ping Rate f_p (Hz)	$I_{SPPA\_1°C}$ (W/cm²) $\Delta t = 60$ s	$\Delta t = 300$ s	$\Delta t = 600$ s
Acoustic Lens Imaging Sonar [11]	1.10	0.0005	15	0.877	0.175	0.088
Blazed Array Imaging Sonar [12]	0.500	0.001	20	0.724	0.145	0.072
Diver Detection Sonar [13]	0.070	0.040	0.5	0.517	0.103	0.052

The I_{SPPA} of a sonar that produces a pulse with sound pressure level of SPL in dB re 1-µPa^2 at a point in the far field is

$$I_{SPPA} = \frac{10^{(SPL/10)}}{\rho c} \times 10^{-16} \ \frac{\mathrm{W}}{\mathrm{cm}^2}, \tag{16}$$

in which ρ is the density of water, which is nominally $\rho \approx 1000$ kg/m^3 for seawater. The upper bound on TI for a given SPL is then

$$TI < \frac{(\ln 10) f_{MHz} \tau\, f_P\, \Delta t}{\rho c} 10^{(SPL/10)} \times 10^{-16}\,. \tag{17}$$

Setting $TI = 1$ and isolating the exposure time Δt gives an upper bound on the safe exposure time in seconds, conservatively estimated, for a given measured SPL in the sonar beam,

$$\Delta t < \frac{\rho c}{(\ln 10) f_{MHz} \tau\, f_P} 10^{(-SPL/10)} \times 10^{16} \quad \mathrm{s}. \tag{18}$$

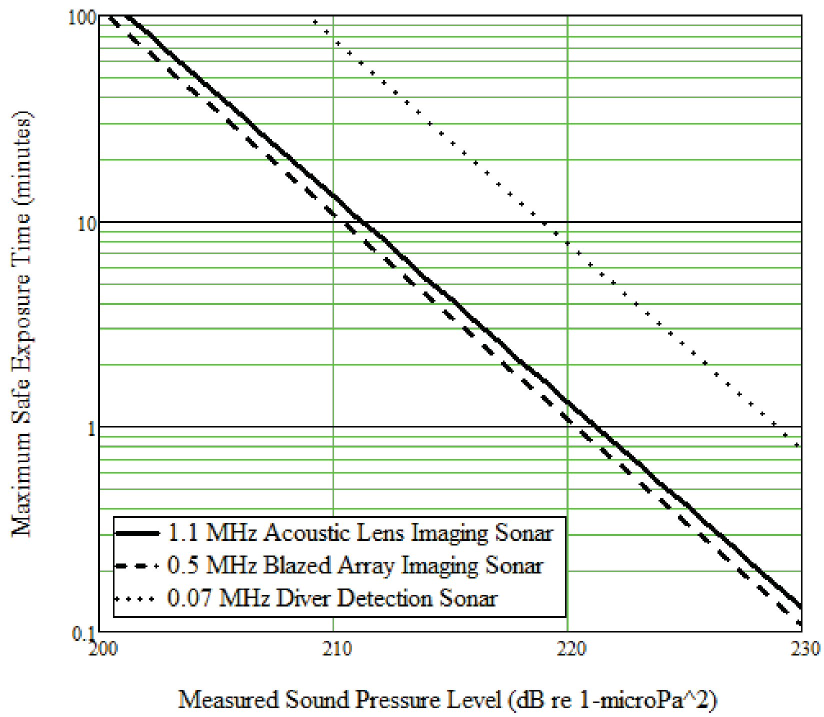

Figure 2 Maximum safe exposure time Δt (with no cooling mechanisms at work) as a function of the measured free-space sound pressure level SPL for the three sonars in Table (2).

3.1 Point-Like Sonar Source (In the Far Field of the Sonar)

The far field of the sonar occurs where one is far enough from the sonar face that the sonar appears to be a point source. Nominally this occurs at ranges (distances) [14]

$$R > \frac{D^2 f_{MHz} \times 10^6}{4c}, \qquad (19)$$

in which D is the largest dimension in meters across the actively radiating parts of the sonar transducer, and c is the speed of sound in water in meters per second (m/s), which, for seawater, is nominally $c = 1500$ m/s. For a typical imaging sonar, $D = 0.15$ m and $f_{MHz} = 0.6$ MHz, placing the far field at ranges $R > 2.25$ m.

In the farfield, then, it is usual for sonar engineers to report an effective source level SL for the sonar, in units of dB re 1-µPa^2 at 1 m when viewed from points along the central axis of the sonar transmit beam. And then the SPL as a function of range on axis (without refraction or reflection of sound) is

$$SPL = SL - 20\log_{10} R - aR \qquad (20)$$

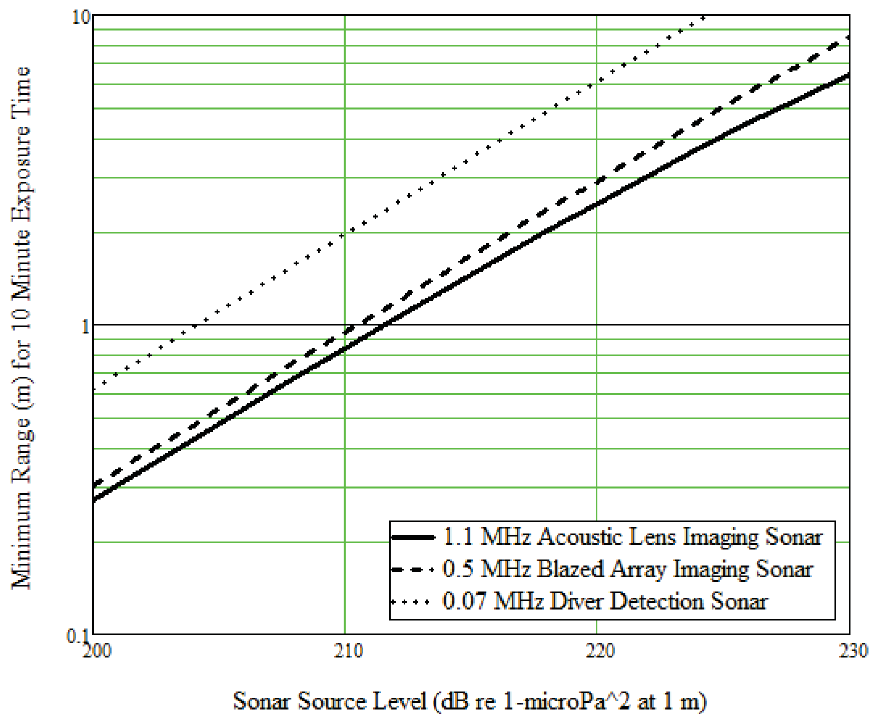

Figure 3 Minimum safe range R on the axis of the sonar for a continuous exposure time of $\Delta t = 10$ minutes (with no cooling mechanisms at work) as a function of the sonar source level SL when viewed in the far field from a point on the axis of the sonar beam.

in which $a(f_{kHz})$ in dB/m is the attenuation of sound due to the absorption loss by seawater for the frequency f_{kHz} expressed in kHz [15],

$$a(f_{kHz}) = 0.001\left[\frac{0.11 f_{kHz}^2}{1+f_{kHz}^2} + \frac{44 f_{kHz}^2}{4100+f_{kHz}^2} + 0.0003 f_{kHz}^2\right], \tag{21}$$

Then the upper bound on the TI faced by a diver at the center of the sonar beam, expressed as a function of range (subject to the far-field constraint (19)), is

$$TI < \frac{(\ln 10) f_{MHz} \tau\, f_P\, \Delta t}{\rho c} 10^{([SL - 20\log_{10} R - a(f_{kHz})R]/10)} \times 10^{-16}\,. \tag{22}$$

Once again, setting $TI = 1$ and isolating the exposure Δt time gives an upper bound on the safe exposure time in seconds, conservatively estimated now for exposure on axis at range R (presumably the smallest proximity, greater than the far-field constraint (19), that diver is foreseen to approach the sonar during sonar operations), or a given apparent source level SL on axis,

$$\Delta t < \frac{\rho c}{(\ln 10) f_{MHz} \tau\, f_P} 10^{(-[SL - 20\log_{10} R - a(f_{kHz})R]/10)} \times 10^{16} \quad \text{s}. \tag{23}$$

Alternatively, setting $TI = 1$ and isolating the range on axis R gives an upper bound on the safe exposure time in seconds, conservatively estimated for a given apparent source level SL and

4 Exacerbating Conditions

Reflective acoustic boundaries such as a calm sea surface (sea-state 0) or submerged smooth plane rigid surfaces can reflect the sonar beam to illuminate and expose divers who are not in the direct main beam of the sonar, and the source image they create can double exposure levels I_{SPPA} (see Fig. (4)). Concave reflective surfaces can furthermore focus and intensify reflected ultrasonic energy. These situations were not considered here. Exposure of the unprotected eye (divers without goggles) should be avoided.

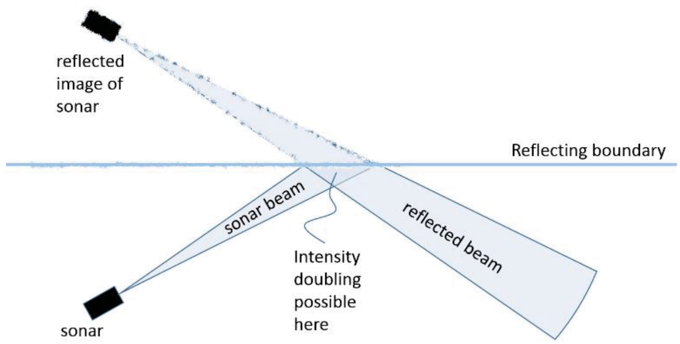

Figure 4 Schematic diagram of specular reflection of the sonar beam.

5 Conclusions

Estimates of the thermal index TI for assessing safe ultrasonic exposure levels, exposure time, and stand-off distances were estimated and illustrated for imaging sonars and diver detection sonars.

The estimates are conservative inasmuch as:

1. The safe exposure regime ($TI < 1$) was taken from medical diagnostic ultrasound applied to the particularly sensitive developing fetus during pregnancy.
2. The model of the power required to raise temperature $1\ ^{o}$C assumed the relatively large attenuation (highest energy capture) for bone and the relatively low heat capacity (highest temperature sensitivity) for fat, in order to conservatively set an upper bound on TI with no need then to consider (as in diagnostic ultrasound) where the ultrasonic illumination falls and passes through the body.
3. Significant mitigating factors against ultrasonic waves and their thermal effects were ignored here, namely:
    a. the protection against ultrasonic waves that will be provided by a diver's wet-suit or dry suit and other equipment such as mask and flotation vest;
    b. cooling of the diver by immersion in water; and
    c. 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.

4. In effect, then, the sonar and exposed diver were very conservatively assumed to be stationary, and the diver is furthermore assumed to be
    a. diving without a suit or equipment;
    b. the diver body consists of an artificial biological material whose thermal sensitivity to ultrasonic waves is somewhat higher than any part of the human body, and
    c. the water is at body temperature and perfectly still.

One could take steps to remove these very conservative assumptions, 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. As they stand, for instance (Fig. (3)), the safety constraints on the use of imaging sonars with respectable source levels of $SL = 212$ dB permit a 10 minute exposure time at 1 m, with closer exposures for shorter times, and more distant exposures at longer times.

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. These were excluded here owing to (1) the lack of data on the protection that different suits and equipment provide, (2) the significant analytic complexity that these mitigating factors introduce, and (3) the large scope that the present conservative safety recommendations already afford to operations.

It must not be forgotten that ultrasonic waves can have mechanical effects that are in no way addressed by the thermal measure, and which may have other, possibly more restrictive safety recommendations. These are considered elsewhere in this project.

6 References

1. Canadian Ministry of Health, "Guidelines for the Safe Use of Diagnostic Ultrasound", Published by authority of the, Minister of Public Works and Government Services Canada, 2001.
2. J.G. Abbott, "Rationale and Derivation of MI and TI – A Review", Ultrasound in Med. & Biol., Vol. 25, No. 3, pp. 431–441, 1999.
3. B. Smagowska, "Effects of Ultrasonic Noise on the Human Body—A Bibliographic Review", International Journal of Occupational Safety and Ergonomics (JOSE) 2013, Vol. 19, No. 2, 195–202.
4. T.A. Bigelow, C.C. Church, K.Sandstrom, J.G. Abbott, M.C. Ziskin, P.D. Edmonds, B. Herman, K.E. Thomenius, and T.J. Teo , "The Thermal Index Its Strengths, Weaknesses, and Proposed Improvements", Journal of Ultrasound in Medicine, JUM May 1, 2011 vol. 30 no. 5 714-734
5. National Council on Radiation Protection and Measurements. Exposure Criteria for Medical Diagnostic Ultrasound, I: Criteria Based on Thermal Mechanisms, Bethesda, MD: National Council on Radiation Protection and Measurements; 1192. NCRP report 113.
6. S.K. Miller, "Diagnostic Ultrasound Safety: A summary of the technical report "Exposure Criteria for Medical Diagnostic Ultrasound: II. Criteria Based on all Known Mechanisms", National Council on Radiation Protection and Measurements, undated, http://www.domrebenok.ru/videotestik/5_Ultrasound%20Summary--NCRP.pdf , last accessed 01-Mar-2017.

7. C.R.B. Merritt, F.W. Kremkau, and J.C., Hobbins, “Diagnostic Ultrasound: Bioeffects and Safety”, Ultrasound Obstet. Gynecol. 2 (1993) 366-374.

8. G. Pinton, J.F. Aubry, E. Bossy, M. Muller, M. Pernot, and M. Tanter, "Attenuation, scattering, and absorption of ultrasound in the skull bone", Med Phys. 2012 Jan;39(1):299-307.

9. M.J. Haney and W.D. O’Brien, “Temperature Dependency of Ultrasonic Propagation Properties in Biological Materials”, Chapt 2 in Tissue Characterization with Ultrasound: Volume I Methods, J.F. Greenleaf Ed., CRC Press Inc, Florida, 1986.

10. T.R. Nelson, J.B. Fowlkes, J.S. Abramowicz, and C.C. Church, "Ultrasound Biosafety Considerations for the Practicing Sonographer and Sonologist", J Ultrasound Med 2009; 28:139–150, 2009

11. Sound Metrics Corporation, DIDSON Diver Held, 35 m range, Imaging Sonar, Washington, USA,

    http://www.soundmetrics.com/Products/DIDSON-Sonars/DIDSON-Diver-Held-100m/DIDSON_DH_Product_Specs, last visited 01-Mar-2017

12. Teledyne Teledyne RESON A/S, BlueView, Slangerup, BlueView P450-45, http://www.blueview.com/products/2d-imaging-sonar/pseries-archives/p450-series/

13. Sonardyne, Sentinel IDS, Diver Interdiction Sonar, Hampshire, GBR, http://sonardyne-ms.net/technologies/diver-detection/diver-detection-sonar-sentinel/ , last visited 01-Mar-2017

14. Signal Processing SA, “The Ultrasonic Field”, Signal Processing SA, Savigny, Switzerland, http://www.signal-processing.com/us_field.html, last accessed 10-Mar-2017.

15. M. Ainslie, Principles of Sonar Performance Modelling, Springer, New York, 2010