The safety of diver exposure to ultrasonic imaging sonars

Ronald Kessel
Craig Hamm
Maritime Way Scientific

Vincent Myers
DRDC – Atlantic Research Centre

UACE2017 – 4th Underwater Acoustics Conference and Exhibition

Conference Location: Skiathos Island, Greece
Pagination info: 847–854

Date of Publication from Ext Publisher: March 2017

Defence Research and Development Canada
External Literature (N)
DRDC-RDDC-2018-N010
February 2018

IMPORTANT INFORMATIVE STATEMENTS

This document was reviewed for Controlled Goods by Defence Research and Development Canada (DRDC) using the Schedule to the *Defence Production Act*.

Disclaimer: This document is not published by the Editorial Office of Defence Research and Development Canada, an agency of the Department of National Defence of Canada but is to be catalogued in the Canadian Defence Information System (CANDIS), the national repository for Defence S&T documents. Her Majesty the Queen in Right of Canada (Department of National Defence) makes no representations or warranties, expressed or implied, of any kind whatsoever, and assumes no liability for the accuracy, reliability, completeness, currency or usefulness of any information, product, process or material included in this document. Nothing in this document should be interpreted as an endorsement for the specific use of any tool, technique or process examined in it. Any reliance on, or use of, any information, product, process or material included in this document is at the sole risk of the person so using it or relying on it. Canada does not assume any liability in respect of any damages or losses arising out of or in connection with the use of, or reliance on, any information, product, process or material included in this document.

© Her Majesty the Queen in Right of Canada (Department of National Defence), 2017

© Sa Majesté la Reine en droit du Canada (Ministère de la Défense nationale), 2017

THE SAFETY OF DIVER EXPOSURE TO ULTRASONIC IMAGING SONARS

Ronald Kessel[a], Craig Hamm[a], Vincent Myers[b]

[a]Maritime Way Scientific, 1420 Youville Drive, Unit 5a, Ottawa, Canada, K1C 7B3
[b]Defence R&D Canada – Atlantic, P.O. Box 1012, Dartmouth, Nova Scotia, Canada, B2Y 3Z7

Ronald Kessel, Chief Technical Officer, Maritime Way Scientific, 1420 Youville Drive, Unit 5a, Ottawa, Canada, K1C 7B3, +1 613-841-0505, rkessel@maritimeway.ca

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 ^{0} 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.

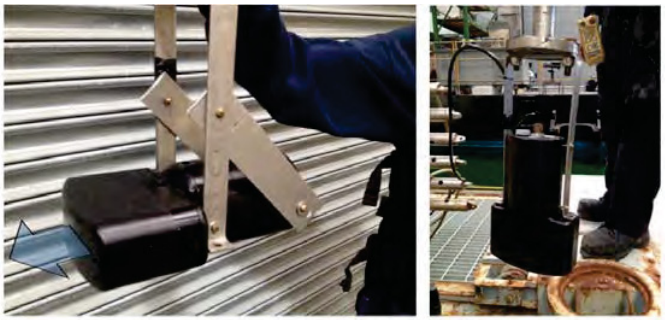


Fig. 1: The Teledyne BlueView P450-45 sonar head [8]. Two mounting positions were used for anechoic ultrasonic field measurements: horizontal mounting (left) for far-field measurements (beyond 2 m from the sonar face), and vertical mounting (right) for near-field.. The sonar beam direction (axis) is 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 ^{0} 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].

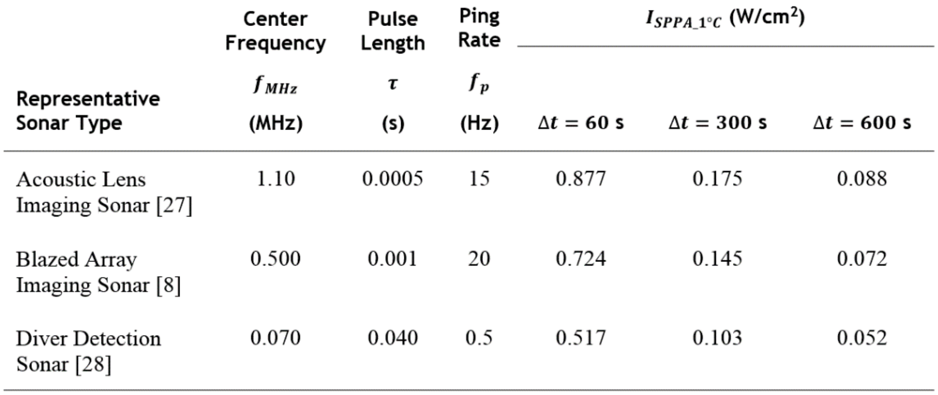
2. ULTRASONIC THREMAL INDEX

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^o} 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

$$TI < \frac{I_{SPPA}}{I_{SPPA\_1°C}}, \quad \text{in which} \quad I_{SPPA\_1°C} = \frac{1}{(\ln 10) f_{MHz}\tau \, f_{Ping}\Delta t} \quad \frac{\mathrm{W}}{\mathrm{cm}^2} \tag{1}$$

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*), $I_{SPPA\_1°C}$ 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 $I_{SPPA\_1°C}$ are given in Table (1). Here $I_{SPPA\_1°C}$ 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 f_{MHz} (MHz)	Pulse Length τ (s)	Ping Rate f_p (Hz)	$I_{SPPA\_1°C}$ (W/cm^2) $\Delta t = 60$ s	$\Delta t = 300$ s	$\Delta t = 600$ 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 $I_{SPPA\_1°C}$ 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]

$$MI = \frac{p^{-}_{peak\_MPa}}{\sqrt{f_{MHz}}} \tag{2}$$

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].

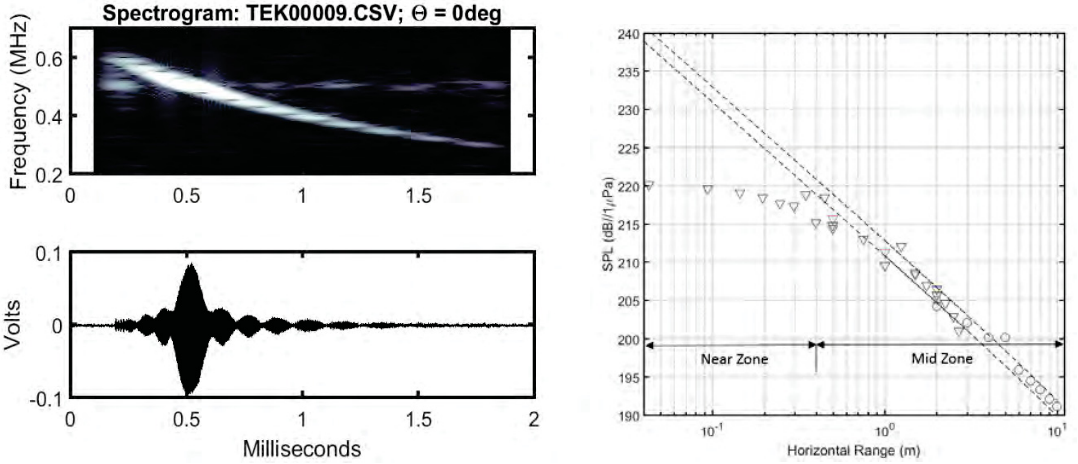


Fig. 2: (Left) example spectrogram and time series 4 m on axis of the sonar in relative units. (Right) Measurements of sound pressure level (SPL) on the axis of the sonar.

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	$I_{SPTA} \leq 720$ mW/cm^2 (highest intensity measured in the ultrasound beam averaged over the pulse repetition period)
Spatial-Peak Pulse-Average Intensity	$I_{SPPA} \leq 190$ 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 1µPa) 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.

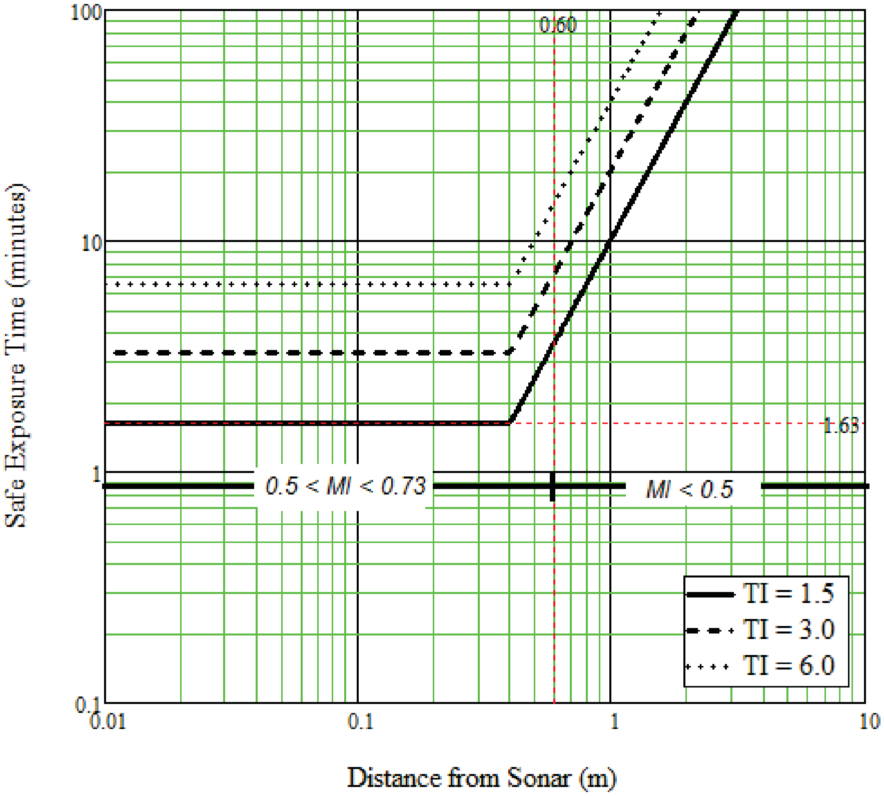


Fig. 3: The safe exposure time and distance, conservatively estimated, for a diver on the axis of the P450-45 sonar.

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 m, 10 min) and (2 m, 40 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 ^{0}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 cloer 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 ±2.6 ^{0} 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.

7. REFERENCES

1. **M.A. Ainslie**, "Review of published safety thresholds for human divers exposed to underwater sound", TNO Report TNO-DV 2007 A598, April 2008.
2. NATO Undersea Research Centre Human Diver and Marine Mammal Risk Mitigation Rules and Procedures, NURC-SP-2006-008, September 2006.
3. Effects of Intense Water-Borne Sound on Divers. Prepared by Naval Submarine Medical Research Laboratory, Groton, CT, Department of the Navy, 1996.
4. **S.J. Parvin, E.A Cudahy & D.M Fothergill**, "Guidance for diver exposure to underwater sound in the frequency range 500 to 2500 Hz", Proceedings of Underwater Defence Technology (UDT) (2002).
5. **E. Cudahy and S. Parvin**, "The effects of underwater blast on divers", Naval Submarine Medical Research Laboratory, NSMRL Report 1218, 08 February 2001
6. **R. Kessel and C. Hamm**, “Ultrasonic Exposure Safety Recommendations for High Frequency Hand-Held Sonars”, Maritime Way Scientific, Full Report, Project 13-027.9, 23-Mar-2017. (To appear as DRDC – Atlantic Contractor’s Report).
7. **V. Myers**, "Health and safety recommendations for the use of ultra-high frequency handheld sonars (U)", Defence Research and Development Canada Scientific Report, DRDC-RDDC-2015-R233, Protected A, November 2015
8. Teledyne BlueView, “P450 Series Sonar Imaging Sonar”, Teledyne RESON A/S, Slangerup, Denmark, http://www.blueview.com/products/2d-imaging-sonar/pseries-archives/p450-series/, last accessed 01-Mar-2017.
9. **M. Ainslie**, Principles of Sonar Performance Modelling, Srpinger, New York, 2010
10. **R.J. Urick**, Principles of Underwater Sound , 3rd Edition, McGraw-Hill, 1988
11. 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.
12. National Council on Radiation Protection and Measurements. Exposure Criteria for Medical Diagnostic Ultrasound, II: Criteria Based on All Known Mechanisms. Bethesda, MD: National Council on Radiation Protection and Measurements; 2002. NCRP report 140.
13. 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

14. **J.G. Abbott,** “Rationale and Derivation of MI and TI – A Review”, Ultrasound in Med. & Biol., Vol. 25, No. 3, pp. 431–441, 1999.
15. **G. ter Haar**, "Ultrasonic imaging: safety considerations", Interface Focus (2011) 1, 686–697
16. **K.E. Thomenius, M.C. Ziskin, P.L. Carson, and G.R. Harris,** “Section 7—Discussion of the Mechanical Index and Other Exposure Parameters”, Journal of ultrasound in medicine : official journal of the American Institute of Ultrasound in Medicine. 2000;19(2):143-168.
17. **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.
18. **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
19. 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.
20. The British Medical Ultrasound Society (BMUS), "Guidelines for the safe use of diagnostic ultrasound equipment", Safety Group of the British Medical Ultrasound Society, 2009.
21. U.S. Department of Health and Human Services, "Guidance for Industry and FDA Staff Information for Manufacturers Seeking Marketing Clearance of Diagnostic Ultrasound Systems and Transducers", Food and Drug Administration, Center for Devices and Radiological Health, Radiological Devices Branch, Division of Reproductive, Abdominal, and Radiological Devices Office of Device Evaluation, September 9, 2008
22. **K. Maeda and A. Kurjak**, "Diagnostic Ultrasound Safety", Review Article, The Donald School Journal of Ultrasound in Obstetrics and Gynecology (DSJUOG), Vol. 8, April-June 2014: 178-183
23. **C.R.B. Merritt, F.W. Kremkau and J.C. Hobbins**, "Diagnostic Ultrasound: Bioeffects and Safety", Ultrasound Obstet. Gynecol. 2 (1992) 366-374
24. **F. Ahmadi, I.V.McLoughlin, S. Chauhan, and G. ter-Haar**, "Bioeffects and safety of low intensity,low frequency ultrasonic exposure", Progress in biophysics and molecular biology (2012) 108 (3), 119-138
25. **J. Joy, I. Cooke, M. Love**, "Review: Is ultrasound safe?", The Obstetrician & Gynaecologist, 2006;8:222–227.
26. **R. Kessel**, “The Thermal Index for Assessing Diver Exposure Risk to Ultrasonic Sonars”, Maritime Way Scientific Ltd., Full Report, to appear Apr 2017.
27. 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
28. Sonardyne, Sentinel IDS, Diver Interdiction Sonar, Hampshire, GBR, http://sonardyne-ms.net/technologies/diver-detection/diver-detection-sonar-sentinel/ , last visited 01-Mar-2017
29. “Section 6—Mechanical Bioeffects in the Presence of Gas-Carrier Ultrasound Contrast Agents”, Journal of ultrasound in medicine : official journal of the American Institute of Ultrasound in Medicine. 2000;19(2):120-168.

DOCUMENT CONTROL DATA

*Security markings for the title, authors, abstract and keywords must be entered when the document is sensitive

1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.) DRDC – Atlantic Research Centre Defence Research and Development Canada 9 Grove Street P.O. Box 1012 Dartmouth, Nova Scotia B2Y 3Z7 Canada	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) CAN UNCLASSIFIED 2b. CONTROLLED GOODS NON-CONTROLLED GOODS DMC A

3. TITLE (The document title and sub-title as indicated on the title page.)

The safety of diver exposure to ultrasonic imaging sonars

4. AUTHORS (last name, followed by initials – ranks, titles, etc., not to be used)

Kessel, R.; Hamm, C.; Myers, V.

5. DATE OF PUBLICATION (Month and year of publication of document.) February 2018	6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.) 8	6b. NO. OF REFS (Total references cited.) 29

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

External Literature (N)

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

DRDC – Atlantic Research Centre
Defence Research and Development Canada
9 Grove Street
P.O. Box 1012
Dartmouth, Nova Scotia B2Y 3Z7
Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC-RDDC-2018-N010	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.) Imaging Sonar; Diver Handheld Sonar; Ultrasonic Safety; Diver Ultrasonic Safety
13. ABSTRACT/RESUME (When available in the document, the French version of the abstract must be included here.)