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Evaluation of potential bone mimicking materials for ultrasound thermal test objects

N.M. Pay, A. Shaw and A.D. Bond

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ABSTRACT

It is generally accepted that ultrasound has the potential to produce biologically significant temperature rises. At NPL, we have developed a thermal test object to enable the temperature rise produced by diagnostic ultrasound equipment to be measured experimentally. This report investigates the thermal and acoustic properties of potential bone mimics that are important when determining ultrasound induced temperature rises. An *ideal* foetal and adult bone specification is suggested, determined from the literature currently available, and suitable bone mimics are identified. Temperature rise predictions using the properties of the candidate bone mimics are then compared with those from the *ideal* specification. PTFE (glass-filled) is identified as a suitable adult bone mimic; high-density polyethylene is suggested as a foetal bone mimic.

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1 INTRODUCTION

It is recognised that there is a potential for current diagnostic ultrasound equipment to cause significant heating of biological tissue. Many national and international bodies are active in this area, including the World Federation for Ultrasound in Medicine (WFUMB, 1992 and 1997), the European Federation of Societies for Ultrasound in Medicine (EFSUMB, 1996) and the National Council for Radiation Protection (NCRP, 1992). There are several methods of determining this potential hazard such as the AIUM/NEMA Output Display Standard (AIUM/NEMA 1992) which uses theoretical predictions based on simplified clinical models and acoustic output data. There are limitations associated with these models, some of which NPL has addressed by developing a thermal test object. (Shaw, 1994; Shaw *et al.*, 1998)

A thermal test object (TTO) consists of a thermal sensor sandwiched between layers of tissue mimicking material (Bacon and Shaw, 1993); different configurations of mimics can be used depending on the clinical situation being simulated. To produce a standard TTO, the desired properties for a bone mimicking material need to be determined and suitable candidate materials identified. Values for the acoustic and thermal properties of biological tissues are available in the literature (Duck, 1990; NCRP, 1992). However, different types of bone exhibit different properties and the methods of storing and fixing before and during measurements can substantially affect these values.

Polytetrafluroethylene (PTFE) filled with 25% glass fibre by volume has been used as a bone mimic material in the TTOs for several years. Although it is a reasonable approximation to bone, it does have several shortcomings such as a peak in its specific heat capacity around room temperature and a slightly low value of thermal conductivity. Given these shortcomings, a number of studies have been carried out to re-assess the suitability of PTFE (glass-filled) as a bone mimicking material and to investigate other aspects. This report summarises these studies which include:

1. Effect of variation in specific heat capacity of PTFE (glass-filled) on the temperature rise produced in a soft tissue/bone test object.
2. Theoretical modelling to identify the most important material properties when performing temperature measurements, enabling each parameter required for the calculation of ultrasound induced temperature rise to be ranked in order of importance.
3. Construction of a specification for the properties of an *ideal* foetal and adult bone mimic, by consideration of published bone properties information.
4. Search of various data sources to identify suitable bone mimics.
5. Comparison of temperature rise predictions for *ideal* bone and candidate materials.
6. Identification of alternative bone mimics based on the results of the theoretical analysis.

2 ASSESSMENT OF PTFE (GLASS-FILLED)

2.1 Measurement of temperature rise

PTFE (glass-filled) is currently being used as a bone mimic material in thermal test objects as its thermal and acoustic properties are similar to those for bone; thermal conductivity = 0.332 W m^{-1} K^{-1}, attenuation = 10.5 dB cm^{-1} MHz^{-1}, thermal diffusivity = 0.146 x 10^{-6} m^2 s^{-1}. Figure 10 in appendix A shows that there is a peak in the specific heat capacity of PTFE (glass-filled) between 20 and 25 °C. In order to assess the effect of this peak on the temperature rise measurements, a series of heating measurements were performed with a soft-tissue/bone test object at different ambient temperatures, over the range 16 to 34 °C. Measurements were performed at the focus of a Panametrics cylindrically symmetrical transducer with a -6 dB focal beamwidth of 2.4 mm.

The output of the transducer was monitored during the measurements to check for variations of power output with temperature. This was achieved using a 0.5 mm bilaminar hydrophone, the sensitivity of which was stable to within ± 0.8 % over the temperature range of interest. The hydrophone was connected to a 16.5 dB gain amplifier and then an oscilloscope, with a 50 Ω terminator. At each temperature, the hydrophone was placed on the top of the test object and the separation between the test object and transducer adjusted in order to place the hydrophone at the focus, previously found using the NPL Ultrasound Beam Calibrator (UBC) (Preston, 1988; Shaw and Preston, 1995). The transducer was driven with a 20 cycle tone burst during the acoustic measurements, to eliminate any standing waves. The hydrophone signal was maximised by lateral manual adjustment of the hydrophone.

As a reference, the pressure at the focus was measured with the hydrophone at a temperature of 22 °C and found to agree with measurements of peak-positive acoustic pressure performed on the UBC to within 2 %.

2.2 Results and discussion

Temperature rise measurements of 30 s and 180 s duration were carried out over a range of ambient temperatures from 16 to 34 °C. Values for the temperature rise after 5 s, 10 s and 20 s were also obtained from the data recorded during the 30 s temperature rise.

Corrections for the variation of the output of the transducer with temperature were derived from Figure 1 which shows that the focal pressure decreases with temperature by approximately 0.65 kPa/°C, which is equivalent to a decrease in power output of approximately 0.57 %/°C. As the temperature rise is proportional to the power deposited into the material, it is necessary to normalise each measured temperature rise to the same nominal acoustic power by multiplying by the following factor:

$$Correction\ at\ T\,°C = \left(\frac{Hydrophone\ voltage\ \ at\ 16\,°C}{Hydrophone\ voltage\ at\ T\,°C} \right)^2$$

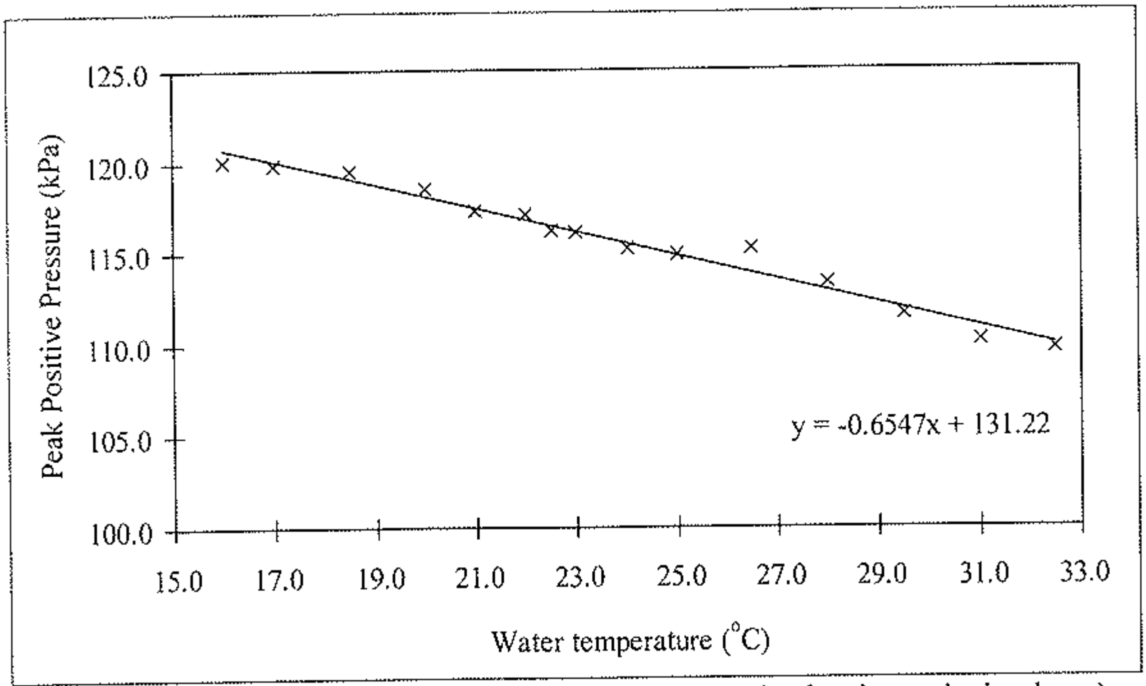

Figure 1. Variation of transducer focal pressure (determined using a hydrophone) with temperature.

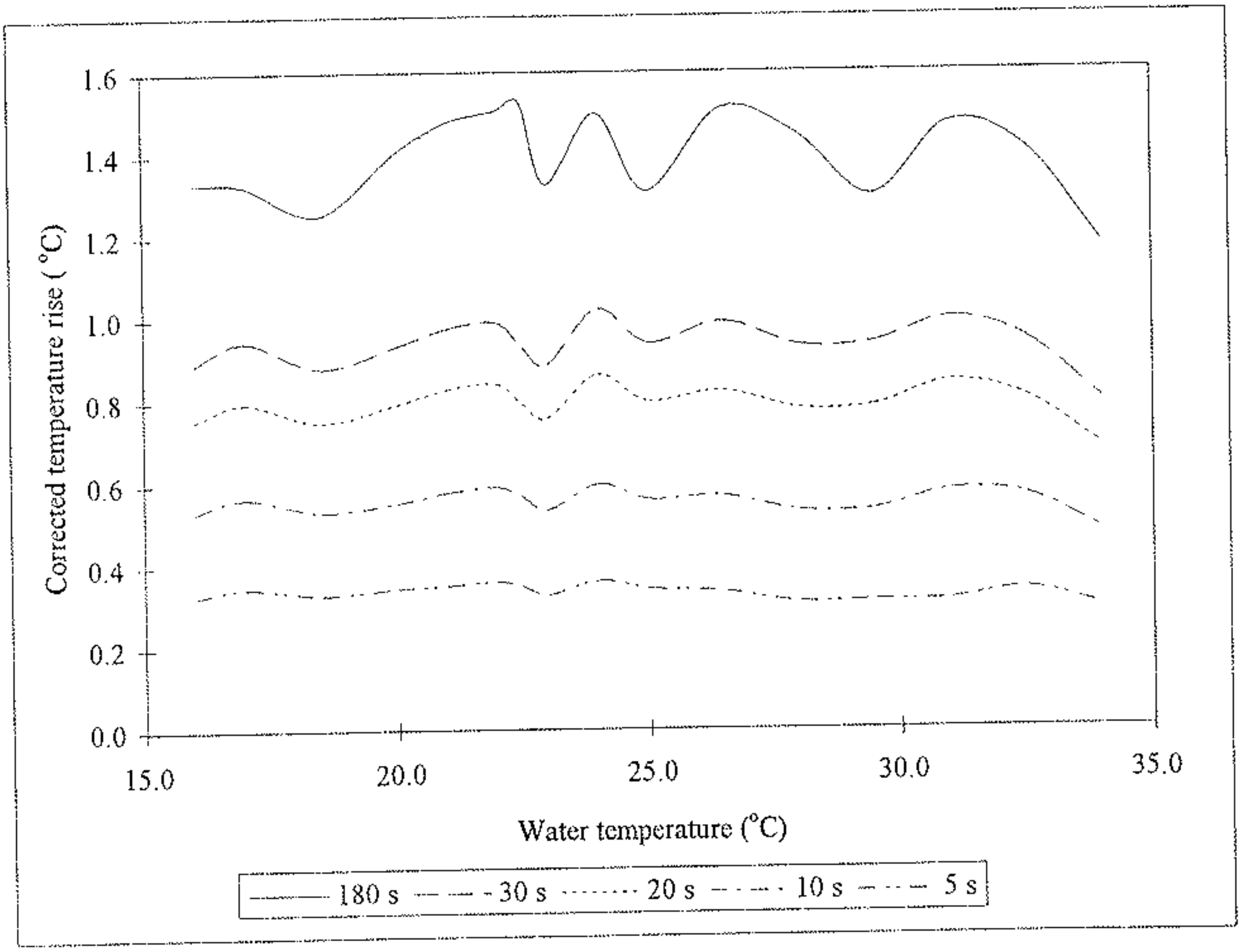

Figure 2. Variation of corrected temperature rise in a soft tissue/bone test object with ambient water temperature

Figure 2 shows the variation in corrected temperature rise for a soft tissue/bone test object with different ambient temperatures. There are fluctuations in temperature rise between 22 and 25 °C which may be related to the peak in specific heat capacity, however, the variation in the measured temperature rise is ± 5% (95% confidence) which is within the ± 16% (95% confidence) reproducibility of the measurements (Shaw *et al.*, 1998).

Theoretical predictions suggest that changes in the specific heat capacity would have a greater effect on temperature rise measurements with heating times less than 30 s (see section 3.3.2). Figure 2 shows that the fluctuation in temperature rise for 5 s heating is approximately the same for 180 s heating, 180 s heating actually shows slightly greater variation(2σ = 5 % for 180 s and 2σ = 3 % for 30 s).

Therefore, the effect of the peak in the specific heat capacity of PTFE (glass-filled) at 22.5 °C is within measurement tolerances and is considered acceptable. The heating at the focus is very localised radially; it is possible that the effect of the change in specific heat capacity would be greater in broader beams.

3 THEORETICAL MODELLING

To assess which physical parameters are most important in determining the temperature rise in a bone mimic, modelling was carried out to examine the effect of varying i) absorption coefficient, ii) volumetric heat capacity, iii) thermal conductivity and iv) sensor position.

3.1 Theoretical background

In principle, the temperature rise in a test object can be calculated if the geometry of the propagation path and the properties of the different tissue mimics in the path are known. The temperature rise at any point can be calculated from the bio-heat transfer equation (BHTE):

$$(1)\quad c_v \frac{\mathrm{d}\,T(\vec{r})}{\mathrm{d}\,t} = \nabla \cdot (K \nabla T(\vec{r})) + q_v(\vec{r}) + C(\vec{r})$$

where $\vec{r}$ is the positional vector, T is the temperature, K is the thermal conductivity, c_v is the volumetric heat capacity, q_v is the absorbed power per unit volume (normally assumed to be proportional to the product of the temporal-average intensity and the absorption coefficient of the medium) and C is a term (generally called the perfusion term) which results from blood flow in the heated region. The BHTE describes the energy balance within an incremental tissue volume and can be solved by appropriate techniques if the form of the perfusion term is known. The most widely quoted perfusion term is that due to Pennes (1948), which has the form $C(\vec{r}) = T/\tau$ where τ is known as the perfusion time constant; it is this form which is assumed in the Output Display Standard (AIUM/NEMA 1992) with a perfusion time constant of 720 seconds.

To calculate the expected temperature rise in the thermal test objects, the perfusion term is ignored and the solution given by Nyborg (1988) is applied, leading to:

$$(2)\quad T(s,t) = \frac{q_v(\underline{r})}{8\pi K s} \mathrm{erfc}\ (R)\ \mathrm{d}V$$

where $T(s, t)$ is the temperature increase at a distance s from the incremental heat source of volume $\mathrm{d}V$ after time t, K is the thermal conductivity,

$$R = \left(\frac{s}{4\kappa t}\right)^{1/2}$$

and κ is the thermal diffusivity.

The temperature rise resulting from a continuum of heat sources can be calculated by first estimating the *in situ* intensity, I_{is} from the free-field intensity, and then assuming:

$$q_v(\underline{r}) = 2\alpha(\underline{r})\, I_{is}(\underline{r})$$

where $\alpha(\underline{r})$ is the local absorption coefficient (in Np cm^{-1} MHz^{-1}), and integrating equation (2) over the entire heated volume. The free-field intensity is derived from a weighted mean of the four scans along the beam-axis. This is essentially the method used by Shaw (1994), and was used to predict the temperature rise for a layered soft tissue and bone mimic thermal test object.

3.2 Prediction of temperature rise

Predictions were carried out using a program written for a software package called Mathcad (Mathsoft Inc, Massachusetts, USA), to calculate the temperature rise that would occur in the TTO as a result of exposure to the ultrasound field.

Calculations were carried out by dividing the TTO into a series of cylindrical volume elements, with the contribution from each volume element to the temperature rise, at the location of the sensor, calculated and all the contributions summed. The element size depends upon the size of the grid on which the intensity is defined, which is generally 0.12 mm wide by 1 mm deep; this is reduced by a factor of 5 in each direction for the temperature calculation, giving cylindrical shells 0.2 mm long by 0.024 mm thick. This small element size reduces errors at the interface between different materials.

Initially, a *default* calculation was carried out, then key parameters were varied individually to determine their effect on the temperature rise. For the *default* calculation, a TTO was defined with a 3 mm layer of tissue mimicking material (TMM), 2 mm of bone mimic, sensor, 3 mm of bone mimic and finally an 8 mm layer of TMM. The incident ultrasound was defined as a Gaussian beam of total power 106 mW and with a 1/e radius of between 0.75 mm and 6.0 mm; a *default* frequency of 5 MHz was used and the heating time was 180 s.

The *default* bone mimic had properties derived from an early IEC working group draft (IEC, 1995). The value for thermal diffusivity was derived by dividing the thermal conductivity by the volumetric heat capacity as defined in the IEC draft.

Absorption coefficient, α:	0.65 Np cm^{-1} MHz^{-1} (equivalent to 5.6 dB cm^{-1} MHz^{-1})
Thermal conductivity, K:	0.5 W m^{-1} K^{-1}
Volumetric heat capacity, c_V:	3.6 x 10^6 J m^{-3} K^{-1}
Density, ρ:	1400 kg m^{-3}
Propagation speed, c:	2100 m s^{-1}.

All of the calculations assume homogeneous thermal properties throughout the test object. Since TMM is more conducting than bone mimics, the calculations will tend to overestimate the true temperature rise. This overestimate will tend to increase the closer the sensor is to the interface between the two materials.

3.3 Results and discussion

3.3.1 Absorption coefficient

The absorption coefficient of the bone mimic within the test object model was varied from 2.15 to 17.2 dB cm^{-1} MHz^{-1} for 5 MHz Gaussian beams with various 1/e radii, and the temperature rise predicted. Figures 3 and 4 show the predicted temperature rise 1 mm and 2 mm below the surface of the bone mimic.

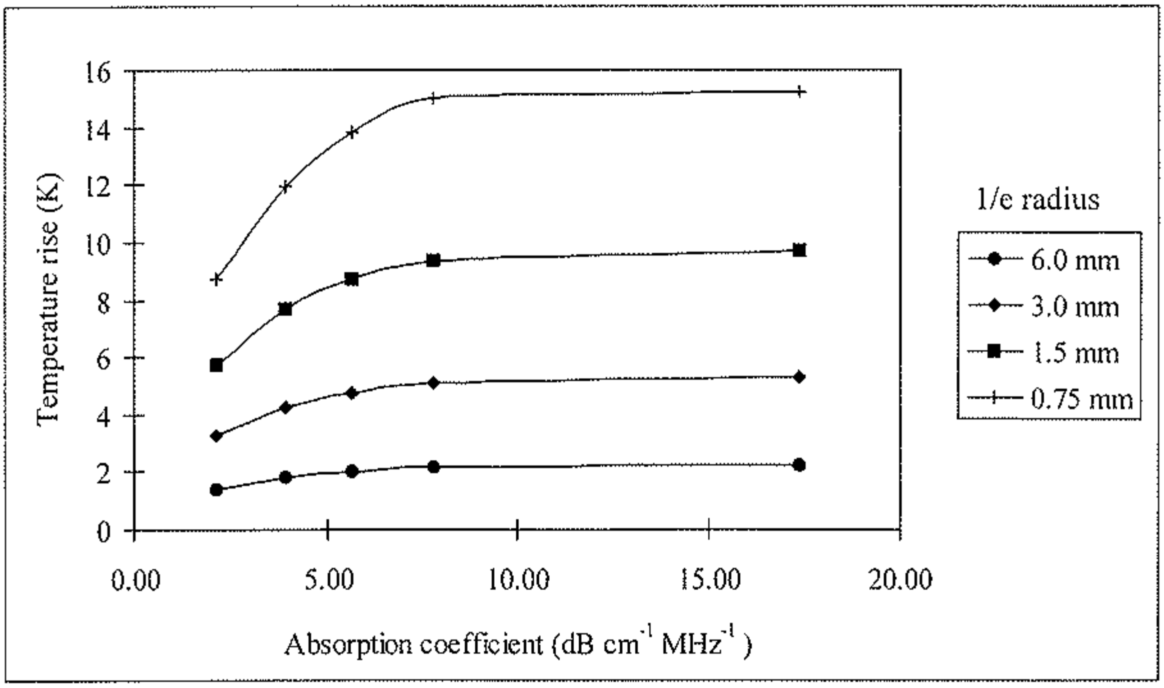

Figure 3. Variation of predicted temperature rise with absorption coefficient, for 4 different 1/e beam radii, with the sensor 1 mm below the bone surface.

At 1 mm below the bone surface, Figure 3 shows that the temperature rise is essentially independent of absorption coefficient if α is greater than 8 dB cm^{-1} MHz^{-1}. Decreasing α from 8 dB cm^{-1} MHz^{-1} to 2 dB cm^{-1} MHz^{-1} reduces the temperature rise by between 30 % and 40 % for all beamwidths. Figure 4 shows that, 2 mm below the bone surface, the temperature rise is lower than at 1 mm. The temperature rise reaches a maximum when α is approximately 5.8 dB cm^{-1} MHz^{-1}depending on beamwidth. For α greater than 8 dB cm^{-1} MHz^{-1}, the temperature rise decreases due to increasing energy absorption close to the bone surface.

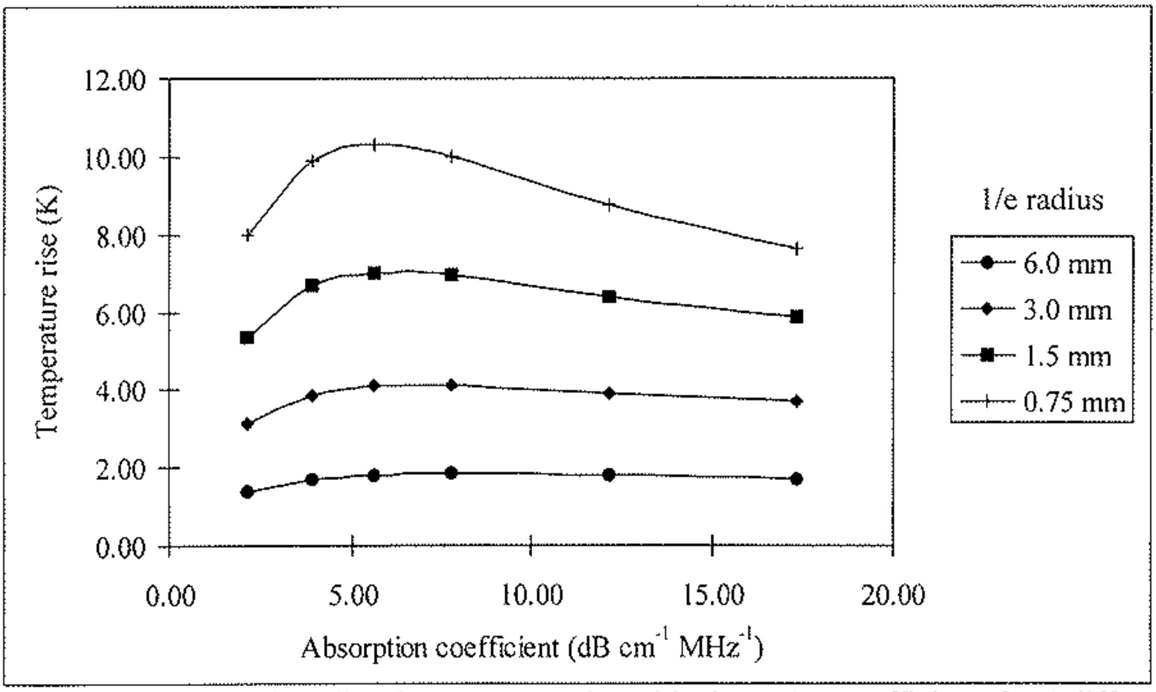

Figure 4. Variation of predicted temperature rise with absorption coefficient, for 4 different 1/e beam radii, with the sensor 2 mm into the bone.

The absorption of the bone mimic will therefore be of greater importance for the foetal bone specification since the absorption will be lower than for the adult bone. The absorption coefficient for adult bone is typically greater than 10 dB cm^{-1} MHz^{-1} (see section 4).

3.3.2 Volumetric heat capacity, c_v

The volumetric heat capacity c_v was increased by a factor of $\sqrt{2}$ in the TTO model, and the temperature rise was predicted for heating times of 1, 5, 30 and 180 s. Increasing c_v produces a lower temperature rise. The temperature rise produced from a beam of 1/e radius 6 mm after 1 second was approximately 45 % lower than the *default* value. Whereas, for a beam with 1/e radius of 0.75 mm the temperature rise after 180 s was only 3% lower than the *default* value. The 180 s temperature rise, for all 1/e beam radii, was within 10% of the *default*. Decreasing c_v by a factor of $1/\sqrt{2}$ from the *default* resulted in temperature rises which were higher by approximately the same amount.

Therefore, the sensitivity to c_v is greatest for heating times less than 30 s and for larger beamwidths. After long heating times, greater than 30 s, equilibrium is reached and the temperature rise is governed by the conductive heat loss, making c_v less important than the absorption coefficient.

3.3.3 Thermal conductivity, K

The thermal conductivity K, and consequently the thermal diffusivity κ, were increased by a factor of $\sqrt{2}$, and the temperature rise was predicted for heating times of 1, 5, 30 and 180 s. Increasing K produces lower temperature rises, with narrow beams and longer heating times being most sensitive to changes in K. The temperature rise is proportional to $1/K$ if κ is kept constant, by increasing c_v in proportion. Decreasing K by a factor of $\sqrt{2}$ increases the temperature rise.

In establishing experimental TTOs, it may not be possible to realise a material with the *ideal* thermal conductivity (see section 4). In this case, if κ is within the required tolerance and if the thermal conductivity is known, a scaling factor can be applied to the result. However, if a scaling factor is not being used, then of all the parameters, deviations of the thermal conductivity from the *ideal* value is the most undesirable.

3.3.4 Sensor position

To alter the sensor position in the TTO model, the thickness of the first bone layer was varied from 0.115 mm to 2 mm for frequencies of 2.5, 5 and 10 MHz and for 4 beam radii. Figures 5, 6 and 7 show the results of the temperature rise predictions for three frequencies.

At 2.5 MHz, the maximum temperature rise occurs approximately 1 mm below the bone surface. The temperature rise at 2 mm is reduced by about 10 % for the narrowest beams and 5% at 0.5 mm.

At 5 MHz, the maximum temperature rise occurs at 0.5 mm below the bone surface. The temperature rise at 2 mm is reduced by about 35 % for the narrowest beams and by about

20 % for beams of 3 mm radius.

At 10 MHz, the maximum temperature rise occurs approximately 0.3 mm below the bone surface. The temperature rise at 0.5 mm is reduced by about 5 % for the narrowest beams. The temperature rise at 2 mm is reduced by about 50% for the narrowest beams and by about 25% for beams of 3 mm radius.

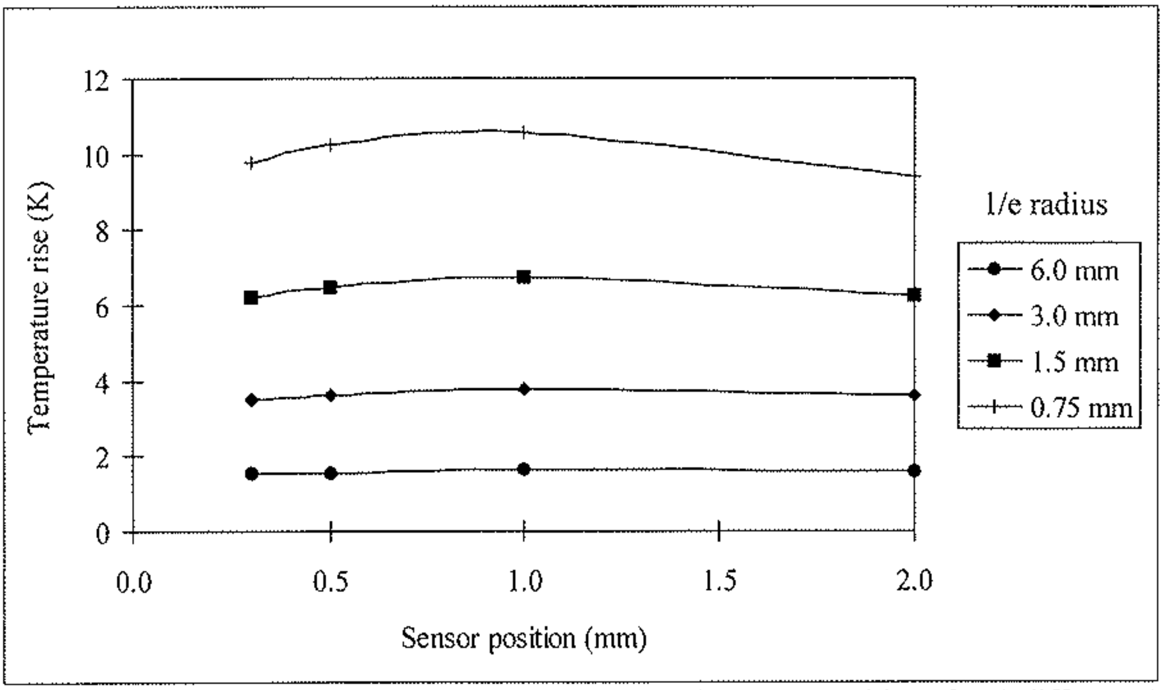

Figure 5. Variation of predicted temperature rise with sensor position, for 4 different 1/e beam radii, at a frequency of 2.5 MHz.

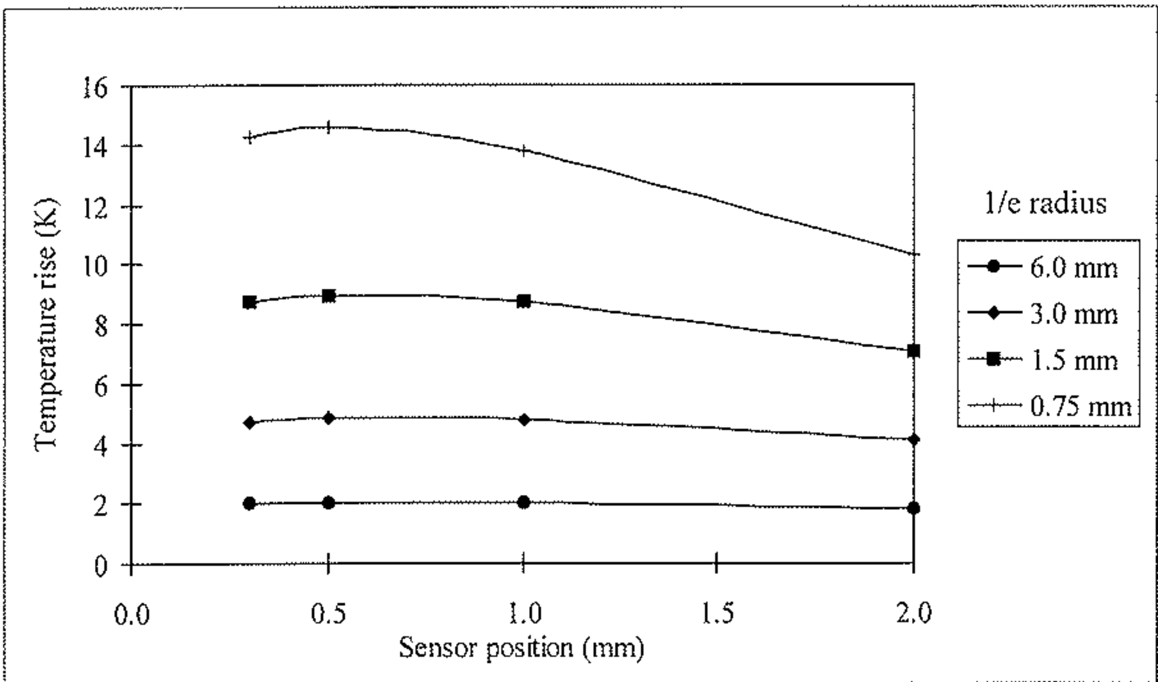

Figure 6. Variation of predicted temperature rise with sensor position, for 4 different 1/e beam radii, at a frequency of 5 MHz.

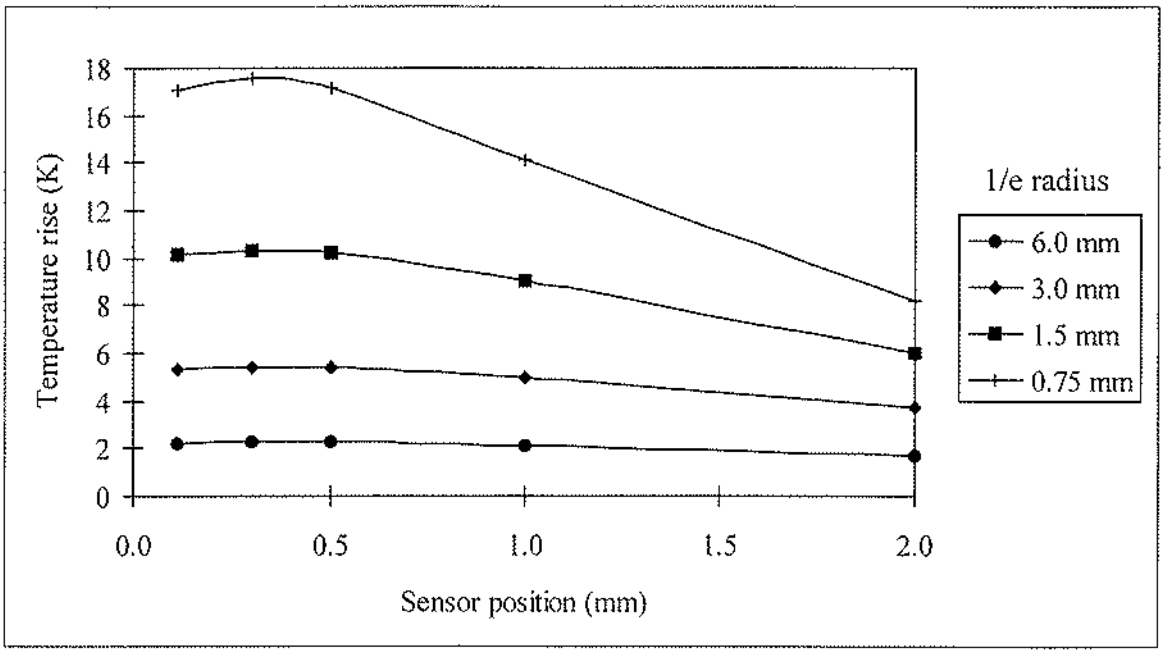

Figure 7. Variation of predicted temperature rise with sensor position, for 4 different beam 1/e radii, at a frequency of 10 MHz.

Therefore, if the aim is to produce a test object to be used over a range of frequencies, the optimum position for the sensor is 0.5 mm from the surface of the bone mimic. The position of maximum temperature rise moves closer to the surface of the bone for increasing frequencies with broad beams showing less dependence on sensor position than narrow beams.

3.4 Criticality ranking

Absorption coefficient, volumetric heat capacity, thermal conductivity and sensor position have been assessed in terms of their importance for bone mimicking materials, to be used in thermal test objects for determining the temperature rise from diagnostic ultrasound. The conclusions are:

- Thermal conductivity is the most important parameter for determining temperature rise in foetal or adult bone mimics (see Section 3.3.3).
- Absorption coefficient is important for foetal bone mimics since they will have absorption coefficients lower than 8 dB cm^{-1} MHz^{-1}. For more highly absorbing adult bone mimics, the absorption coefficient is less important (see Section 3.3.1).
- Volumetric heat capacity is not a major factor in determining the temperature rise in either foetal or adult bone mimics (see Section 3.3.2).
- The maximum temperature rise is expected to occur approximately 0.5 mm below the surface of the bone mimic (see Section 3.3.4).
- If it is not possible to match the thermal conductivity, a normalisation factor can be applied as long as the values for thermal diffusivity and volumetric heat capacity are within *ideal* range.

4 IDENTIFICATION OF *IDEAL* PROPERTIES

As the properties of bone vary greatly depending on the subject type of bone, it is not possible to produce one bone mimic specification which would be appropriate for all. Therefore, after careful consideration of bone properties specified in the literature (Duck 1990[1]; NCRP 1992[2]) a specification was compiled for an *ideal* foetal bone mimic and an *ideal* adult bone mimic.

Attenuation values are often quoted in the literature. It is assumed here that the materials are non-scattering and that the attenuation coefficient is the same as the absorption coefficient.

Parameter	Foetal Bone	Adult Bone
Thermal conductivity, K ($\mathrm{W\,m^{-1}\,K^{-1}}$)	0.45 to 0.55	0.35 to 0.45 [1]
Acoustic attenuation, α ($\mathrm{dB\,cm^{-1}\,MHz^{-1}}$)	5.0 to 6.5 [1]	> 10 [1]
Thermal diffusivity, κ ($10^{-6}\,\mathrm{m^2\,s^{-1}}$)	0.17 to 0.25	0.13 to 0.21
Density, ρ ($10^3\,\mathrm{kg\,m^{-3}}$)	1.3 to 1.7 [2]	1.6 to 1.9 [1]
Volumetric heat capacity, c_V ($10^6\,\mathrm{J\,m^{-3}\,K^{-1}}$)	2.1 to 2.7 [2]	2.1 to 2.7 [2]
Propagation speed, c ($\mathrm{m\,s^{-1}}$)	1600 to 2500 [1]	2500 to 4000 [1]

Table 1. Parameter values for the *ideal* foetal and adult bone mimic materials.

Note:

1. The value quoted for the attenuation of foetal bone comes from measurements of child bone, therefore the actual value for foetal bone is probably lower.

2. As only one set of values was found for the heat capacity of bone, this has been used for both foetal and adult bone.

3. There is a large variation in the values for thermal conductivity of bone quoted in the literature, from approximately 0.3 $\mathrm{W\,m^{-1}\,K^{-1}}$ to 0.8 $\mathrm{W\,m^{-1}\,K^{-1}}$ (Duck 1990; Moses *et al* 1995). The thermal conductivity value chosen for the *ideal* adult bone specification is at the lower end of the range found in the literature, in order to produce a 'worst-case' temperature rise.

4. The thermal conductivity for foetal bone was obtained by assuming it to be slightly higher than that for adult bone, based on data given by Duck (1990), which shows that the thermal conductivity of bone decreases with age.

5. The thermal diffusivity was derived from the ratio of the thermal conductivity to the volumetric heat capacity.

5 IDENTIFICATION OF BONE MIMIC MATERIALS

5.1 Compilation of available data

Many materials have been considered and some of the possibilities are given in more detail in Table 2. Most of the materials considered were polymers as these are readily available, easy to machine and work with, and values for their thermal and acoustic properties were available.

For Table 2, the volumetric heat capacity was derived by multiplying the specific heat capacity by the density, and the thermal diffusivity was derived by dividing the thermal conductivity by the volumetric heat capacity. A range of values for the volumetric heat capacity and diffusivity of PTFE (glass-filled) are shown due to the large variation in its specific heat capacity as shown in appendix A. The following sources were used to compile the table:

① Kaye, G. W. C. and Laby, T. H. *Tables of Physical and Chemical Constants*, sixteenth edition, 1995, Longman.
② NPL measurements.
③ Brandrup, J. and Immergut, E. H. *The Polymer Handbook*, third edition, 1989, John Wiley and Sons.

To identify the materials with the best match to the *ideal* properties, scatter diagrams of attenuation against thermal conductivity (α versus K) and attenuation against thermal diffusivity (α versus κ) were plotted (figures 6 and 7). K and α were chosen as being the properties which have the most effect on final temperature rise, and κ is important when looking at the initial variation of temperature rise with time.

Table 2.

Material	Density 10^3 kg m^{-3}	Thermal conductivity W m^{-1} K^{-1}	Specific heat capacity 10^3 J kg^{-1} K^{-1}	Volumetric heat capacity 10^6 J m^{-3} K^{-1}	Thermal diffusivity 10^{-6} m^2 s^{-1}	Attenuation coefficient dB cm^{-1} MHz^{-1}	Propagation speed m s^{-1}
Epoxy cast resin	1.125	0.190	1.00	1.13	0.169		
Nylon-6	1.125 ①	0.250 ①	1.60 ①	1.80	0.139	0.23 @ 5 MHz ①	2680 ①
Nylon-66	1.140 ①	0.249 ①	1.70 ①	1.94	0.129		
Polycarbonate	1.200 ①	0.190 ①	1.21 ①	1.45	0.131	5.00 @ 3.5 MHz ②	2220 ①
Polyethylene (LD)	0.920 ①	0.330 ①	2.30 ③	2.12	0.157	5.40 @3.5 MHz ②	2100 ①
Polyethylene (HD)	0.950 ①	0.500 ①	2.30 ③	2.19	0.229	2.20 @ 3.5 MHz ②	2400 ①
Polyisoprene (natural rubber)	0.910 ①	0.130 ①	1.88 ①	1.71	0.076	3.70 @ 0.35 MHz ①	1600 ①
Polyisoprene (hard rubber)	1.160 ①	0.160 ①	1.38 ①	1.60	0.100		
TPX	0.850	0.168	2.17	1.84	0.091	0.85 @3.5 MHz ②	2160 ②
Polypropylene	0.900 ①	0.120 ①	1.92 ①	1.73	0.069	3.60 @3.5 MHz ②	2600 ①
Polystyrene (Styron 666)	1.060 ①	0.134 ①	1.40 ①	1.48	0.093	0.799 @ 2.5 MHz ①	2350 ①
PTFE	2.170 ①	0.250 ①	1.00 ①	2.17	0.115	10.50 @ 3.5 MHz ②	1400 ②
PTFE - glass filled	2.170 ②	0.332 ②	1.05 ②	2.28 - 3.08	0.108 - 0.146	10.50 @ 3.5 MHz ②	1400 ②
Polyvinyl chloride	1.350 ①	0.140 ①	1.00 ①	1.35	0.104	0.87 @ 0.35 MHz ①	2330 ①
Polyvinylidene chloride	1.680 ①	0.130 ①	1.34 ①	2.25	0.058	7.20 @ 2.5 MHz ①	2400 ①
Polyvinyl acetate	1.190 ③	0.159 ③	1.67	1.97	0.085	11.00 @ 10 MHz ①	2250 ①
Polymethyl methacrylate	1.190 ①	0.210 ①	1.50 ①	1.79	0.118	1.30 @3.5 MHz ②	2720 ②

Table 2. Compilation of materials data, at room temperature, for possible bone mimic materials.

Figure 8.

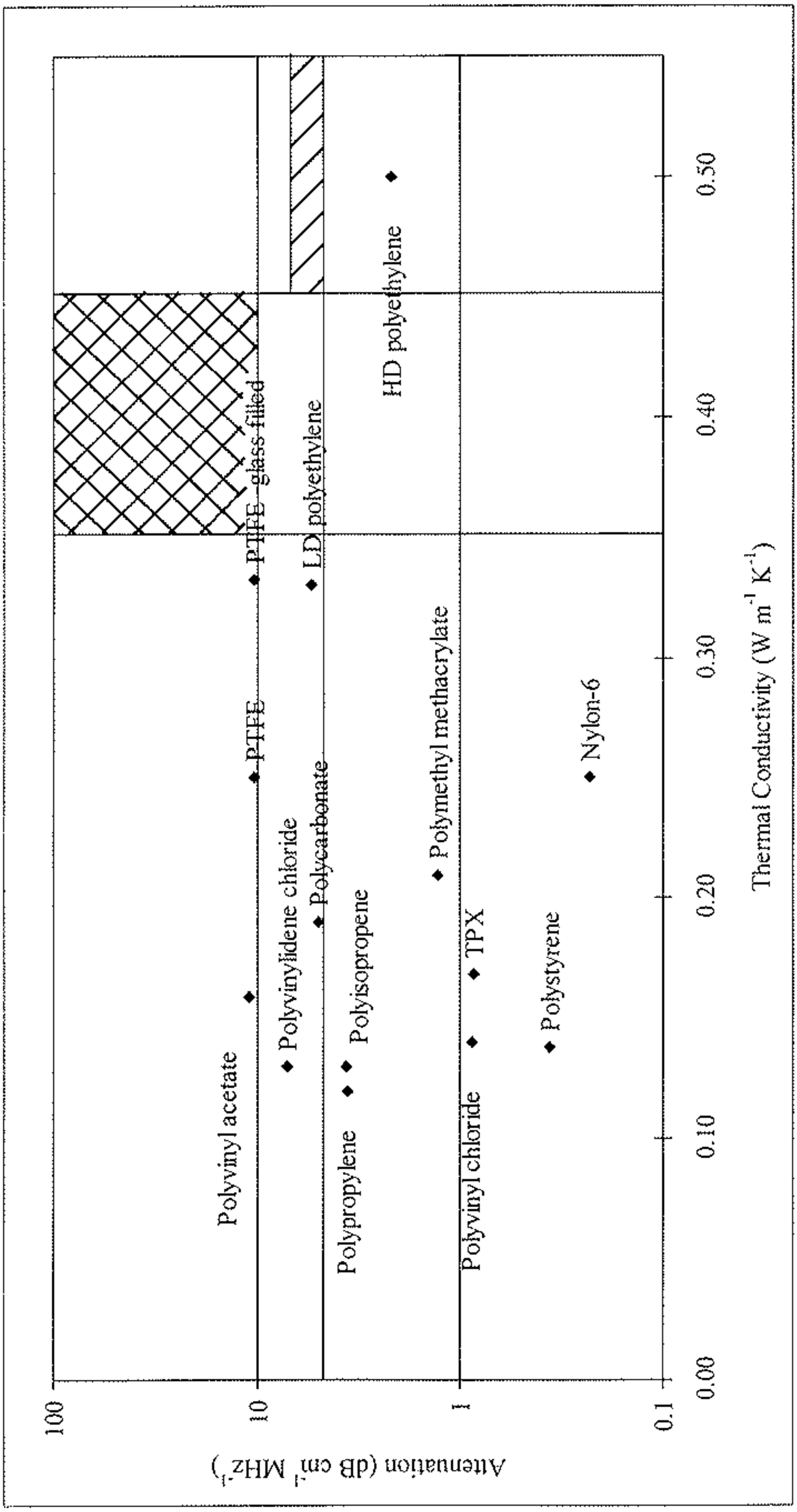

Figure 8. Scatter diagram of attenuation against thermal conductivity, for various materials, where [hatched box] corresponds to the *ideal* foetal bone specification and [cross-hatched box] corresponds to the *ideal* adult bone specification.

Figure 9.

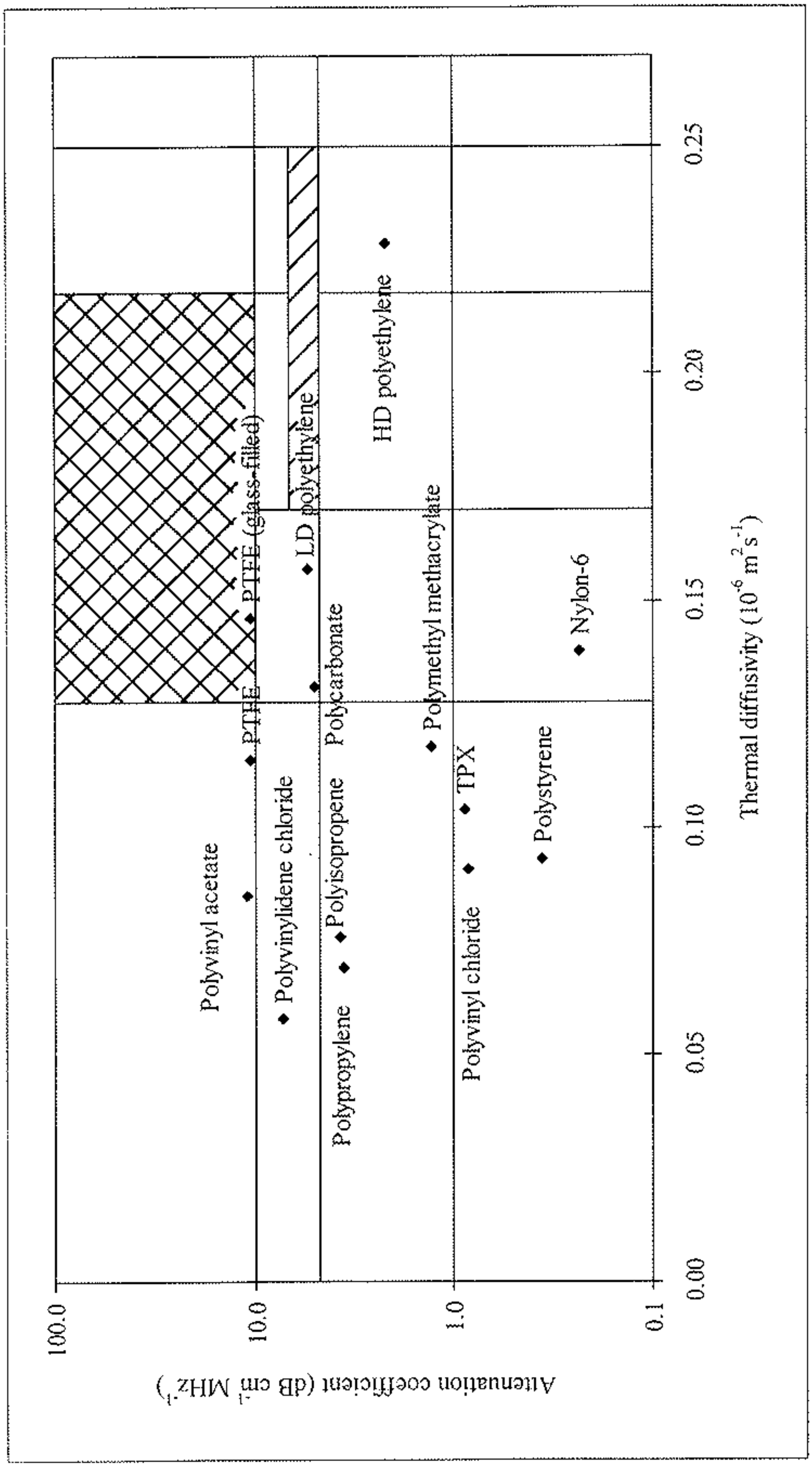

Figure 9. Scatter diagram of attenuation against thermal diffusivity, for various materials, where [hatched box] corresponds to the *ideal* foetal bone specification and [cross-hatched box] corresponds to the *ideal* adult bone specification.

5.2 Analysis

From Figure 8 it is clear that most materials have a thermal conductivity which is much lower than the *ideal* range. Only PTFE (glass-filled), low-density polyethylene and high-density polyethylene are close enough to consider. Figure 9 indicates that polycarbonate has an acceptable thermal diffusivity for *ideal* adult bone and should also be considered.

- PTFE (glass-filled) is the best match to the *ideal* adult bone mimic specification. One problem identified is its variation in specific heat capacity around room temperature; its value doubles at approximately 22.5 °C. The effect of this variation on temperature rise was investigated in section 2 and found to be acceptable within measurement tolerances.

- High density polyethylene (HDPE) is the best match to the *ideal* foetal bone mimic, with a thermal conductivity and diffusivity within the *ideal* range, but low attenuation. As stated in section 4 the *ideal* value quoted actually comes from measurements of child bone; the absorption coefficient for foetal bone varies with gestational age but even in the third trimester it would probably be lower than the quoted *ideal* value making high-density polyethylene a closer mimic. The density is also below the *ideal* range but this will have a negligible effect on the temperature rise.

- Low density polyethylene (LDPE) could be used as a foetal bone mimic. It has a thermal conductivity below the *ideal* value which will tend to overestimate the temperature rise by approximately 10%. The thermal diffusivity is close to the *ideal* range which means that a normalisation factor could be applied to correct for the difference in K.

- Polycarbonate is not as good as PTFE (glass-filled) but it could be used as an adult bone mimic. The thermal conductivity is lower than the *ideal* adult range, but since its thermal diffusivity is within the *ideal* range, a normalisation factor could be applied. The attenuation coefficient is about a factor of two too low, but the 180 s temperature rise is not very sensitive to changes in this parameter.

5.3 Theoretical modelling

Having identified PTFE, HDPE and LDPE as the three main candidate bone mimicking materials, theoretical predictions were carried out using their properties. These were then compared with the maximum and minimum predicted temperature rises calculated from the *ideal* foetal bone mimic specification. The calculations were carried out for a range of beam widths with the sensor positioned 2 mm below the bone surface. Table 3 shows the values used in the calculations and Table 4 shows the resulting temperature rises. The values for *ideal* maximum and minimum thermal diffusivity in Table 3 are not the *ideal* values given in section 4; the prediction method requires that they are calculated from the thermal conductivity and volumetric heat capacity (see section 3).

	Ideal foetal bone minimum	Ideal foetal bone maximum	Low-density polyethylene	High-density polyethylene	PTFE (glass-filled)
Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	0.55	0.45	0.33	0.50	0.33
Attenuation Coefficient ($dB\ cm^{-1}\ MHz^{-1}$)	5.0	6.5	5.4	2.2	10.5
Volumetric Heat Capacity ($10^6\ J\ m^{-3}\ K^{-1}$)	2.7	2.1	2.12	2.19	3.08
Density ($10^3\ kg\ m^{-3}$)	1.7	1.3	0.92	0.95	2.2
Propagation Speed ($m\ s^{-1}$)	2500	1600	2100	2400	1400
Thermal Diffusivity ($10^{-6}\ m^2\ s^{-1}$)	0.204	0.214	0.157	0.229	0.108

Table 3. Parameter values used for temperature rise predictions.

1/e radius (mm)	ΔT (°C) for ideal minimum	ΔT (°C) for ideal maximum	ΔT (°C) for low-density polyethylene	ΔT (°C) for high-density polyethylene	ΔT (°C) for PTFE (glass-filled)
6.00	1.55	2.41	3.04	1.64	2.53
3.00	3.44	5.31	6.87	3.60	5.81
1.50	5.75	8.81	11.69	6.00	9.94
0.75	8.34	12.66	17.11	8.75	14.36

Table 4. Predicted temperature rises using the parameter values from Table 3 for different beam radii.

The predicted temperature rise for PTFE (glass-filled) is approximately 10% higher than the maximum for *ideal* foetal bone, confirming that it is more suitable as an adult bone mimic.

The predicted temperature rise for high-density polyethylene falls within the *ideal* range for foetal bone. The temperature rise is at the lower end of the acceptable range partly because the attenuation coefficient is approximately half the *ideal* value. In reality the attenuation coefficient for foetal bone is probably lower than the value given here as *ideal* (see Section 4), which makes HDPE a better match to real foetal bone.

The predicted temperature rise for low-density polyethylene is above the *ideal* range for foetal bone mimics, this is mainly due to its low value of thermal conductivity which could be corrected for as discussed in section 3.3.3.

6 SUMMARY

This report has investigated the thermal and acoustic properties which are relevant for materials intended to mimic foetal and adult bone in thermal test objects for diagnostic ultrasound. It has also compiled data for possible bone mimicking materials and compared their properties with those of idealised bone mimics. Theoretical modelling has compared the expected temperature rise in the most suitable materials with the temperature expected in the idealised mimics in a standard configuration. The main conclusions are:

- High-density polyethylene is recommended as a foetal bone mimic.
- PTFE (glass-filled) is recommended as an adult bone mimic.
- Generally, thermal conductivity is the most important parameter governing temperature rise in a bone mimic. If it is not possible to match K then a material with the correct diffusivity may be used and a normalisation factor applied.
- The temperature rise is not sensitive to changes in absorption coefficient, if α is greater than approximately 8 dB cm^{-1} MHz^{-1} and the sensor or point of interest is within 2 mm of the bone surface.
- The temperature rise after more than 30 seconds is not sensitive to changes in volumetric heat capacity and the peak in the specific heat capacity of PTFE (glass-filled) around room temperature does not appear to be thermally significant.
- The maximum temperature rise is expected to occur at approximately 0.5 mm below the surface of the bone mimic for the majority of fields encountered in diagnostic ultrasound.

The development of reference methods, both theoretical and experimental, for determining thermal hazard is becoming more important as the output from diagnostic ultrasound equipment increases. This report has ranked physical properties in terms of their influence on temperature rise in bone mimicking materials and has suggested materials which meet the requirements for typical foetal and adult bone.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

AIUM/NEMA (1992) *Standard for real-time display of thermal and mechanical acoustic output indices on diagnostic ultrasound equipment,* AIUM report UD3-1992 (American Institute of Ultrasound in Medicine, Rockville, Maryland, USA).

BACON DR and SHAW A (1993) *Experimental validation of predicted temperature rises in tissue-mimicking materials,* Physics in Medicine and Biology, **38**, p1647-1659.

BRANDRUP J and IMMERGUT E H. (1989) *The Polymer Handbook, third edition,* (John Wiley and Sons.)

DUCK FA (1990) *Physical properties of tissue - a comprehensive reference book,* Academic Press Ltd.

EUROPEAN FEDERATION OF SOCIETIES FOR ULTRASOUND IN MEDICINE AND BIOLOGY (EFSUMB) (1996, London, W1N 3DG, UK.) *Clinical safety statement for diagnostic ultrasound,* EFSUMB Newsletter, **10** No1, p10.

IEC WORKING GROUP DRAFT (March 1995) *Ultrasonics - Field Safety, Part 2: Classification of medical diagnostic fields based on physical tissue models experimental and theoretical test method,*. 87/WG12/Secretary/28.

KAYE GWC. and LABY TH (1995) *Tables of Physical and Chemical Constants, sixteenth edition,* Longman.

MOSES WM, WITTHAUS FW, HOGAN HA AND LASTER WR (1995) *Measurement of the Thermal Conductivity of Cortical Bone by an Inverse Technique*, Experimental Thermal and Fluid Science, 11:34-39

NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS (NCRP) (1992, NCRP Publications, Bethesda, MD 20814, USA.) *Exposure criteria for medical diagnostic ultrasound: I. Criteria based on thermal mechanisms.*, NCRP report no. 113.

NYBORG WL. (1988) *Solutions of the bio-heat transfer equation.* Physics in Medicine and Biology, **33**, no 7, p685-722.

PENNES HH (1948) *Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm,* Journal of Applied Physiology, **1**, no 2, p93-122.

PRESTON RC (1988) *The NPL Ultrasound Beam Calibrator,* IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, **35**, no 2, p122-139.

SHAW A (1994) *Prediction of temperature rise in layered media from measured ultrasonic intensity data,* Physics in Medicine and Biology, **39**, p1203-1218.

SHAW A and PRESTON RC (1995) *The NPL Ultrasound Beam Calibrator: cost effective measurements to IEC 1157*, Proceedings of the World Congress on Ultrasonics, pp 923-926.

SHAW A, PAY NM, PRESTON RC AND BOND AD (1998) *A proposed standard thermal test object for medical ultrasound,* Submitted to Ultrasound in Medicine and Biology

WORLD FEDERATION FOR ULTRASOUND IN MEDICINE AND BIOLOGY (WFUMB) (1992) WFUMB *symposium on safety and standardisation in medical ultrasound.*, Ultrasound in Medicine and Biology, **18** No.9, 748.

WORLD FEDERATION FOR ULTRASOUND IN MEDICINE AND BIOLOGY (WFUMB) (1997) *WFUMB news 1997: 4(2),* Ultrasound in Medicine and Biology, **23,** p974 *et seq.*

APPENDIX A Temperature dependence of the specific heat capacity for PTFE (glass-filled)

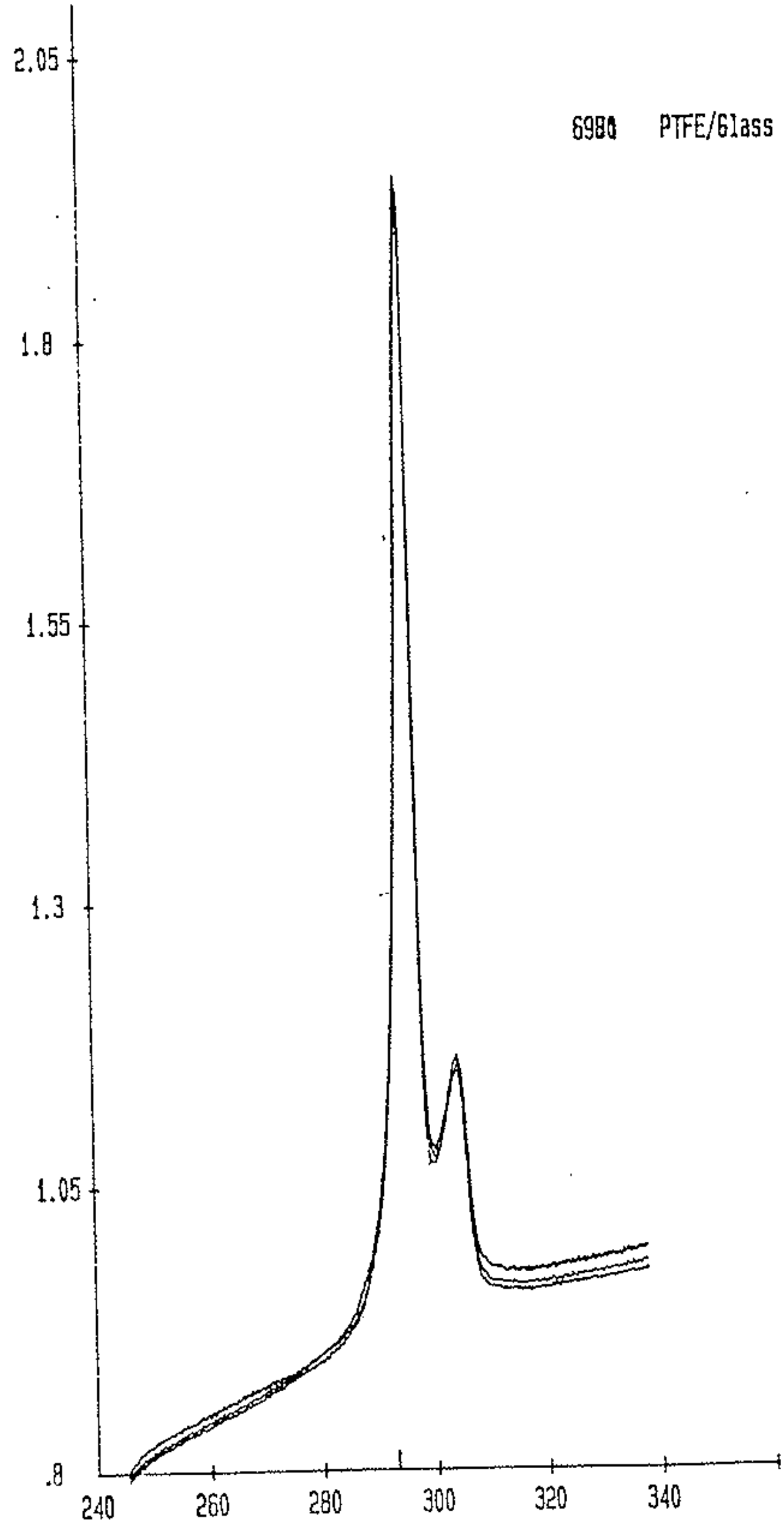

Figure 10. Variation of the specific heat capacity (J g^{-1} K^{-1}) of PTFE (glass-filled) with temperature (K).