LETTER TO THE EDITOR

Journal of Ultrasound in Medicine 8, 653–654, 1989

An Alternative Simple Formula for Temperature Estimates

To the Editor:—In a recently published report (hereafter called “AIUM 1988”), tables and formulae were given for purposes of estimating acoustic conditions under which beams of diagnostic ultrasound would cause the temperature to rise by no more than a designated amount. These were based on simplifications and assumptions that were pointed out in the report. A Table 2.3 (hereafter called “AIUM Table 2.3”) gave values for the acoustic power, such that an ultrasound source emitting this or any lower value of the power would not produce a temperature rise greater than 1°C. For brevity, such a value was called the "1° power". AIUM Table 2.3 gave estimates of the 1° power for a series of values of the source diameter $D$ and frequency $f$; specifically, entries were tabulated for diameters varying from 1 cm to 2 cm (10 mm to 20 mm) and frequencies from 2 to 10 MHz. It was found by examining this table that all the entries followed a simple rule, namely, that in no case was the entry in milliwatts, less than 23 times the ratio of diameter ($D$) in millimeters to the frequency ($f$) in megahertz. Thus an upper limit to the tabular data was found to be given by

$$1° \text{ power} = 23 \times \frac{D}{f}$$

(1)

It was explained in AIUM 1988 that this formula is conservative in that computations based on it always give values for the 1° power that are equal to or less than the entries in AIUM Table 2.3 (which are themselves conservative). Specifically, it was found that Equation 1 gives values for the 1° power that are less than the entries in AIUM Table 2.3 by percentages varying from 2% to 65%.

As pointed out in AIUM 1988, the known range of usefulness of Equation 1 is that of AIUM Table 2.3 itself, namely, diameters from 10 to 20 cm and frequencies from 2 to 10 MHz. Questions have been raised as to the applicability outside this range, especially to smaller diameters. To test the possibilities, we have carried out computations to extend AIUM Table 2.3 to smaller values of the diameter. We do not present the tabular data here but instead summarize the findings. With decreasing diameter, Equation 1 becomes increasingly conservative. For example, at a frequency of 7 MHz, values of the 1° power calculated from Equation 1 are less than tabulated values by factors of 1.6, 1.8, 2.7, 3.2, 5.1, and 8.5 when the diameter ($D$) has the values 8 mm, 6 mm, 4 mm, 2 mm, 1 mm, and 0.5 mm, respectively. Clearly, Equation 1 should not be used for applications involving transducers of very small diameter, unless a very conservative estimate will suffice.

Another empirical formula was tested and found to be more satisfactory for small values of $D$. By analogy to Equation 1 it is written

$$1° \text{ power} = 75 \times \sqrt[3]{D/f}$$

(2)

where, again, the 1° power is in milliwatts, $D$ in millimeters, and $f$ in megahertz. Comparisons were made between computations based on Equation 2 and entries in the above-mentioned extension to AIUM Table 2.3; the new entries are based on the same algorithm as before, but include values for diameters varying from 0.4 to 20 mm. It was found that calculations of 1° power from Equation 2 are less than corresponding tabulated values by percentages varying from 6% to 100%. Thus Equation 2 is conservative, but (at small values of $D$) not nearly as much as Equation 1.

There is some theoretical justification for a $\sqrt[3]{D}$ dependence from theory developed by Nyborg and Steele, although the latter does not take perfusion into account. In this reference, it is shown that for a fairly wide range of conditions, the steady-state temperature rise in a beam, at the surface where it enters an absorbing medium, is approximately proportional to $ID^\frac{3}{4}$, where $I$ is the intensity averaged over the beam cross-sectional area. Because the total power ($W$) passing through the same area is proportional to $ID^2$, the temperature elevation is then proportional to $W/\sqrt{D}$ and the 1° power to $\sqrt{D}$.

When applied appropriately, Equation 2 appears to be useful as an upper limit to the temperature rise produced by a beam of ultrasound passing through homo-
An Alternative Simple Formula for Temperature Estimates

To the Editor:—In a recently published report (hereafter called “AIUM 1988”), tables and formulae were given for purposes of estimating acoustic conditions under which beams of diagnostic ultrasound would cause the temperature to rise by no more than a designated amount. These were based on simplifications and assumptions that were pointed out in the report. A Table 2.3 (hereafter called “AIUM Table 2.3”) gave values for the acoustic power, such that an ultrasound source emitting this or any lower value of the power would not produce a temperature rise greater than 1°C. For brevity, such a value was called the “1º power”. AIUM Table 2.3 gave estimates of the 1º power for a series of values of the source diameter D and frequency f; specifically, entries were tabulated for diameters varying from 1 cm to 2 cm (10 mm to 20 mm) and frequencies from 2 to 10 MHz. It was found by examining this table that all the entries followed a simple rule, namely, that in no case was the entry in milliwatts, less than 23 times the ratio of diameter (D) in millimeters to the frequency (f) in megahertz. Thus an upper limit to the tabular data was found to be given by

\[ 1º \text{ power} = 23 \times \frac{D}{f} \]  

(1)

It was explained in AIUM 1988 that this formula is conservative in that computations based on it always give values for the 1º power that are equal to or less than the entries in AIUM Table 2.3 (which are themselves conservative). Specifically, it was found that Equation 1 gives values for the 1º power that are less than the entries in AIUM Table 2.3 by percentages varying from 2% to 65%.

As pointed out in AIUM 1988, the known range of usefulness of Equation 1 is that of AIUM Table 2.3 itself, namely, diameters from 10 to 20 cm and frequencies from 2 to 10 MHz. Questions have been raised as to the applicability outside this range, especially to smaller diameters. To test the possibilities, we have carried out computations to extend AIUM Table 2.3 to smaller values of the diameter. We do not present the tabular data here but instead summarize the findings. With decreasing diameter, Equation 1 becomes increasingly conservative. For example, at a frequency of 7 MHz, values of the 1º power calculated from Equation 1 are less than tabulated values by factors of 1.6, 1.8, 2.7, 3.2, 5.1, and 8.5 when the diameter (D) has the values 8 mm, 6 mm, 4 mm, 2 mm, 1 mm, and 0.5 mm, respectively. Clearly, Equation 1 should not be used for applications involving transducers of very small diameter, unless a very conservative estimate will suffice.

Another empirical formula was tested and found to be more satisfactory for small values of D. By analogy to Equation 1 it is written

\[ 1º \text{ power} = 75 \times \sqrt{D}/f \]  

(2)

where, again, the 1º power is in milliwatts, D in millimeters, and f in megahertz. Comparisons were made between computations based on Equation 2 and entries in the above-mentioned extension to AIUM Table 2.3; the new entries are based on the same algorithm as before, but include values for diameters varying from 0.4 to 20 mm. It was found that calculations of 1º power from Equation 2 are less than corresponding tabulated values by percentages varying from 6% to 100%. Thus Equation 2 is conservative, but (at small values of D) not nearly as much as Equation 1.

There is some theoretical justification for a \( \sqrt{D} \) dependence from theory developed by Nyborg and Steele, although the latter does not take perfusion into account. In this reference, it is shown that for a fairly wide range of conditions, the steady-state temperature rise in a beam, at the surface where it enters an absorbing medium, is approximately proportional to \( ID^{1.5} \), where I is the intensity averaged over the beam cross-sectional area. Because the total power (W) passing through the same area is proportional to \( ID^2 \), the temperature elevation is then proportional to \( W/\sqrt{D} \) and the 1º power to \( \sqrt{D} \).

When applied appropriately, Equation 2 appears to be useful as an upper limit to the temperature rise produced by a beam of ultrasound passing through homo-
An Alternative Simple Formula for Temperature Estimates

To the Editor:—In a recently published report1 (hereafter called “AIUM 1988”), tables and formulae were given for purposes of estimating acoustic conditions under which beams of diagnostic ultrasound would cause the temperature to rise by no more than a designated amount. These were based on simplifications and assumptions that were pointed out in the report. A Table 2.3 (hereafter called “AIUM Table 2.3”) gave values for the acoustic power, such that an ultrasound source emitting this or any lower value of the power would not produce a temperature rise greater than 1°C. For brevity, such a value was called the “1° power”. AIUM Table 2.3 gave estimates of the 1° power for a series of values of the source diameter D and frequency f; specifically, entries were tabulated for diameters varying from 1 cm to 2 cm (10 mm to 20 mm) and frequencies from 2 to 10 MHz. It was found by examining this table that all the entries followed a simple rule, namely, that in no case was the entry in milliwatts, less than 23 times the ratio of diameter (D) in millimeters to the frequency (f) in megahertz. Thus an upper limit to the tabular data was found to be given by

\[ 1° \text{ power} = 23 \times \frac{D}{f} \]  

(1)

It was explained in AIUM 1988 that this formula is conservative in that computations based on it always give values for the 1° power that are equal to or less than the entries in AIUM Table 2.3 (which are themselves conservative). Specifically, it was found that Equation 1 gives values for the 1° power that are less than the entries in AIUM Table 2.3 by percentages varying from 2% to 65%.

As pointed out in AIUM 1988, the known range of usefulness of Equation 1 is that of AIUM Table 2.3 itself, namely, diameters from 10 to 20 cm and frequencies from 2 to 10 MHz. Questions have been raised as to the applicability outside this range, especially to smaller diameters. To test the possibilities, we have carried out computations to extend AIUM Table 2.3 to smaller values of the diameter. We do not present the tabular data here but instead summarize the findings. With decreasing diameter, Equation 1 becomes increasingly conservative. For example, at a frequency of 7 MHz, values of the 1° power calculated from Equation 1 are less than tabulated values by factors of 1.6, 1.8, 2.7, 3.2, 5.1, and 8.5 when the diameter (D) has the values 8 mm, 6 mm, 4 mm, 2 mm, 1 mm, and 0.5 mm, respectively. Clearly, Equation 1 should not be used for applications involving transducers of very small diameter, unless a very conservative estimate will suffice.

Another empirical formula was tested and found to be more satisfactory for small values of D. By analogy to Equation 1 it is written

\[ 1° \text{ power} = 75 \times \sqrt{D/f} \]  

(2)

where, again, the 1° power is in milliwatts, D in millimeters, and f in megahertz. Comparisons were made between computations based on Equation 2 and entries in the above-mentioned extension to AIUM Table 2.3; the new entries are based on the same algorithm as before, but include values for diameters varying from 0.4 to 20 mm. It was found that calculations of 1° power from Equation 2 are less than corresponding tabulated values by percentages varying from 6% to 100%. Thus Equation 2 is conservative, but (at small values of D) not nearly as much as Equation 1.

There is some theoretical justification for a \( \sqrt{D} \) dependence from theory developed by Nyborg and Steele,2 although the latter does not take perfusion into account. In this reference, it is shown that for a fairly wide range of conditions, the steady-state temperature rise in a beam, at the surface where it enters an absorbing medium, is approximately proportional to \( ID^{1/2} \), where I is the intensity averaged over the beam cross-sectional area. Because the total power \( (W) \) passing through the same area is proportional to \( ID^3 \), the temperature elevation is then proportional to \( W/\sqrt{D} \) and the 1° power to \( \sqrt{D} \).

When applied appropriately, Equation 2 appears to be useful as an upper limit to the temperature rise produced by a beam of ultrasound passing through homo-
An Alternative Simple Formula for Temperature Estimates

To the Editor:—In a recently published report (hereafter called "AIUM 1988"), tables and formulae were given for purposes of estimating acoustic conditions under which beams of diagnostic ultrasound would cause the temperature to rise by no more than a designated amount. These were based on simplifications and assumptions that were pointed out in the report. A Table 2.3 (hereafter called "AIUM Table 2.3") gave values for the acoustic power, such that an ultrasound source emitting this or any lower value of the power would not produce a temperature rise greater than 1°C. For brevity, such a value was called the "1° power". AIUM Table 2.3 gave estimates of the 1° power for a series of values of the source diameter D and frequency f; specifically, entries were tabulated for diameters varying from 1 cm to 2 cm (10 mm to 20 mm) and frequencies from 2 to 10 MHz. It was found by examining this table that all the entries followed a simple rule, namely, that in no case was the entry in milliwatts, less than 23 times the ratio of diameter (D) in millimeters to the frequency (f) in megahertz. Thus an upper limit to the tabular data was found to be given by

\[ 1° \text{ power} = 23 \times \frac{D}{f} \]  

(1)

It was explained in AIUM 1988 that this formula is conservative in that computations based on it always give values for the 1° power that are equal to or less than the entries in AIUM Table 2.3 (which are themselves conservative). Specifically, it was found that Equation 1 gives values for the 1° power that are less than the entries in AIUM Table 2.3 by percentages varying from 2% to 65%.

As pointed out in AIUM 1988, the known range of usefulness of Equation 1 is that of AIUM Table 2.3 itself, namely, diameters from 10 to 20 cm and frequencies from 2 to 10 MHz. Questions have been raised as to the applicability outside this range, especially to smaller diameters. To test the possibilities, we have carried out computations to extend AIUM Table 2.3 to smaller values of the diameter. We do not present the tabular data here but instead summarize the findings. With decreasing diameter, Equation 1 becomes increasingly conservative. For example, at a frequency of 7 MHz, values of the 1° power calculated from Equation 1 are less than tabulated values by factors of 1.6, 1.8, 2.7, 3.2, 5.1, and 8.5 when the diameter (D) has the values 8 mm, 6 mm, 4 mm, 2 mm, 1 mm, and 0.5 mm, respectively. Clearly, Equation 1 should not be used for applications involving transducers of very small diameter, unless a very conservative estimate will suffice.

Another empirical formula was tested and found to be more satisfactory for small values of D. By analogy to Equation 1 it is written

\[ 1° \text{ power} = 75 \times \sqrt{D/f} \]  

(2)

where, again, the 1° power is in milliwatts, D in millimeters, and f in megahertz. Comparisons were made between computations based on Equation 2 and entries in the above-mentioned extension to AIUM Table 2.3; the new entries are based on the same algorithm as before, but include values for diameters varying from 0.4 to 20 mm. It was found that calculations of 1° power from Equation 2 are less than corresponding tabulated values by percentages varying from 6% to 100%. Thus Equation 2 is conservative, but (at small values of D) not nearly as much as Equation 1.

There is some theoretical justification for a \( \sqrt{D} \) dependence from theory developed by Nyborg and Steele, although the latter does not take perfusion into account. In this reference, it is shown that for a fairly wide range of conditions, the steady-state temperature rise in a beam, at the surface where it enters an absorbing medium, is approximately proportional to \( ID^{15} \), where I is the intensity averaged over the beam cross-sectional area. Because the total power (W) passing through the same area is proportional to \( ID^2 \), the temperature elevation is then proportional to \( W/\sqrt{D} \) and the 1° power to \( \sqrt{D} \).

When applied appropriately, Equation 2 appears to be useful as an upper limit to the temperature rise produced by a beam of ultrasound passing through homo-
An Alternative Simple Formula for Temperature Estimates

To the Editor:—In a recently published report (hereafter called "AIUM 1988"), tables and formulae were given for purposes of estimating acoustic conditions under which beams of diagnostic ultrasound would cause the temperature to rise by no more than a designated amount. These were based on simplifications and assumptions that were pointed out in the report. A Table 2.3 (hereafter called "AIUM Table 2.3") gave values for the acoustic power, such that an ultrasound source emitting this or any lower value of the power would not produce a temperature rise greater than 1°C. For brevity, such a value was called the "1° power." AIUM Table 2.3 gave estimates of the 1° power for a series of values of the source diameter D and frequency f; specifically, entries were tabulated for diameters varying from 1 cm to 2 cm (10 mm to 20 mm) and frequencies from 2 to 10 MHz. It was found by examining this table that all the entries followed a simple rule, namely, that in no case was the entry in milliwatts, less than 23 times the ratio of diameter (D) in millimeters to the frequency (f) in megahertz. Thus an upper limit to the tabular data was found to be given by

\[ 1° \text{ power} = 23 \times D/f \]  

(1)

It was explained in AIUM 1988 that this formula is conservative in that computations based on it always give values for the 1° power that are equal to or less than the entries in AIUM Table 2.3 (which are themselves conservative). Specifically, it was found that Equation 1 gives values for the 1° power that are less than the entries in AIUM Table 2.3 by percentages varying from 2% to 65%.

As pointed out in AIUM 1988, the known range of usefulness of Equation 1 is that of AIUM Table 2.3 itself, namely, diameters from 10 to 20 cm and frequencies from 2 to 10 MHz. Questions have been raised as to the applicability outside this range, especially to smaller diameters. To test the possibilities, we have carried out computations to extend AIUM Table 2.3 to smaller values of the diameter. We do not present the tabular data here but instead summarize the findings. With decreasing diameter, Equation 1 becomes increasingly conservative. For example, at a frequency of 7 MHz, values of the 1° power calculated from Equation 1 are less than tabulated values by factors of 16, 18, 27, 32, 51, and 85 when the diameter (D) has the values 8 mm, 6 mm, 4 mm, 2 mm, 1 mm, and 0.5 mm, respectively. Clearly, Equation 1 should not be used for applications involving transducers of very small diameter, unless a very conservative estimate will suffice.

Another empirical formula was tested and found to be more satisfactory for small values of D. By analogy to Equation 1 it is written

\[ 1° \text{ power} = 75 \times \sqrt{D/f} \]  

(2)

where, again, the 1° power is in milliwatts, D in millimeters, and f in megahertz. Comparisons were made between computations based on Equation 2 and entries in the above-mentioned extension to AIUM Table 2.3; the new entries are based on the same algorithm as before, but include values for diameters varying from 0.4 to 20 mm. It was found that calculations of 1° power from Equation 2 are less than corresponding tabulated values by percentages varying from 6% to 100%. Thus Equation 2 is conservative, but (at small values of D) not nearly as much as Equation 1.

There is some theoretical justification for a \( \sqrt{D} \) dependence from theory developed by Nyborg and Steele, although the latter does not take perfusion into account. In this reference, it is shown that for a fairly wide range of conditions, the steady-state temperature rise in a beam, at the surface where it enters an absorbing medium, is approximately proportional to \( ID^{1/2} \), where \( I \) is the intensity averaged over the beam cross-sectional area. Because the total power (W) passing through the same area is proportional to \( ID^2 \), the temperature elevation is then proportional to \( W/\sqrt{D} \) and the 1° power to \( \sqrt{D} \).

When applied appropriately, Equation 2 appears to be useful as an upper limit to the temperature rise produced by a beam of ultrasound passing through homo-