Absorption of finite amplitude focused ultrasound

Diane Dalecki, Edwin L. Carstensen, and Kevin J. Parker
Department of Electrical Engineering and the Rochester Center for Biomedical Ultrasound, University of Rochester, Rochester, New York 14627

David R. Bacon
[illegible]
TW11 OLW, United Kingdom

(Received 4 August 1990; accepted for publication 6 December 1990)

Predictions of the absorption of focused finite amplitude waves based on weak shock theory have been tested experimentally. The characteristics of this absorption are qualitatively different from those associated with small signal losses. Under appropriate conditions, the absorption of finite amplitude ultrasound is determined largely by source amplitude, field geometry, and the nonlinear properties of the medium and is only weakly dependent upon the small signal absorption coefficient of the material. These effects are seen most dramatically in sharply focused sound fields. To emphasize nonlinear absorption in an experimental test of these predictions, measurements of heating were made in agar which has a very small linear absorption coefficient. Under appropriate conditions, nonlinear losses can make the effective absorption coefficient of this poorly absorbing material somewhat greater than the soft tissues of the body.

PACS numbers: 43.80.Cs, 43.25.Ed, 43.35.Bf

INTRODUCTION

In a homogeneous medium at small signal levels, it is possible to characterize the losses of ultrasound and the con-

experimental arrangement which demonstrates the interesting characteristics of α_{ws}. First, because sharply focused fields yield the largest values of α_{ws}, we have used focused sound to emphasize finite amplitude absorption as opposed lead to an increase in the effective absorption coefficient of

as the wave progresses and for media with low linear absorption coefficients, serves as a descriptor of the degree of finite amplitude distortion.[3] [For $\sigma < 1$, there are no discontinuities in the wave but the waveform may be distorted. For this reason, σ is sometimes called the distortion parameter.] In its general form, the shock parameter is given by the line integral along the path l [ray tube (Blackstock 1972)] as

$$\sigma = \beta k \int \epsilon(l) dl, \tag{8}$$

where β is the nonlinearity parameter of the medium.

Thus, the expression for α_{ws} can be separated into a purely geometrical factor which depends upon the convergence of the sound field [Eq. (8)]

$$F^{-1} = \frac{1}{\sigma} \frac{\partial \sigma}{\partial l} = \frac{\epsilon(l)}{\int \epsilon(l) dl}, \tag{16}$$

and a part which can be determined generally, since it is just

[right-hand side of Eq. (17)]

$$\alpha_{\mathrm{ws}} F = -\frac{\sigma(\partial / \partial \sigma) [\Sigma B_n^2(\sigma)]}{2 \Sigma B_n^2(\sigma)}. \tag{17}$$

The expression on the right-hand side of Eq. (17) has been

$1/[z \ln(z/z)]$. ence on propagation distance, frequency, and material propming over a modest number of harmonics. A number of methods exist for determining the maximum number of harmonics to be used in the summation. For a nonzero propaga-

whereas the absorption in water has a quadratic frequency dependence. Hence, there is some frequency $f_{\max}$ where the two absorption coefficients will be equal and this was taken

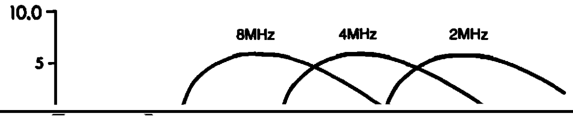
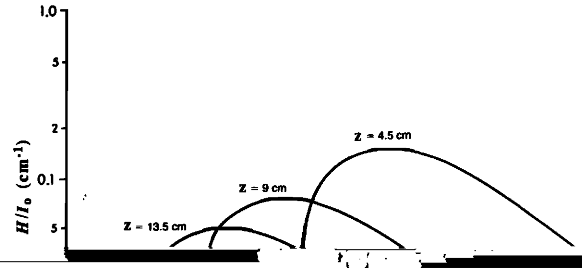


FIG. 5. Predicted heating rate H resulting from excess material absorption normalized to the source intensity I_0. Frequency = 4 MHz; observation point is 0.5 cm beyond the surface of a 3% agar sample; focal length of the



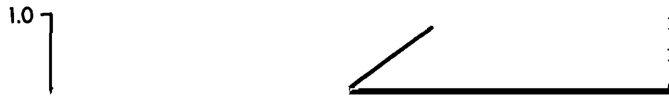
II. EXPERIMENTAL PROCEDURES

A. Source intensity

Focused sound fields were generated by one inch diameter piezoceramic disks (and, in one case, a 2-in. diameter quartz element) which were coupled to planoconcave aluminum lenses. The source intensity I_0 was measured by placing a large absorbing target directly in front of the lens and de-

[illegible]

[illegible]



namic system considered here, but an estimate based on the formulation of Dickinson (1985) gave the error to be typically 20% at low amplitudes. Experimental comparisons of

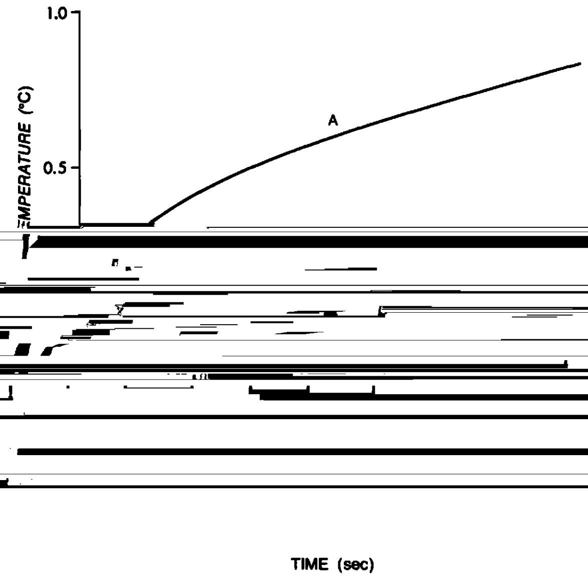


FIG. 12. Raw temperature data demonstrating nonlinear heating. In both examples, the temporal average source intensity is 0.25 W/cm^2. Curve B is c.w., whereas, in Curve A the waveform consists of a train of 100 μs pulses

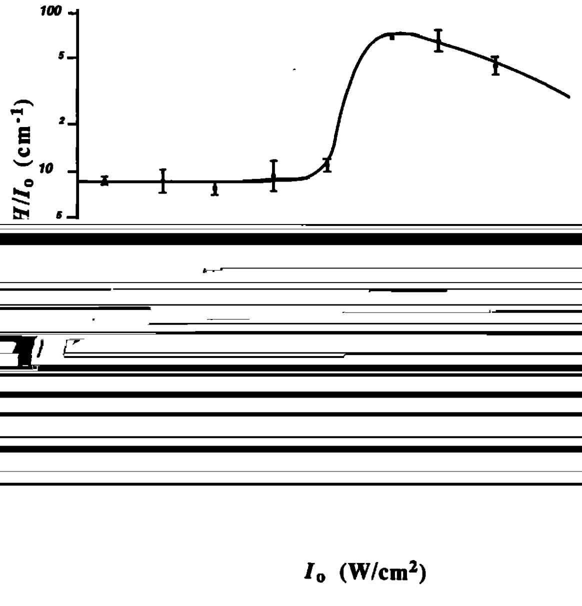


FIG. 14. Focal heating in a sharply focused sound field. Observed and predicted, normalized, heating rates are compared at the focus of a 3.6-MHz source with a focal length of 4.7 cm; $G = 11$; thermocouple depth = 0.5 cm

comes evident but this does not increase the magnitude of the finite amplitude losses. The small-signal absorption coefficient of materials do increase with frequency, however, and, hence, the finite amplitude losses tend to be obscured at higher frequencies. This is illustrated by comparison of the 6 MHz data in Fig. 15 with that for lower frequencies. A

conditions of this study. In particular, the spherically converging model is a good predictor of nonlinear loss on-axis in the prefocal region before diffraction effects limit the wave amplitude, and by using a Gaussian beam the model becomes a reasonable predictor of nonlinear loss near and at the focus. Even the Gaussian model, though, does not acdepends upon being able to deposit heat selectively at depths . (— 2r)

Bacon, D. R., and Baker, A. C. (1989). "Comparison of two theoretical

models for predicting non-linear propagation in medical ultrasound

tic ultrasound due to nonlinear propagation," J. Acoust. Soc. Am. 88

stantan thermocouple arrays," Phys. Med. Biol. 30, 445–453.

Duck, F. A., and Starritt, H. C. (1989). "The spatial distribution of excess

Fry, F. J., Dines, K. A., Reilly, C. R., and Goss, S. A. (1989). "Losses in