EVALUATION OF THE SOFT TISSUE THERMAL INDEX AND THE MAXIMUM TEMPERATURE INCREASE FOR HOMOGENEOUS AND LAYERED TISSUES

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ABSTRACT

Theoretical tissue temperature increases due to focused diagnostic ultrasound fields have been evaluated for both homogeneous and three-layer tissue models. Applying the monopole-source solution, the general acoustic pressure field distribution is obtained for a specific source temporal average power. The axial steady-state temperature increase is calculated by applying the point-source solution of the bio-heat transfer equation to the pressure field distribution. Homogenous and three-layer fetal tissue model examples for 3 MHz for circular source apertures are presented and compared to the Thermal Index of the recently approved *Standard for Real-Time Display of Thermal and Mechanical Acoustic Output Indices on Diagnostic Ultrasound Equipment.*

INTRODUCTION

A new method for determining the temperature increase in tissue generated by diagnostic ultrasound was presented [1]. This general method, called the monopole-source solution, can be applied to any transducer geometry as well as any tissue model.

Briefly, the monopole-source solution is used to estimate the maximum temperature increase generated in a medium exposed to ultrasound. Initially, the complex pressure field distribution is determined be modeling the transducer as a set of monopole sources evenly distributed over the transducer's surface. The pressure at a single point in the medium is the summation of the individual complex pressures generated by each monopole source on the transducer (source) surface (see Figure 1).

Once the complex pressure field has been determined, the temperature increase can be calculated using a point-source solution to the bio-heat transfer equation [2]. The temperature increase at each point in the medium is the summation of the temperature increase generated by all of the surrounding heated point-sources. In [1] the tissue was restricted to being homogeneous, while both circular and rectangular aperture transducers were compared. In this paper, we present the modified equations for the monopole-source solution for a layered tissue model.

The axial temperature increases are presented for several cases similar to those encountered during fetal imaging. The effect of the abdominal wall on the maximum temperature increase as well as its location are evaluated. In addition, the soft-tissue thermal index (TIS) [3] is presented and evaluated for both the homogenous and layered tissue models. A direct comparison between the TIS and the maximum temperature increase is performed in order to evaluate the TIS and its prediction concerning tissue heating.

THEORY

Multilayer Geometry

The geometry of the multilayered tissue case is shown in Figure 2. In this case, each layer is modeled with uniform but not necessarily the same thicknesses and with the boundaries perpendicular to the ultrasound beam axis. The boundaries are planar. Each layer of tissue has a unique attenuation (=absorption) coefficient denoted by A_i, and a unique perfusion length, L_i, where i is the layer number. As indicated in Figure 2, layers are numbered consecutively, with the layer in contact with the transducer labeled as Layer 1. For this simulation, the tissue characteristics (thermal conductivity K, tissue density ρ, and propagation speed c) are assumed to be the same for each layer, i.e., $c_1=c_2=c_3 \ldots c_{n-1}=c_n$. In addition, it is assumed that all of the incident energy is transmitted across each boundary, i.e., there is no reflection of energy at the tissue boundaries.

Pressure Field Distribution

The pressure field distribution is calculated using the monopole-source solution [1]. The theory presented in [1] is for the homogenous tissue model. In this case, we are also evaluating the layered tissue model which requires that the equations for the relative complex pressure p_{rel} and temperature increase ΔT be slightly modified. Due to the different attenuation values for each of the layers, the calculation of the relative pressure (Equation (10) of [1]) must modified. The equation representing the p_{rel} for the layered media case ($n \geq 2$) is

$$p_{rel}(x_m,y_m,z_m)=\sum\left[\frac{\exp(-jk\,|P_m-P_t|)}{|P_m-P_t|}\right.$$

$$\left. x\left(\prod_{i=1}^{n-1}\exp(-A_i\,|P_i-P_{i-1}|)\right)\exp(-A_n|P_m-P_{n-1}|)\right] \quad (1)$$

where P_m is the point in the medium, P_t is the transducer point-source, n is defined as the number of the layer that contains P_m, and P_i is defined as the point of intersection of P_m-P_t and the boundary between layers i and i-1 (for i=0, P_0 is defined as P_t). The product term accounts for the attenuation in all of the layers preceding the layer containing P_m. The last term represents the attenuation of the signal by the layer containing the point, P_m.

The p_o^2 distribution at the point, $P_m(x_m,y_m,z_m)$, is calculated using Equations (2) and (3) as for the homogeneous case.

$$p_o^2 = G^2\, p_{rel}p_{rel}^* \quad (2)$$

$$G^2(z) = \frac{W(z)}{\sum \frac{p_{rel}p_{rel}^*}{2\rho c}\Delta x\Delta y} \quad (3)$$

In order to scale the relative intensity to reflect the source power, W_{source}, the fact that the attenuation coefficient is not a constant throughout the media must be considered. Therefore the power at a distance z for the homogeneous case given by

$$W(z) = W_{source}\exp(-2Az) \quad (4)$$

is rewritten as

$$W(z) = W_{source}\left[\prod_{i=1}^{n-1}\exp(-A_i(z_{i+1}-z_i))\right]\exp(-A_{i+1}(z-z_i)) \quad (5)$$

where i and n are defined as for Equation (1).

Temperature Increase

When calculating the temperature increase using the monopole-source solution for the layered tissue model, it must be noted that the rate of heat generation by a point source is dependent on the absorption coefficient of the tissue that contains the point source, that is,

$$q_v = \frac{\alpha_n p_o^2(x_m,y_m,z_m)}{\rho c} \quad (6)$$

Thus, when calculating the temperature increase using the monopole-solution, it should be noted that point-sources in different layers generate heat at a different rate due to the difference in the absorption coefficient, α_n.

Calculation of the Soft-Tissue Thermal Index (TIS)

The Output Display Standard [3] describes the specific procedures for determining the soft-tissue thermal index (TIS) for unscanned modes. This procedure is applied from the ultrasonic field results derived using the monopole-source solution for the homogeneous case. Two calculation procedures [3] are based on whether the active aperture area is greater than 1 cm^2 or less than or equal to 1 cm^2. These two procedures are based on the assumption that the perfusion length is 1 cm. Theory for a heated cylinder suggests that if the beam area is less than 1 cm^2, then the power in the beam controls the temperature increase. If the beam area is greater than 1 cm^2, then intensity controls the temperature increase. The active aperture area (A_{aprt}) provides the basis for determining which procedure is used. For the case presented here, A_{aprt}> 1 cm^2, whereby intensity controls the temperature increase. The general mathematical description for calculating TIS is given by [3]

$$TIS = \frac{\min\left(W_{.3}(z_1);\, I_{TA.3}(z_1)\ x\ 1\ cm^2\right)}{\left(\frac{210}{fc}\right)} \quad (7)$$

where z_1 is determined from z_{bp} = 1.5 A_{aprt} and z_1=z where z ≥ z_{bp} and where the min of {$W_{.3}(z)$; $I_{TA.3}$ x 1 cm^2}is max.

That is, z_1 is the value of z (beyond the break point location, z_{bp}) that maximizes the function min {$W_{.3}(z)$; $I_{TA.3}$ x 1 cm^2}. The purpose of the break point and determining it by this procedure is to avoid the need for complicated field pressure measurements near the source.

RESULTS

In order to evaluate the effect of the thickness of the maternal abdominal wall on the temperature increase in the tissue, four cases are evaluated. The first case is that of the homogeneous tissue model. This model is used as a baseline result. This is due to the fact that the FDA regulates ultrasound equipment on the homogeneous tissue model. The homogeneous tissue model is used to determine the source power that will yield a derated spatial peak temporal average intensity ($I_{SPTA.3}$) of 720 mW/cm^2, the maximum derated value allowed by FDA. Using this power level, the layered tissue model is then evaluated. The data presented for the homogeneous and layered media are for a source power, W_{source}, of 225 mW, based on $I_{SPTA.3}$ of 720 mW/cm^2. Table 1 lists the operating parameters of the focused circular aperture transducer (see Figure 1) and Table 2 lists the homogeneous tissue characteristics. The resulting axial temperature increase profile for this case is shown in Figure 3. Table 3 summarizes the thermal index information for the homogeneous case.

Table 1. Transducer parameters

f	frequency (MHz)	3.0
D	source diameter (cm)	2.0
ROC	radius of curvature	10.0
A_{aprt}	active area aperture (cm^2)	3.14
W_{source}	source power (mW)	225

Table 2. Homogeneous Tissue Properties

c	propagation speed	1540 m/s
$A=\alpha$	attenuation=absorption	0.3 dB/cm-MHz
ρ	tissue density	0.001 kg/cm^3
L	perfusion length	1.18 cm
K	thermal conductivity	0.006 W/cm^2

Table 3. Thermal Index Information (Homogeneous Case)

$I_{SPTA.3}$	derated SPTA intensity* (mW/cm^2)	720
W_{source}	source power (mW)	225
z_{bp}	break point depth (cm)	3.0
z_1	assessment depth (cm)	3.5
$W_{.3}(z_1)$	derated W at z_1 (mW)	123
TIS	soft-tissue thermal index	1.76
ΔT_{max}	max temperature increase (°C)	0.84
z_{max}	range of ΔT_{max} (cm)	1.61
$\frac{\Delta T_{max}}{TIS}$	ratio of ΔT_{max} to TIS	0.48

*denotes derated according to Table 2.

Typical fetal imaging consists of propagating the ultrasound beam through the anterior abdominal wall and the fluid filled bladder before reaching the conceptus (see Figure 4). These cases are evaluated using the monopole-source solution approach discussed above and detailed in Table 4.

Table 4.Tissue parameters used in the layered tissue model.

	Fetal Case	#1	#2	#3
d_{aw}	abdominal wall thickness (cm)	0.1	1.0	2.0
d_b	bladder thickness (cm)	5.0	5.0	5.0
A_{aw}	abd. wall attenuation (dB/cm-MHz)	0.5	0.5	0.5
A_b	bladder attenuation (dB/cm-MHz)	0.0	0.0	0.0
A_c	conceptus attenuation (dB/cm-MHz)	0.3	0.3	0.3

The three cases are denoted Fetal-1, Fetal-2 and Fetal-3 and are compared against the homogenous medium case for which the TIS was given in Table 3. The three fetal cases listed in Table 4 differ only with respect to the abdominal wall thicknesses of 0.1, 1.0, and 2.0 cm. These thicknesses tend to be on the "thin" side of results reported by Siddiqi et al. [4,5] and within the "minimum measured thicknesses" range reported by Carson et al. [6,7] and NCRP [8]. A bladder thickness of 5 cm is typical of being fluid-filled [4,5]

The abdominal wall attenuation coefficient of 0.5 dB/cm-MHz is similar to that used by Carson et al. [6,7] and NCRP [8] for purposes of estimating "worst-case fetal exposures during the first and third trimesters" and less than that estimated for human in-situ measurements (1.39±0.89 dB/cm-MHz) by Siddiqi et al. [5]. For lack of available data, the conceptus attenuation coefficient was assumed to be 0.3 dB/cm-MHz, typical of relatively high-water content tissue. Figures 4, 5 and 6 show the axial temperature increase for Fetal-1, Fetal-2 and Fetal-3, respectively. The axial temperature increase for the homogenous tissue case is plotted for comparison.

Table 5 lists the maximum temperature increases in the abdominal wall ($\Delta T_{max;aw}$) and in the conceptus ($\Delta T_{max;c}$) along with the derated spatial-peak, temporal-average intensity ($I_{SPTA.d}$) for the three fetal examples (see Table 4). In addition, the ratios of $\Delta T_{max;aw}$ and $\Delta T_{max;c}$ to TIS are presented for each layered tissue case studied.

Table 5. Maximum Temperature Increases for the Three Fetal Cases (see Table 4) under the same set of conditions (see Tables 1 & 2) and Comparison of the Maximum Temperature Increase to the TIS for the homogenous case.

	Fetal Case	#1	#2	#3
Wsource	source power (mw)	225	225	225
TIS	soft-tissue thermal index	1.76	1.76	1.76
$I_{SPTA.d}$	SPTA intensity* (mW/cm^2)	2007	1772	1543
$\Delta T_{max;aw}$	abd wall max temp increase (°C)	0.10	0.83	1.10
$\Delta T_{max;c}$	conceptus max temp increase (°C)	1.52	1.23	0.94
$\frac{\Delta T_{max;aw}}{TIS}$	ratio of $\Delta T_{max;aw}$ to TIS	0.057	0.47	0.63
$\frac{\Delta T_{max;c}}{TIS}$	ratio of $\Delta T_{max;c}$ to TIS	0.86	0.70	0.53

*denotes derated according to Table 4.

Assuming that the soft-tissue thermal index, TIS, and the maximum temperature increase, ΔT, represent equivalent ideas, that is, the maximum soft-tissue temperature increase, the following observations from Table 5 are made. In other words, it is assumed that the

TIS is intended to provide information to the operator about the maximum soft-tissue temperature increase.

(1) Among the three cases, $\Delta T_{max;aw}$ does not exceed 1.5 °C.
(2) Among the three cases $\Delta T_{max;c} > 1.5$ °C for the thinnest abdominal wall thickness.
(3) For the three cases, as the anterior abdominal wall thickness increases, $\Delta T_{max;aw}$ increases.
(4) For the three cases, as the anterior abdominal wall thickness increases, $\Delta T_{max;c}$ decreases.
(5) For the three cases, TIS is greater than $\Delta T_{max;aw}$. In other words, TIS consistently overestimates $\Delta T_{max;aw}$ by a factor of between 1.5 and 1.8.
(6) For the three cases, TIS is greater that $\Delta T_{max;c}$. In other words, TIS consistently overestimates $\Delta T_{max;c}$ by a factor of between 1.2 and 1.8.
(7) For the three cases, as the anterior abdominal wall thickness increases, TIS consistently overestimates $\Delta T_{max;aw}$ to a lesser extent..
(8) For the three cases, as the anterior abdominal wall thickness increases, TIS consistently overestimates $\Delta T_{max;c}$ to a greater extent..
(9) For the three cases, the above observations are probably due to the fact that a thicker abdominal wall absorbs and attenuates more of the propagated ultrasonic energy.
(10) For the three cases, the derated spatial-peak, temporal-average intensity, $I_{SPTA.d} > 720$ mW/cm^2.

CONCLUSIONS

In this paper we have presented the modifications to the monopole-source solution to allow for a layered tissue medium. The axial temperature increases for three typical fetal imaging cases have been presented and compared to the axial temperature increase for the homogeneous case. Using these axial temperature increase profiles, the maximum temperature increase as calculated using the monopole-source solution has been compared to the Soft-Tissue Thermal Index that would be calculated for the identical cases.

In comparing the maximum temperature increase in the medium to the TIS, it was found that the TIS is conservative in estimating the maximum temperature increase in all four cases (as limited as they may be). This is significant as in industry, the TIS is calculated for the homogeneous tissue model and assumed valid for the layered tissue cases.

While the results are promising, additional work is being conducted to evaluate the effects of different transducer parameters (frequency, aperture size, etc.) and medium characteristics (attenuation, perfusion, etc.) on the relationship between the maximum temperature increase and the TIS for both the homogeneous and layered tissue models.

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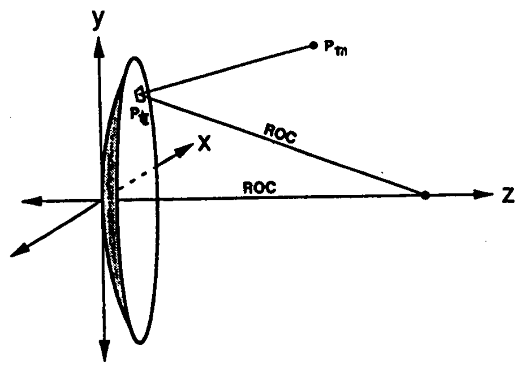

Figure 1:Geometrical model of a focused circular aperture. The coordinates on the surface of the source, P_t, are (x_t,y_t,z_t) and the corrdinates in the medium, P_m are, (x_m, y_m, z_m). ROC denotes the radius of curvature of and the beam axis is the z-axis.

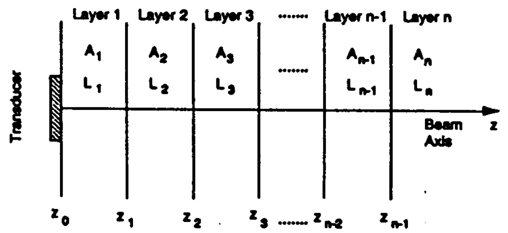

Figure 2: Geometry for multilayered medium. A_i is the attenuation coefficient of layer i; z_i is the axial distance of the boundary between layer i and layer i+1.

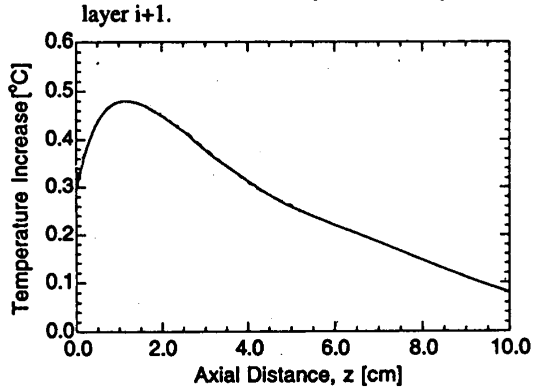

Figure 3: The axial temperature increase for the circular aperture transducer (Table 1) and the homogeneous tissue medium (Table 2) generated using the monopole-source solution [1]

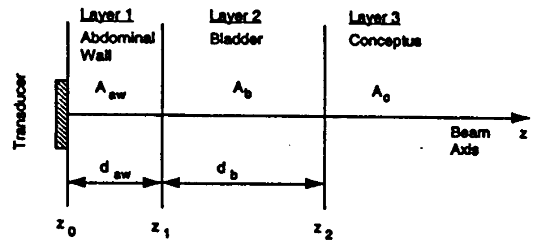

Figure 4:Layered tissue model representing tissues normally encountered during diagnostic fetal imaging.

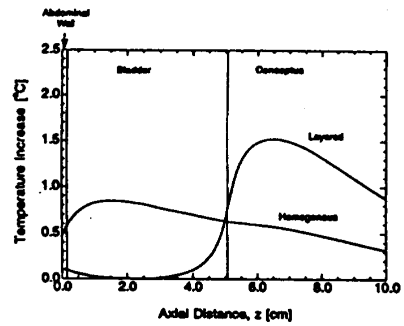

Figure 5: The axial temperature increase for the layered tissue case Fetal-1 (see Tables 2 and 4).

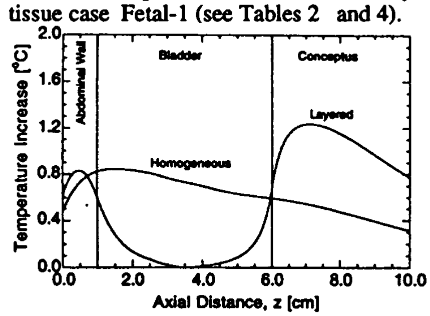

Figure 6: The axial temperature increase for the layered tissue case Fetal-2 (see Tables 2 and 4).

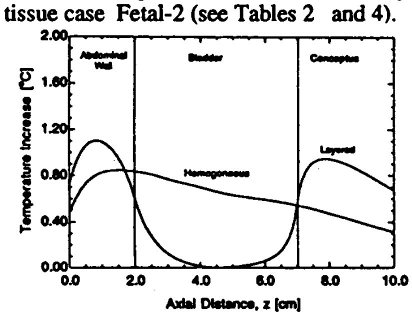

Figure 7: The axial temperature increase for the layered tissue case Fetal-3 (see Tables 2 and 4).