A new definition for acoustic dose

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Abstract. This paper discusses a recent proposal for definitions of acoustic dose and acoustic dose-rate. Acoustic dose is defined as the energy deposited by absorption of an acoustic wave per unit mass of the medium supporting the wave. Its time-derivative, acoustic dose-rate, \( Q_m \), in W kg\(^{-1} \), is central to the prediction of both rate of temperature rise and radiation force. These quantities have spatial and temporal dependency, depending on the local field parameters (acoustic pressure, particle velocity, intensity) and local material properties (absorption coefficient, \( \alpha_a \), and mass density, \( \rho_0 \)). Spatial and/or temporal averaging can be applied where appropriate. For plane-wave monochromatic conditions in a homogeneous medium, \( Q_m = 2 \alpha_a I / \rho_0 \), \( (I \) is the time-averaged intensity), a simple expression which may also incorporate frequency dependencies of energy deposition. Acoustic dose and acoustic dose-rate are exact analogues for Specific Absorption and Specific Absorption Rate (SAR), quantities central to radiofrequency (RF) and microwave dosimetry. Acoustic dosimetry in the presence of tissue/gas interfaces remains a considerable challenge.

1. Introduction

The term ‘acoustic dose’ has never gained clear definition and usage in the context of the biological effects of ultrasound. This has often led to confusion in the description of the conditions pertaining to such effects and the interactions that give rise to them. Instead, a form of dosimetry terminology has evolved in connection with two of the mechanisms, heating and cavitation, rather than being associated with any more fundamental physical quantity. Concepts and definitions of thermal dose [1] and cavitation dose have evolved. Thermal dose is the time to achieve, on average, a particular biological outcome at a specified temperature rise (or time-temperature-rise integral). If the thermal dose is known for one temperature, it is possible to estimate, from the assumed Arrhenius relationship between time and temperature rise, the time to achieve the same outcome at a different temperature rise [2]. Thermal dose is really a threshold, however, for which scaling of dose has no meaning. It is not possible to predict the outcome of halving or doubling the thermal dose (that is halving or doubling the heating time) from knowledge of a particular thermal dose, nor does this thermal dose have any independent meaning relating it to another cell line or tissue, or biological endpoint. The term ‘cavitation dose’ has also been used by several authors, usually derived from the time-integral of the signal from a passive cavitation detector [3,4]. Such approaches do not give an absolute quantity that may be compared between laboratories, however, nor do they relate quantitatively and directly to the interaction process.

New definitions for acoustic dose, and its time-derivative acoustic dose-rate, based upon energy deposition per unit mass, have recently been proposed [5,6]. The present paper reiterates these definitions and develops the underlying concepts. The definitions have arisen in part from
consideration of the way in which those concerned with dosimetry for electromagnetic radiations, both ionizing and non-ionizing, have dealt with the need to quantify the energy deposited in tissues, from which subsequent biological outcomes may be predicted. For ionizing radiations, absorbed dose is defined as the energy deposited per unit mass of a medium, because the biological effects of ionizing radiation depend strongly on this quantity. For RF and microwave radiation, Specific Absorption similarly quantifies the energy deposited per unit mass. The Specific Absorption Rate (SAR) is much more useful, however, since it is related directly to temperature rise and hence thermal biological effects. The definitions of acoustic dose and acoustic dose-rate are formulated to align with these dosimetric quantities, which are in widely-accepted use for other radiations. As will be seen below, the acoustic dose-rate relates more closely to biological effects mechanisms than does acoustic dose.

Acoustic dose and its time-derivative acoustic dose-rate are both spatially-dependent and time-dependent quantities. As with more conventional acoustic exposure quantities, it would be possible (and perhaps in some cases appropriate) to use a derived value as a descriptor of the whole field. For example the spatial average or spatial peak value, or the value at a specified point, could be calculated, being the dosimetric analogues of, for example, the commonly-used ultrasound safety parameters for acoustic exposure such as Thermal Index, or estimated in-situ spatial-peak temporal-average intensity. It is not the primary purpose, however, to develop here such derived values, but rather to set the general dosimetric principles in place, and to leave such possible developments to follow as and when they may be found to be useful.

2. Definitions of acoustic dose and acoustic dose-rate.
Acoustic dose, $\Phi$, is defined as the energy deposited per unit mass of a medium supporting an acoustic wave. The SI unit for acoustic dose is joule per kilogramme (J kg$^{-1}$). Acoustic dose-rate, $q_m$, is defined as the instantaneous temporal rate of deposition of energy per unit mass of a medium supporting an acoustic wave. The SI unit for acoustic dose-rate is joule per second per kilogramme (J s$^{-1}$ kg$^{-1}$) or, equivalently, watt per kilogramme (W kg$^{-1}$). Both acoustic dose and acoustic dose-rate may vary with position, and take values that are location-dependant. Acoustic dose-rate may be time-varying whilst acoustic dose relates to an acoustic exposure over a specified time period.

3. Expressions for acoustic dose and acoustic dose-rate
A closely analogous quantity to the acoustic dose-rate, the dissipation function, $q_v$, was used by Nyborg as the starting point for the calculation of the temperature rise in a relaxing medium [7]. The dissipation function is the instantaneous rate of energy deposition per unit volume. The local time-average of $q_v$ over an appropriate time interval is

$$\langle q_v \rangle = -\nabla \cdot I = -\nabla \cdot \langle pu \rangle = -\nabla \cdot \langle i \rangle \quad (1)$$

where $i$ and $I$ are the instantaneous and time-averaged intensities respectively, $p$ is the local acoustic pressure and $u$ is the particle velocity. Thus, equivalently, the local time-average of acoustic dose-rate is

$$\langle q_m \rangle = -\frac{\nabla \cdot I}{\rho_0} = -\frac{\nabla \cdot \langle pu \rangle}{\rho_0} = -\frac{\nabla \cdot \langle i \rangle}{\rho_0} \quad (2)$$

where $\rho_0$ is the mean mass density.

Under the specific conditions of the uniform deposition of energy in a homogeneous absorbing medium from a plane travelling wave, the dissipation factor is

$$Q_v = 2\alpha_a I \quad (3)$$
where \(2\alpha_a\) is the intensity absorption coefficient of the medium in nepers, and the notation \(Q\) is used for the time-average \(\langle q_v \rangle\). This expression may be also applied, to good approximation in the far field of a piston source and in the focal region: more general expressions may be derived for other positions on the axis of symmetry of plane and focused transducers [8].

It follows that the rate of energy absorption per unit mass, or acoustic dose-rate, \(Q_m\), (that is, \(\langle q_m \rangle\)) is

\[
Q_m = \frac{2\alpha_a I}{\rho_0}. \tag{4}
\]

The total energy deposited per unit mass of a medium, acoustic dose \(\Phi\), during a time period \(t\), is

\[
\Phi = \frac{2\alpha_a I t}{\rho_0}. \tag{5}
\]

Equations 4 and 5 assumed an acoustic wave of a single frequency, but may be easily rewritten to accommodate broadband exposure by integrating the product \(2\alpha_a I\) over frequency, for which equation 4 may be re-written

\[
Q_m = \frac{2 \int (\alpha_a I) df}{\rho_0}. \tag{6}
\]

4. Acoustically inhomogeneous media: scattering and reflection

Real materials supporting an ultrasound wave are generally not homogeneous. To be useful, concepts of acoustic dose and acoustic dose-rate must retain definition and meaning within an acoustically inhomogeneous medium. Acoustic phenomena such as scattering, reflection and refraction must be accommodated. None of these phenomena alter the material properties of the medium, \(\alpha_a\) and \(\rho_0\), however, only changing the intensity \(I\) (or more fundamentally the instantaneous intensity \(i\)). Exact acoustic dose estimates therefore require the local intensity to be estimated or measured. Soft tissue scattering is weak, so conventional approximations to estimating soft-tissue exposure in-situ may often be sufficient. Close to strong scatterers and reflecting surfaces, such as at soft-tissue/bone interfaces, and soft tissue/gas interfaces, the influence of the surface on the local intensity would require quantification. Amongst the conditions previously considered for the dissipation factor [8], the particular case of the superposition of two travelling waves was evaluated. This case is relevant for conditions close to tissue/bone or tissue/air interface.

5. Acoustic dose-rate and mechanical and thermal effects

The relationships between the product \(2\alpha_a I\) and specific thermal and mechanical responses are well described in the literature. The initial rate of increase in temperature caused by the absorption of ultrasound is

\[
\frac{dT}{dt} = \frac{2\alpha_a I}{\rho_0 C} = \frac{Q_m}{C} \tag{7}
\]

where \(C\) is the specific heat capacity of the medium. Standard methods for estimating temperature rise from the absorption of ultrasound use this expression as the energy source term, depending on assumed thermal conduction and convection and 3D intensity distributions (ie 3D acoustic dose-rate distributions for uniform media) in order to predict the time-course and final steady-state increase in temperature.
In a travelling wave, the medium also experiences a volumetric force, \( F_v \), in the direction of wave propagation, associated with radiation pressure. This force, expressed per unit mass, \( F_m \), is

\[
F_m = \frac{F_v}{\rho_0} = \frac{2\alpha_a I}{\rho_0 c_0} = \frac{Q_m}{c_0}
\]

where \( c_0 \) is the sound speed. Comparison between equations 7 and 8 demonstrates the close relationship between heating and body force caused by acoustic absorption. In particular, the central role played by acoustic dose-rate in both these mechanisms demonstrates explicitly that both thermal and mechanical mechanisms are present under all exposure conditions, and that one cannot exist in the absence of the other. Pulsing regimes may be expected to elicit different relative outcomes, however. The recovery times may be expected to be much shorter for stress effects than for thermal effects: to a first approximation stress effects may be expected to depend on the pulse-average intensity, and thermal effects to the time-averaged intensity.

6. Dose estimation in the presence of gas bubbles

For the majority of situations the principles of estimation of acoustic dose-rate outlined above should lead to reasonable estimates of distributions of energy deposition, from the point-by-point product of absorption coefficient and intensity and knowledge of the mean mass density. Considerable challenges remain, however, in the measurement or prediction of acoustic dose-rate in the presence of bubbles. These may be introduced into the medium (assumed to be tissue), for example, either as the result of cavitation or boiling from high intensity ultrasound exposure, or from the introduction of gas-bubble contrast agents. In both these cases, the introduction of bubbles adds a new time-variation for all the three quantities in the dose-rate expressions, \( \alpha_a, \rho_0 \) and \( I \). \( Q_m \) is inherently a time-varying quantity, and in principle to should be possible to quantify this time variation through the time-variation of these three quantities as the bubbles form, grow, coalesce, move and disperse. Clearly, however, there would be a huge challenges arising from the wide range of bubble behaviour, characteristic of acoustic cavitation, and also from the variety of forms into which energy may be converted, including thermal, radiative, potential, kinetic and chemical.

One outcome of the presence of bubbles is to increase the effective absorption coefficient of the medium above its native value in the absence of bubbles. This in turn enhances heating. Under some conditions it may be possible to assign an average effective absorption coefficient to the bubbly medium. An alternative approach might enable the power deposited per unit mass to be estimated from calculation of the power deposited per bubble, and knowledge of the bubble concentration [5].

7. Discussion

This paper brings together several known aspects related to energy deposition from sound into its supporting medium in order to develop a coherent definition of the terms “acoustic dose” and “acoustic dose-rate”. This is done with the intention of introducing uniformity and clarity for acoustic dosimetry, that is, the quantification of energy deposition from acoustic waves. Simple expressions developed using plane-wave assumptions may be used widely, but not universally. In the focal zone, and for much of an unfocussed near field, the dissipation function (and hence the acoustic dose-rate) is essentially the same whether bulk or shear viscosity is the primary mechanism [8]. Close to the transducer this is not so, but information may, in principle, be obtained by measuring Q distributions in known acoustic fields [8].

Accepting the plane-wave approximation, acoustic dose-rate may be calculated from the product of exposure, specified in terms of intensity, and energy transfer, specified by the absorption coefficient. The measurement of acoustic dose, therefore, requires the measurement of both. Each quantity may vary spatially, and this will be reflected in general by a 3D variation of acoustic dose.
Table 1. Calculated values of acoustic dose-rate, \( Q_m \), and acoustic dose per pulse, \( \Phi \), associated with several conditions of medical uses of ultrasound at 3 MHz. Standard values of absorption coefficient and mass density have been used [9]. An intensity transmission coefficient of 0.5 from tissue to bone is assumed. A pulse duration of 1s is assumed used for HITU exposure, and 1\( \mu \)s for a diagnostic pulse.

| Tissue          | Intensity (W cm\(^{-2}\)) | Acoustic Dose-rate, \( Q_m \) (W g\(^{-1}\)) | Acoustic Dose per pulse, \( \Phi \) (J g\(^{-1}\)) |
|-----------------|---------------------------|---------------------------------------------|---------------------------------------------|
| FDA in-situ I(spta) |                           |                                             |                                             |
| Soft tissue     | 0.72                      | 0.216                                       |                                             |
| Bone            | 0.72                      | 2.25                                        |                                             |
| FDA in-situ I(sppa) |                           |                                             |                                             |
| Soft tissue     | 190                       | 57                                          | \( 5.7 \times 10^{-5} \) (1 \( \mu \)s) |
| Bone            | 190                       | 500                                         | \( 5.0 \times 10^{-4} \) (1 \( \mu \)s) |
| HITU            | Soft tissue               | 1000                                        | 300                                          |
| Physiotherapy   | Soft tissue               | 1.0                                         | 0.3                                          |

(and hence acoustic dose-rate) throughout any region of interest. The spatial distribution of acoustic dose-rate, \( Q_m \), may be predicted from the local product of the \textit{in-situ} intensity (using any standardized or more realistic model) and the absorption coefficient. Such 3D distributions of dose-rate form the appropriate input for computations of 3D temperature increase under real situations. Accurate prediction of the acoustic dose-rate therefore depends on the ability to accurately predict (or measure) \textit{in-situ} intensity, including not only the transmission loss from overlying tissues but also the contributions from scatter and reflection from adjacent tissues. Generalized models of tissue properties are limited in value (the simplest, and therefore the least useful, being the standard soft-tissue model for which an attenuation coefficient of 0.3 dB cm\(^{-1}\) MHz\(^{-1}\)). Reliable experimental data of measured absorption coefficients of body tissues are still relatively rare, and the need to carry out further measurements is therefore emphasized. Examples of calculated values for \( Q_m \) (W g\(^{-1}\)) and \( \Phi \) (J g\(^{-1}\)) are given in table 1 for a few relevant conditions, including the limits given by the FDA for marketing of diagnostic ultrasound equipment in the USA.

In principle it would be possible to develop an experimental acoustic dose-rate meter to measure directly the rate of energy deposition in a standard material by either thermal or mechanical means. A thermal test object [10] might form the basis for a calorimetric method. Radiation force balances offer the basis for a mechanical approach. Critical to the success of such devices would be the need to ensure that the device captures all the acoustic power, and that the absorber is very well characterized. “Standardized” acoustic dose-rate, measured by such an instrument, could then be used for equipment inter-comparison, calibration of therapeutic and surgical devices, and to provide input to estimates of \textit{in-vivo} acoustic dose and dose-rate.

Each of the quantities could have been defined in terms of energy deposited per unit volume, rather than unit mass. By using the definition given here, however, the quantity is identically analogous to Specific Absorption Rate, used as the primary dosimetric quantity for non-ionizing electromagnetic radiation in the RF and microwave frequency range, for which heating is the major, and perhaps the only important, bio-effects mechanism. For acoustics, the dose-rate relates to two bio-effects mechanisms, heating and radiation stress. Thus acoustic dose-rate, and not acoustic dose, is the more meaningful dosimetric quantity for ultrasound studies. Indeed, considerable benefit may accrue to those considering biological outcomes from exposure to low-level ultrasound from a careful review of the very large literature on the biological effects of RF and microwave radiation. If the assumption is made that, in each case, it is heating that dominates the biological processes, then SAR and acoustic dose-rate values are equivalent. It is recognized that there are conditions for which whole-body absorption is studied for RF radiation, conditions not generally relevant in an ultrasonic context. But equally many studies of localized microwave heating, for mobile phone dosimetry for example, concern highly localized patterns of energy
deposition. The geometric conditions are not very different from those used during ultrasound physiotherapy, and approach those arising during some diagnostic ultrasound exposures.

Comparison with absorbed radiation dose for ionizing radiation is perhaps less immediately relevant, because radiation dose relates directly to the biological outcome of exposure to ionizing radiation, whilst there is no evidence of similar integration of the effects of repeated ultrasonic exposures. Nevertheless, and in spite of the widespread use of radiation absorbed dose for ionizing radiation dosimetry, it is insufficient to completely characterize the associated biological responses. In order to allow for the fact that different ionizing radiations (X-rays, α particles, π mesons) cause different biological outcomes for the same energy deposition, a weighting factor, the relative biological effectiveness (RBE), has been introduced. Consideration may be necessary to introduce into ultrasound dosimetry some equivalent means to characterize, for example, dosimetry in the presence of bubbles, for which the energy transfer from the wave to the tissue follows very different routes.

8. Conclusion

Simple universal definitions for acoustic dose and acoustic dose-rate are presented. Using as precedent the definition of dose used for ionizing radiation, acoustic dose is defined as the energy deposited by an acoustic wave per unit mass of the medium supporting it. Under plane-wave assumptions, simple expressions for acoustic dose and acoustic dose-rate may be derived. Using well-established expressions, simple relationships between acoustic dose-rate and both rate of temperature rise and radiation force are demonstrated. The acceptance of well-defined measures of acoustic dose and acoustic dose-rate may help to clarify the usage of terminology associated with ultrasonic exposimetry, ultrasonic dosimetry and biological effects mechanisms.

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