# Absorption and Attenuation in Soft Tissues: I—Calibration and Error Analyses

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*Abstract*—Error estimations are developed for pulse decay absorp- [redacted]

of narrow beamwidths for tissue heating [6]. Given the [redacted]

1) Total acoustic output derived from radiation force on an absorber, as measured by an electronic microbalance.
2) Main lobe beam pattern as measured by embedded

[redacted]

thus

$$I_0 = \frac{P_T}{\pi \beta} \tag{4}$$

[redacted]

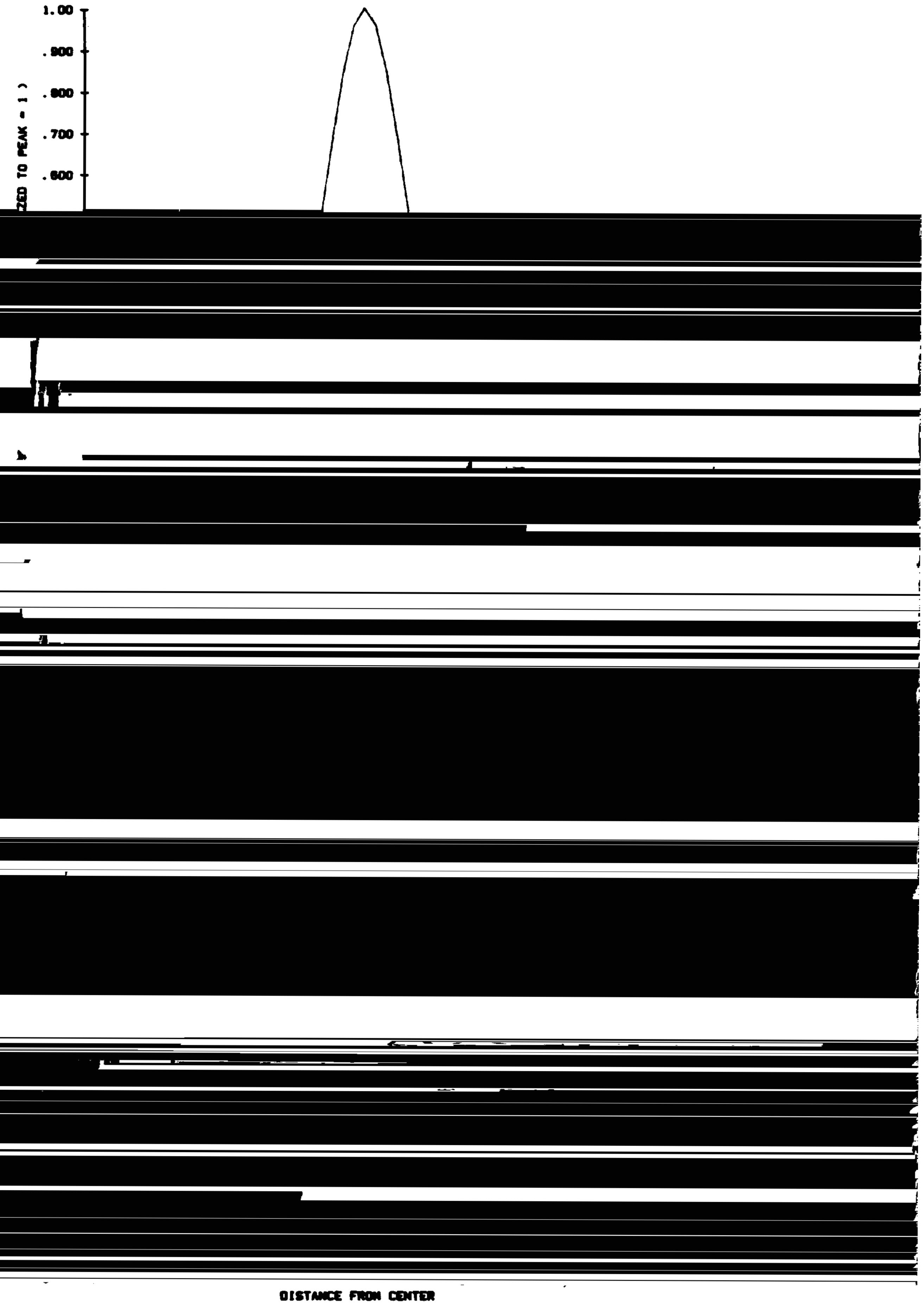



Fig. 2. Least-squares-error curve fit of Gaussian function (dashed) to Bes-sinc (solid). Amplitude weighting is utilized to emphasize main lobe fit.

$$\alpha = \frac{T_{exp}\rho C\left[1 + \left(\frac{4kt}{\beta}\right)\right]}{I_0\left[1 + \operatorname{erf}\left(\frac{z}{\sqrt{4kt}}\right)\right]} \exp\left[\frac{r^2}{(4kt + \beta)}\right] \quad (8)$$

or

$$\alpha = f(T_{exp}, \rho, C, \beta, I_0, r, k, z, t) \quad (9)$$

where $T_{exp}$ is the thermocouple measurement of tempera-

[redacted]

percent error of each term (percent $E_x = \sigma_x/x$) we have

$$(\%E_\alpha)^2 = (\%E_{T_{exp}})^2 + (\%E_\rho)^2 + (\%E_C)^2 + (\%E_\beta)^2\left[\frac{-4kt\left(\frac{4kt}{\beta} + 1\right) - r^2}{\beta\left(\frac{4kt}{\beta} + 1\right)^2}\right]^2$$

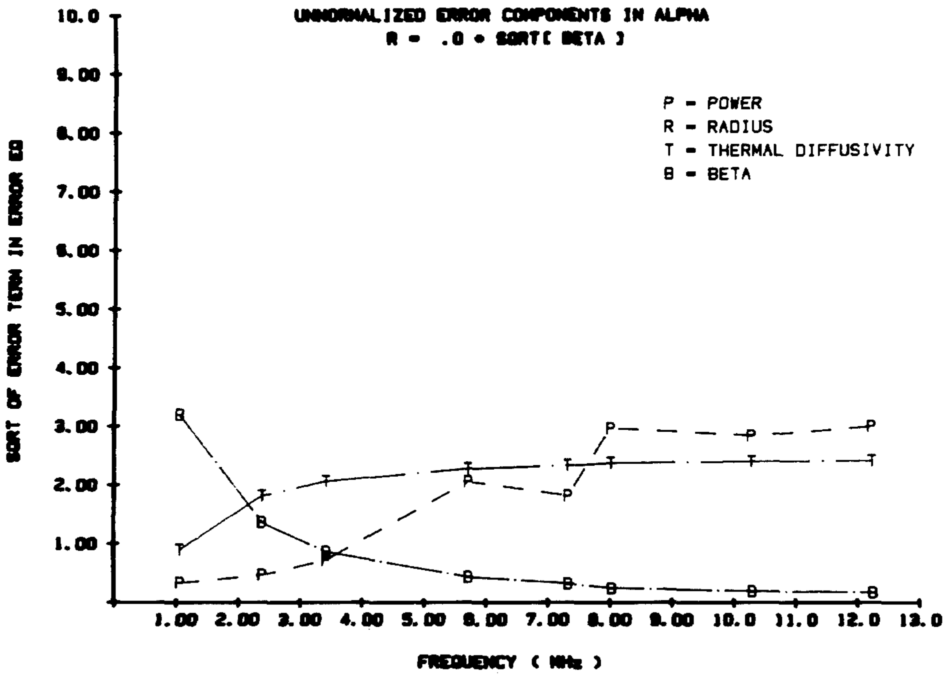
[redacted]

TABLE I
COMPARISON OF ERROR MULTIPLIER FOR BETA TERM[a]

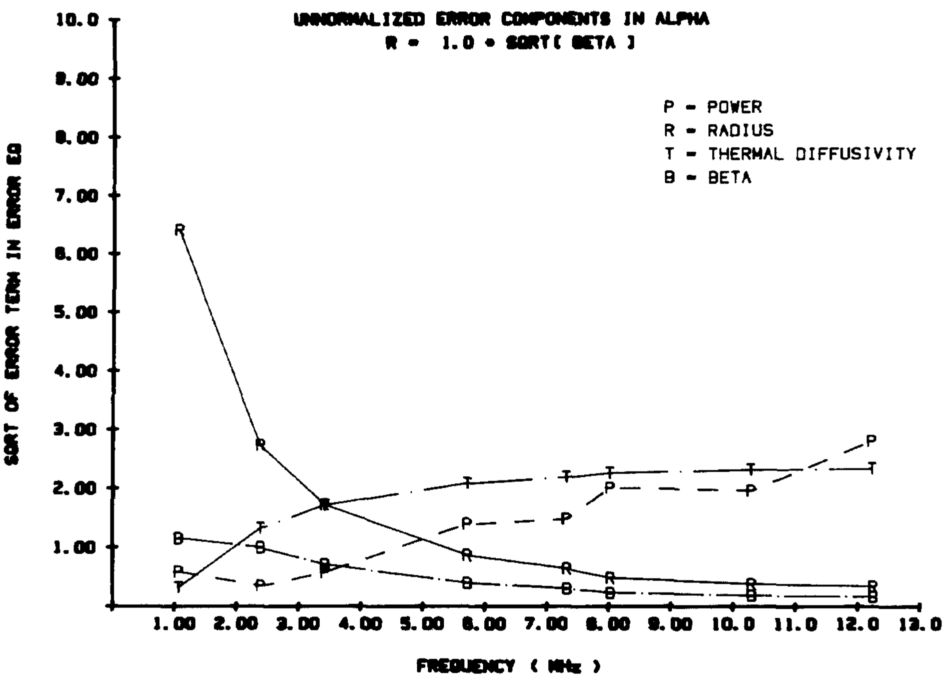
| | Independent measurement of $I_0$ | Calculation of $I_0$ Using $P_T$ and $\beta$ |
|---|---|---|
| $\beta = 5 \times 10^{-2}$ cm$^2$ (~1 MHz) | | |
| $r = 0$ | 0.14 | 0.39 |
| $r = \sqrt{\beta}$ | 0.59 | 0.06 |
| $r = 2\sqrt{\beta}$ | 3.70 | 0.88 |
| $\beta = 3 \times 10^{-3}$ cm$^2$ (~5 MHz) | | |
| $r = 0$ | 0.83 | 0.0083 |
| $r = \sqrt{\beta}$ | 0.84 | 0.0068 |
| $r = 2\sqrt{\beta}$ | 0.89 | 0.0033 |
| $\beta = 1 \times 10^{-3}$ cm$^2$ (~12 MHz) | | |
| $r = 0$ | 0.94 | 0.0010 |
| $r = \sqrt{\beta}$ | 0.94 | 0.0010 |
| $r = 2\sqrt{\beta}$ | 0.95 | 0.0008 |

($k = 0.0015$ cm$^2$/s, $t = 5$ s, all cases)

$$\left[\frac{1}{\beta}\left(\frac{4kt\,(4kt/\beta + 1) + r^2}{(4kt/\beta + 1)^2}\right)\right]^2 \qquad \left[\frac{1}{\beta}\,\frac{(4kt + \beta - r^2)}{(4kt/\beta + 1)^2}\right]^2$$

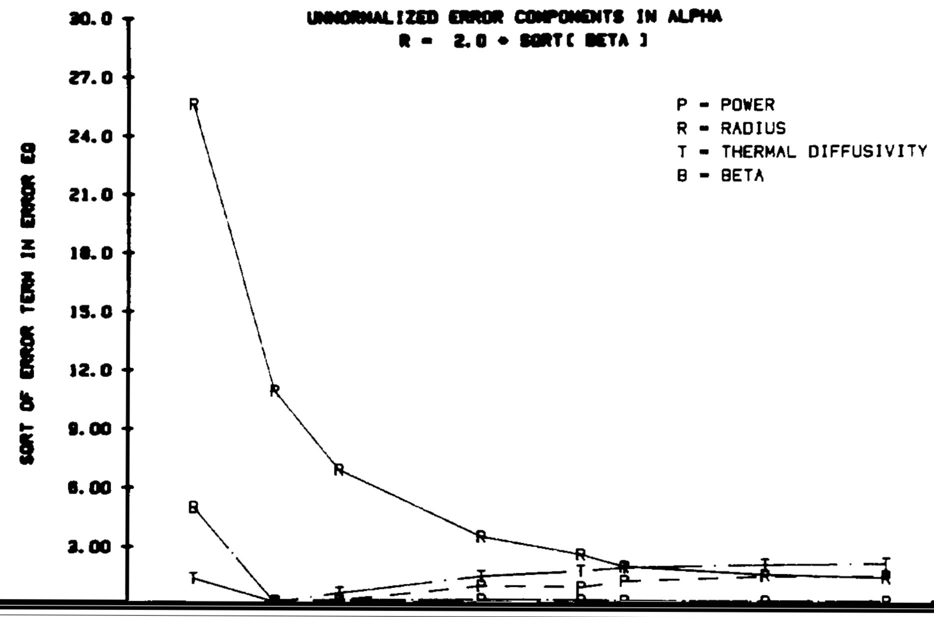



(a)




(b)

Fig. 4. Components of the absorption error equation, for on axis ($r = 0$) and two off-axis ($r = \beta^{1/2}$, $2\beta^{1/2}$) pulse-decay experiments. $P$ is the percent error in acoustic power measurements, obtained from actual experiments. $R$, $T$, and $B$ are square roots of multipliers of percent error in radius, thermal diffusivity, and beta, respectively. These three functions


UNNORMALIZED ERROR COMPONENTS IN ALPHA
R = 2.0 * SQRT[ BETA ]
P - POWER
R - RADIUS
T - THERMAL DIFFUSIVITY
B - BETA
SQRT OF ERROR TERM IN ERROR EQ
30.0
27.0
24.0
21.0
18.0
15.0
12.0
9.00
6.00
3.00

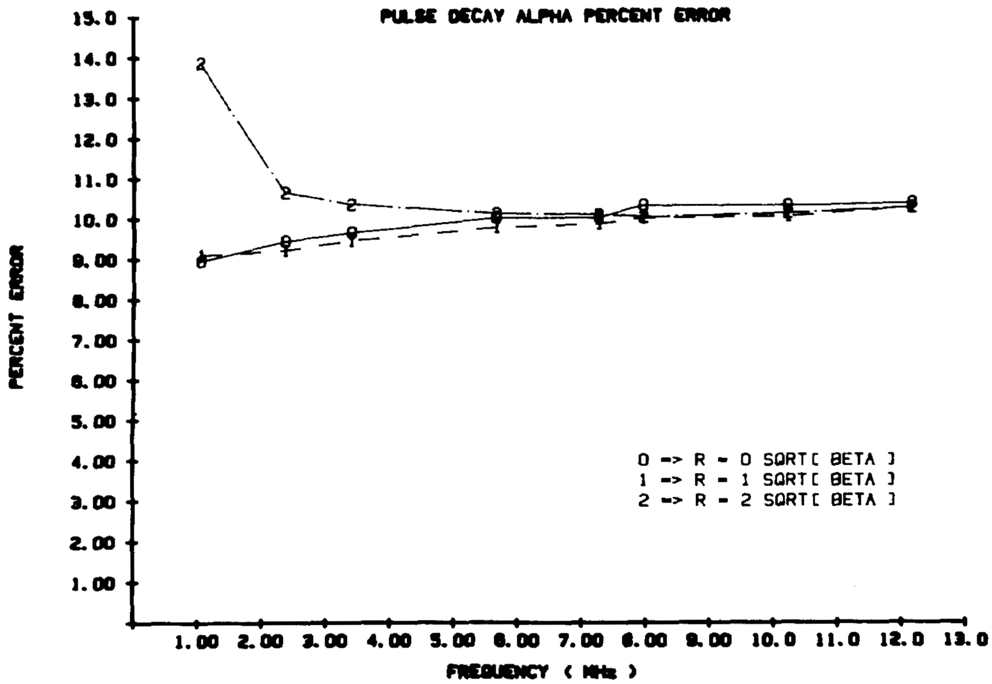
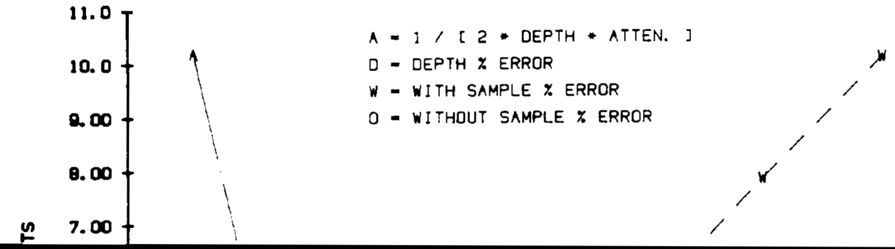



Fig. 6. Total-percent error in pulse-decay absorption measurements for on-

[redacted]


11.0
10.0
9.00
8.00
7.00
A = 1 / [ 2 * DEPTH * ATTEN. ]
D = DEPTH % ERROR
W = WITH SAMPLE % ERROR
O = WITHOUT SAMPLE % ERROR