Towards a portable system for the measurement of thermal and mechanical indices

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Abstract. Users of diagnostic ultrasound equipment are provided with on-screen indices ($TI$ and $MI$) to indicate the potential thermal and non-thermal hazards. It is prudent that these indices be checked for accuracy. Indeed, this is a recommendation of the Safety Guidelines of the British Medical Ultrasound Society. Knowledge of the variation with depth of the derated temporal-average intensity is required for two of the thermal index formulae for non-scanned beams – $TIS$ (large aperture) and $TIB$. A portable system has been designed and built to permit a plot of derated temporal average intensity versus depth to be quickly made for any ultrasound diagnostic scanner. Signals from a membrane hydrophone are amplified and input to an RF power meter. The use of an analogue method for measuring temporal intensity obviates the need for trigger signals from the scanner. The output from the power meter and the output from a hydrophone depth measuring potentiometer are input to a laptop computer, which calculates and displays the plots of derated intensities ($ITA_3$ and $ITA_6$) versus depth. By entering the separately measured acoustic output power of the scanner via the laptop keyboard, the laptop can produce and display $MI$ and $TI$ values.

1. Background.
Prior to 1993, the Food and Drug Administration (FDA) in the USA required manufacturers of diagnostic ultrasound equipment to limit certain acoustic output parameters such as the spatial peak temporal average intensity ($ISPTA$) to application-specific values. Thus $ISPTA$ was limited to 94 mW cm$^{-2}$ for obstetric applications and 17 mW cm$^{-2}$ for ophthalmological applications, while for peripheral vascular applications the limit was much higher at 720 mW cm$^{-2}$. These values were “derated” values, meaning they were in-water values modified to allow for the attenuation that would be introduced by an attenuation coefficient of 0.3 dB cm$^{-1}$ MHz$^{-1}$. In 1993 an alternative route to gaining FDA approval, known as “Track 3” was introduced and widely adopted. This required that two hazard indices, namely Thermal Index ($TI$) and Mechanical Index ($MI$), be displayed on the screen, both being constantly updated according to the control settings selected by the operator. $TI$ gives a rough indication of the potential temperature elevation in the patient’s tissues according to very simple models, while $MI$ gives a measure of the potential hazard from non-thermal mechanisms such as inertial cavitation. In return for the manufacturer providing these indices, Track 3 relaxed the $ISPTA$ limit for ophthalmological applications to 50 mW cm$^{-2}$ and the $ISPTA$ limit for all other applications, including obstetrics, to 720 mW cm$^{-2}$.
This change transferred much of the responsibility for the safe use of diagnostic ultrasound to the operators, who are required to apply the ALARA principle (As Low As Reasonably Achievable) to acoustic exposure of patients, using the displayed $MI$ and $TI$ values as a guide. In the UK, a set of guidelines has been published by the British Medical Ultrasound Society [1] to advise operators how to interpret these indices. It is evident that the operators should be able to rely on the accuracy of the displayed indices, since they must depend on them to judge any potential hazard, or lack of it. This has been acknowledged in the BMUS Guidelines, which states in Note 3 that:

“There should be independent checks that the displayed $TI$ and $MI$ values are accurate. These should be made soon after installation and after hardware or software changes.”

The work described here is intended to facilitate checks on the accuracy of displayed $TI$ and $MI$ values on ultrasound imaging machines situated within hospitals and clinics. The apparatus is designed to be portable without unduly compromising accuracy. This is a work in progress report rather than an account of a fully developed system.

2. Definitions of $TI$ and $MI$.
$TI$ and $MI$ are defined in the Output Display Standard (ODS) of the American Institute of Ultrasound in Medicine (AIUM) and the National Electrical Manufacturers Association (NEMA). These definitions are shown in Table 1. The symbols in the table are defined below:

| Soft tissue at surface | Scanned modes | Formula |
|------------------------|---------------|---------|
| Soft tissue at all depths | $TIS = \frac{W_0 f}{210}$ | |
| Bone at focus | $TIB = \frac{W_0 f}{210}$ | |
| Un-scanned modes | | |
| Soft tissue at all depths | | $TIS_e = \frac{W_0 f}{210}$ |
| $Aperture \leq 1 \text{ cm}^2$ | | \[TIS_{\geq 2 \text{ cm}^2} = \max \left\{ \min \left[ \frac{W_0 f}{210}, \frac{I_{fTA,3} f}{210} \right] \right\}\]
| Bone at focus | $TIB = \min \left[ \frac{W_0 f}{50}, \frac{W_3}{4.4} \right]$ | measured where $I_{fTA,3}$ is maximum |

| Bone at surface | Scanned mode | $TIC = \frac{W_0}{40 D_{eq}}$ |
| Un-scanned mode | $TIC = \frac{W_0}{40 D_{eq}}$ |
The depth of the measurement point below the probe face (cm).

$D_{eq}$

The diameter of a circle having the same area as the transmitting aperture (cm).

$z_{bp}$

“Break point depth”, equal to $1.5D_{eq}$ (cm).

$f$

The centre frequency of the transmitted pulse (MHz).

$W_0$

The total acoustic output power of the probe (mW).

$W_{01}$

The acoustic power of the probe from a 1 cm wide zone at the centre of the probe face (mW).

$W_3$

$W_0$ reduced by a factor to model the effect of an attenuation coefficient of 0.3 dB cm$^{-1}$ MHz$^{-1}$ (mW).

$p_{-3}$

The largest attenuated peak negative pressure amplitude (MPa) at any depth. (Attenuated peak negative pressure amplitude at a given depth is the measured peak negative pressure amplitude at that depth reduced by a factor to model the effect of an attenuation coefficient of 0.3 dB cm$^{-1}$ MHz$^{-1}$.

$I_{TA,3}$

The measured temporal average intensity (mW cm$^{-2}$) at a given depth, reduced by a factor to model the effect of an attenuation coefficient of 0.3 dB cm$^{-1}$ MHz$^{-1}$.

$I_{TA,6}$

The measured temporal average intensity (mW cm$^{-2}$) at a given depth, reduced by a factor to model the effect of an attenuation coefficient of 0.6 dB cm$^{-1}$ MHz$^{-1}$.

$\min(L, M)$

The lesser of two variables $L$ and $M$ at a given depth.

$\max(\min(L, M))$

The maximum value of $\min(L, M)$ anywhere.

From the definitions in Table 1, it is evident that all but two of the thermal indices require only the measurement of two parameters: the centre frequency ($f$) and either $W_0$, or $W_{01}$. Measurements of $TIB$ and $TIS$ (large aperture) are more involved, however, as they require measurements of two derived quantities $I_{TA,3}$ and $I_{TA,6}$ over a range of depths. Measurements of $MI$ also requires measurements over a range of depths, namely of the attenuated peak negative pressure.

In the final measurement system, measurement of $f$ will require a preliminary survey of pulse intensity integral ($PII$) over a range of depths in order to establish the depth of the maximum $PII$ value, as this is the depth at which the ODS specifies $f$ must be measured. In the system as developed to the present time, however, $f$ is simply measured close to the probe.

3. System description

A block diagram of the system is shown in Figure 1. The apparatus in its present form is shown in Figure 2, although it is still being refined to make it as light and compact as possible. A bucket, part-filled with degassed water, forms the measurement tank. A slab of acoustic absorber at the bottom prevents multiple reflections. The bucket is fitted with a rigid metal rim to provide clamp support for the probe under test and a hydrophone micro-positioning device. The latter enables precise manual three dimensional adjustment of the hydrophone position relative to the probe by means of a vertical micrometer (Z direction) and two horizontal micrometers (X and Y directions). The hydrophone is a 0.4 mm diameter 15 mm

Figure 1. Block diagram of the measurement system.
bi-laminar PVDF film type (Precision Acoustics) mounted on a support rod attached to the micro-positioner.

The hydrophone is connected to its own calibrated preamplifier and then to a power amplifier with variable known gain and an output resistance of 50 ohm. The signal from the power amplifier is sufficient to drive a commercial RF power meter (Marconi 6950), taking the form of a 50 ohm resistive load and temperature sensor. This meter has an adjustable time constant, which is set to be large compared to the repetition period of the ultrasonic pulse sequence transmitted by the probe, but not so large that it slows down the measurement process significantly. The signal from the power meter is proportional to the temporal average power of the signal from the hydrophone, and hence to the temporal average acoustic intensity in the acoustic field. It is input to one channel of an analogue to digital converter board in the laptop PC. This analogue method of measuring $I_{TA}$ [2] avoids the need for any triggering signals, or detailed knowledge of the pulse sequences, from the ultrasound machine. The signal into the power meter is monitored on an oscilloscope to ensure it is not so large as to cause clipping, as this would cause an inaccurate measurement. If clipping is observed, the gain of the power amplifier is reduced.

The oscilloscope also provides the laptop PC with the magnitudes of the peak positive and negative voltages of the largest pulse and a digital version of the pulse waveform. From this the laptop PC calculates the pulse centre frequency $f$. The depth of the hydrophone relative to the probe face is measured by a linear potentiometer, the slider of which is connected to the hydrophone support rod (Figure 3). A stabilised voltage is applied across the potentiometer and the output voltage is input to a second channel on the analogue to digital converter board in the laptop PC.

Acoustic output power $W_0$ is measured with an ultrasonic radiation force balance (Figure 4), designed and built in-house [3]. $W_0$ is measured using the same balance, but with a mask of neoprene rubber blocking the output from all but the central 1 cm of the probe. Both values are entered manually into the laptop PC via the keyboard.
4. Method.

Once the ultrasound machine has been set up with the chosen probe, in the chosen mode, and with the controls set in the chosen way, there are four preliminary steps before carrying out a survey of the acoustic field. First, the acoustic powers $W_0$ and $W_{01}$ are measured using the radiation force balance and entered into the laptop PC via the keyboard.

Second, the radiating aperture of the probe is measured for the particular mode selected. A thin layer of coupling gel is applied to the probe face and a fine-edged metal or plastic rule is slowly swept across the probe face, while being held parallel to one edge of the probe face. The onset and termination of reverberant echoes indicates the limits of the radiating area in the direction perpendicular to the probe edge. This technique may be used to determine the radiating dimensions in both the scan and elevation planes.

Third, the voltage from the depth measuring potentiometer is calibrated in terms of the distance between the probe face and the hydrophone. The probe is clamped, pointing vertically down, with its front face just immersed in the water. The hydrophone is moved to a position as close as possible to the probe face and its distance from the probe face is measured using the calipers of the ultrasound system. The hydrophone is then moved to the maximum depth allowed by the vertical micrometer and its new distance from the probe face is measured with the calipers. These two caliper readings are entered into the laptop PC via the keyboard, allowing the potentiometer voltage to be converted to hydrophone depth below the probe face. This conversion includes a correction for the difference between the speed of sound in water and that assumed by the machine’s calipers.

The fourth preliminary is to measure the centre frequency $f$ of the transmitted pulses. The hydrophone is positioned about 1-2 cm below the probe and pulse waveforms are captured by the oscilloscope and exported in digital form to the laptop PC, where the necessary analysis is performed. In the final system, the frequency will be measured at the position of maximum pulse intensity integral ($\text{PII}$), as specified in the ODS.

After these preliminaries, a systematic search is made to find the highest temporal average intensity in each of a series of horizontal planes, distributed over a wide range of depths ($z$). The vertical micrometer is used to move the hydrophone to the first search plane, near the top of its travel, and then to progressively deeper search planes. At each depth, the two horizontal micrometers are used to move the hydrophone in a search for the position that gives the highest temporal average intensity at that depth, as indicated by the reading on the power meter. This search is aided by the generation of a plot on the laptop PC screen showing both the current and the maximum values of $I_{TA3}$ and $I_{TA6}$ found during the horizontal search at each depth. This plot gives an immediate indication as to whether or not the current value is the highest yet found for that depth. When the hydrophone is moved to a new depth, the maximum values of $I_{TA3}$ and $I_{TA6}$ at each depth remain on the screen, forming a sampled plot of these quantities versus depth (Figure 5).

Where the displayed plot indicates that the hydrophone is not near a maximum of either $I_{TA3}$ or $I_{TA6}$, the operator may choose larger vertical steps between horizontal search planes, but when close to a maximum, the vertical steps are likely to be less than a millimetre.
As the measurements proceed, the laptop PC continually re-calculates and displays working values for \( MI \) and \( TIB \) and, if required, \( TIS \) (large aperture). In calculating the working value of \( MI \) it uses the largest \( p_{-3} \) found up to that time. By the time the operator is satisfied that the maximum of \( p_{-3} \) versus depth has been identified, the displayed reading of \( MI \) will be correct. In calculating the working value of \( TIB \) it uses the value of \( I_{TA,3} \) at the depth of the largest \( I_{TA,6} \) found up to that time. By the time the operator is satisfied that the maximum of \( I_{TA,6} \) versus depth has been identified, the displayed reading of \( TIB \) will be correct. In calculating the working value of \( TIS \) (large aperture) the PC takes \( \min (I_{TA,3}, W_{3}) \) at all depths greater than \( z_{bp} \) measured up to that time and uses the maximum. By the time the operator is satisfied that the maximum of \( \min (I_{TA,3}, W_{3}) \) versus depth has been identified, the displayed reading of \( TIS \) (large aperture) will be correct.

5. Laptop PC calculations to find TI and MI values.

The laptop PC is programmed in C++ to calculate the pulse centre frequency \( f \) by performing a FFT on a specimen pulse and finding the arithmetic mean of the -3 dB bandwidth frequencies. Once \( f \) is determined, it can then calculate and store \( W_{3}, I_{TA,3} \) and \( I_{TA,6} \) at each measurement depth, and display them as a function of depth (Figure 5).

N.B. Except where indicated otherwise, the units assumed below are those specified in the ODS definitions. i.e. distances are in cm, frequencies in MHz, acoustic pressures in MPa, acoustic powers in mW and acoustic intensities in mW cm\(^{-2} \).

\( W_{3} \) (mW) for an assumed attenuation coefficient of 0.3 dB cm\(^{-1} \) MHz\(^{-1} \) is calculated from:

\[
W_{3} = W_{0} \exp(-0.3f_{z}/4.343)
\]

The signal of amplitude \( v \) (V) from the hydrophone preamplifier is amplified by the power amplifier (voltage gain \( B \)) and input to the sensor of the power meter. This sensor consists of a 50 ohm resistor, so the temporal average electrical power (W) measured by the power meter is:

\[
P = B^{2}v^{2}/50
\]

(Overlining here indicates a temporal average value over a time period much greater than the repetition period of the ultrasonic pulse sequence transmitted by the probe)

The voltage \( v \) (V) is related to the instantaneous acoustic pressure \( p \) (MPa) at the hydrophone by the hydrophone / preamplifier calibration factor \( A(f) = v/p \) (V MPa\(^{-1} \)).

The peak negative pressure (MPa) at any measurement point can therefore be found from the peak negative value of \( v \). The attenuated peak negative pressure is calculated by multiplying this acoustic pressure by \( \exp(-0.3f_{z}/4.343) \). The largest value of this attenuated quantity versus depth is \( p_{-3} \) (MPa).

The temporal average acoustic intensity (W m\(^{-2} \)) at the hydrophone is:

\[
I_{TA,3} = \frac{p_{-3}^{2}}{\rho c} = \frac{v^{2}}{(A^{2}\rho c)} , \quad \text{where } \rho \text{ is the density (kg m}^{-3}\text{) of water and } c \text{ is the speed of sound (m s}^{-1}\text{) in water, both corrected for temperature. (Overlining here indicates the temporal average value, as above)}
\]

From the previous expression for temporal average electrical power \( P \), it is possible to substitute \( 50 P/B^{2} \) for \( v^{2} \):

\[
I_{TA,3} = 50P/(B^{2}A^{2}\rho c) \quad (W \text{ m}^{-2})
\]

or

\[
I_{TA,6} = 5P/(B^{2}A^{2}\rho c) \quad (mW \text{ cm}^{-2})
\]

From this \( I_{TA,3} \) and \( I_{TA,6} \) can be calculated (mW cm\(^{-2} \)) for assumed attenuation coefficients of 0.3 dB cm\(^{-1} \) MHz\(^{-1} \) and 0.6 dB cm\(^{-1} \) MHz\(^{-1} \) respectively:

\[
I_{TA,3} = I_{TA} \exp(-0.3f_{z}/4.343)
\]

\[
I_{TA,6} = I_{TA} \exp(-0.6f_{z}/4.343)
\]

6. Time needed to make the measurements.
Approximately 30 minutes are needed to assemble the equipment on site, and approximately 20 minutes are needed to dismantle it after the measurements. Searching a sufficient number of horizontal planes to establish the locations of the maxima of $I_{IA,3}$ and $I_{IA,6}$, and hence measure $MI$ and all $TI$ takes about 15 minutes for one probe and one mode. Once the equipment is set up, it should be possible to measure $MI$ and all $TI$ for one probe in three common modes (B-mode, Colour Doppler Imaging and Spectral Doppler) in approximately one hour. Put another way, measurements on an ultrasound machine with three probes would require that machine to be out of clinical use for about half a day.

7. Accuracy.
Our estimates of the overall measurement accuracy are:

- $\pm 11\%$ for acoustic pressure
- $\pm 29\%$ for temporal average intensity
- $\pm 5\%$ for temporal average acoustic power.

These lead to the following estimates of accuracy for the $MI$ and $TI$ measurements:

- $\pm 11\%$ for $MI$
- $\pm 6\%$ for $TIS$ (small aperture)
- $\pm 30\%$ for $TIS$ (large aperture)
- $\pm 18\%$ for $TIB$
- $\pm 6\%$ for $TIC$.

8. Future developments
The ODS requirement that the centre frequency be measured at the point of maximum $PII$ requires a means of locating this point. In non-scanned modes (e.g. M-mode or Spectral Doppler), this can be done with the system in its present form since the point of maximum $ITA$ coincides with the point of maximum $PII$. However, in scanned modes (e.g. B-mode or Colour Doppler Imaging) or in mixed modes, the location of the maximum of $PII$ is less straightforward and further work is needed for this. It is also hoped that the bulk and weight of the equipment can be further reduced.

9. Conclusion.
Progress has been described towards a portable system for checking displayed $TI$ and $MI$ values for diagnostic ultrasound imaging machines at hospital sites. The prototype system can be fitted onto a small trolley for use and portability within a hospital, and the complete system, including the trolley, can be easily transported between hospitals by car. It is anticipated that displayed $MI$ and $TI$ values could be checked for a typical ultrasound machine with three probes in half a day. Measurement accuracies of around 10% are estimated for $MI$, and between 6% and 30% for the various forms of $TI$. In its present form, the system measures pulse centre frequency near the probe. In the next phase of development, the centre frequency will be measured at the point of maximum $PII$, in stricter accordance with the ODS specification. Further reductions in the size and weight of the system are also planned.

10. References.
[1] Guidelines for the safe use of diagnostic ultrasound equipment 2000. British Medical Ultrasound Society Bulletin 8 August 29-33.

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[3] Whittingham T A 1998 The purpose and techniques of acoustic output measurements *Ultrasound in Medicine* ed F A Duck, A C Baker and H C Starritt. (Institute of Physics Publishing) pp 129-148.