data indicate that in the "worst case" the estimated "true" spatial peak value in the measured waveform exceeded the measured value by a factor of 2, depending on frequency and the diameter of the polymer probe used. Work is in progress to estimate more accurately the effect of spatial averaging due to the finite aperture of the hydrophone probes.

DISCUSSION

Wideband piezoelectric polymer (PVDF) hydrophones are now available with well documented performance characteristics; these probes are especially well suited for the measurement and comprehensive characterisation of both pulsed and CW acoustic fields generated by ultrasound diagnostic devices, including peak instantaneous pressure amplitudes as specified in the AIUM/NEMA Standard, IEC Draft document and FDA 510(K) requirements.

Users must be aware of the need to exercise care when using the polymer hydrophone probes and to ensure that the probes are carefully checked when first received from the manufacturer, it is also recommended that two calibrated probes should be acquired and only one of the probes routinely used, while the other is stored and used as a secondary standard or back-up.

For long term stability of performance it is necessary to avoid prolonged immersion in water when the probes are not in use to avoid the possible water corrosion effects due to the electrolysis which may result in the loss of the surface electrode. The ionic activity on the transducer surface can be greatly reduced by using distilled or deionized water for measurements. There is at present insufficient data to fully evaluate the ionic interaction on polymer membrane hydrophones. The data available indicate that the simple construction membrane type hydrophones fail completely when exposed to tap water, while bilaminar construction behaves approximately on a par with the needle type hydrophones. For earlier needle type hydrophone designs, the end-of-cable voltage sensitivity may decrease as a result of partial loss of the aluminum electrode due to ionic interaction/reaction. The use of double nickel/chromium plating on primary aluminum electrode in recent designs improves corrosion resistance.

THE ULTRASONIC NONLINEARITY PARAMETER OF BIOLOGICAL MEDIA AND ITS DEPENDENCE ON TISSUE STRUCTURE

F. DUNN
Bioacoustics Research Laboratory, University of Illinois, Urbana, Illinois, USA

Acoustic phenomena are fundamentally nonlinear and evidence to suggest this relative to biomedical applications has accumulated (Beyer and Letcher, 1969; Carstensen *et al.*, 1980, 1981; Muir and Carstensen, 1980).

The exact one-dimensional equation of motion for acoustic phenomena in fluid media is, in Largrangian coordinates, $\ddot{\xi} = [(\partial p/\partial \rho)/(1 + \xi')^2]\xi''$ where ξ is the particle displacement, p is the sound pressure, and ρ is the density. It is seen that if a linear relationship for the equation of state is employed, such that $\partial p/\partial \rho$ is constant, and if the displacement amplitude of the wave is sufficiently small such that $\partial \xi/\partial x \ll 1$, the ordinary lossless wave equation is obtained, viz., $\ddot{\xi} = c^2\xi''$. The situation for which the equation of state is more complex can be treated by considering it to be expressed in a Taylor's series for isentropic processes such that, to second order

$$\Delta p = As + B/2!\, s^2 + \cdots,$$

where

$$A = \rho_0(\partial p/\partial \rho)_S,\ \rho_0 = \rho_0 c_0^2,$$

$$B = \rho_0^2(\partial^2 p/\partial \rho^2)_S,\ \rho_0$$

and $s = (\rho - \rho_0)/\rho_0$, with ρ_0 being the undisturbed density. For this situation the equation of motion becomes

$$\ddot{\xi} = \frac{c_0^2}{(1 + \xi')^2 + B/A}\,\xi'',$$

where it is seen that when the displacement amplitude cannot be neglected, the parameter B/A becomes a measure of the nonlinearity of the propagating medium.

Table 13. B/A values of biological media

Medium		B/A
Water		5.2
Aqueous solution	dextrose mW 100 Daltons	6.0
	dextran mW 1.5×10^5	5.9
	dextran mW 2×10^6	6.0
Aqueous solution, BSA, (bovine serum albumen)	17 g/dl 25°C	6.0
	20 g/dl 25°C	6.2
	22 g/dl 25°C	6.4
	25 g/dl 25°C	6.6
Aqueous solution, MD, 50%, 30°C		7.6
Blood, porcine, 12%, MD		6.2
Liver (human, canine, porcine)		7.2–7.9
Liver (homogenized)		6.9 ?
Spleen (canine)		6.9 ?
Spleen (human, congested)		7.0
Kidney (canine)		7.2
Muscle (porcine)		6.5
Fat, fatty tissue		11.0

Aqueous solutions of macromolecules constitute tissue models as regards ultrasonic velocity and absorption behaviour. Such specimens have been studied with the result that B/A appears to be linearly dependent upon solute content. This has been found for aqueous solutions of the linear molecules dextran and polyethylene glycol (PEG), and for the proteins bovine serum albumin (BSA) and hemoglobin. Dextran and PEG also provided the opportunity to use molecular weight as a variable, for which it was found that B/A exhibited no dependence (Law *et al.*, 1981; Dunn *et al.*, 1981; Law *et al.*, 1983, 1985; Gong *et al.*, 1984).

Encapsulation of macromolecules within closed structures, such as hemoglobin in the red blood cell, serves to increase B/A slightly. Intact excised tissues yield greater values of B/A; approximately 7.7 for beef liver. However, destruction of the tissue architecture by homogenization reduces this to below 7. These latter two findings suggest that the structural features of tissues contribute significantly to their B/A value. Fatty tissues yield the highest B/A values, approximately 11 (Law *et al.*, 1981; Dunn *et al.*, 1981; Law *et al.*, 1983, 1985; Gong *et al.*,1984; Cobb, 1982; Zhu *et al.*, 1983; Law, 1984).

The data suggest that B/A is expressive of tissue constituencies as regards cellular/architectural features, and tissue structures as regards pathologic condition. Variations of B/A among these tissue/conditions may be sufficiently significant for it to be considered in diagnostic and therapeutic applications (see Table 13).

REFERENCES

Beyer R. T. and Letcher S. V. (1969) *Physical Ultrasonics*. Academic Press, New York.

Carstensen E. L., Becroft A. S., Law W. K. *et al.* (1981) Finites amplitude effects on the threshold for lesion production in tissues by unfocussed ultrasound. *J. Acoust. Soc. Am.* **70**, 302–309.

Carstensen E. L., Law W. K., McKay N. D. *et al.* (1980) Demonstration of non-linear acoustical effects at biomedical frequencies and intensities. *Ultrasound in Med. & Biol.* **6**, 359–368.

Cobb W. N. (1982) Measurement of the acoustic non-linearity parameter for biological media. Ph.D. Dissertation. Yale University, New Haven.

Dunn F., Law W. K. and Frizzell L. A. (1981) Non-linear ultrasonic propagation in biological materials. *Proc. IEEE Ultrasonics Symposium*, 527–532.

Gong X. F., Feng R., Zhu C. Y. *et al.* (1984) Ultrasonic investigation of the non-linearity parameter B/A in biological media. *J. Acoust. Soc. Am.* **76**, 949–950.

Law W. K. (1984) Ph.D. Dissertation. University of Illinois, Urbana-Champaign.

Law W. K., Frizzell L. A. and Dunn F. (1981) Ultrasonic determination of the non-linearity parameter B/A for biological media. *J. Acoust. Soc. Am.* **69**, 1210–1212.

Law W. K., Frizzell L. A. and Dunn F. (1983) Comparisons of thermodynamic and finite amplitude methods of B/A measurement in biological materials. *J. Acoust. Soc. Am.* **74**, 1295–1297.

Law W. K., Frizzell L. A. and Dunn F. (1985) Determination of the non-linearity parameter B/A of biological media. *Ultrasound in Med. & Biol.* **11**, 307–318.

Muir T. G. and Carstensen E. L. (1980) Prediction of non-linear acoustic effects at biomedical frequencies and intensities. *Ultrasound in Med. & Biol.* **6**, 345–357.

Starritt H. C., Perkins M. A., Duck F. A. *et al.* (1985) Evidence for finite-amplitude distortion in muscle using medical equipment. *J. Acoust. Soc. Am.* **77**, 302–306.

Zhu Z., Roos M. S., Cobb W. N. *et al.* (1983) Determination of the acoustic non-linearity parameter B/A from phase measurements. *J. Acoust. Soc. Am.* **74**, 1518–1521.

SUMMARY

The magnitude of the nonlinearity parameter depends on the macromolecular content of tissue and B/A is greater for an intact organ, which has structural integrity, than for the same organ which has been macerated.

The nonlinearity parameter has not been measured *in vivo.*

Finite amplitude distortion of ultrasonic waves from medical equipment has been observed in human calf muscle (Starritt *et al.*, 1985).

A principal effect of the nonlinearity of tissues is the generation of higher harmonics, which can increase the heating effect.

DISCUSSION

Knowledge of the ultrasonic nonlinearity parameter is essential for understanding propagation in tissues and organs and for estimating energy deposition. However, as insufficient details are presently available, investigators are encouraged to conduct *in vivo* measurements as soon as practicable.

The relationships of B/A in different media are complex and because of differences in the degree of nonlinearity and attenuation, acoustic measurements made in water cannot be extrapolated to biological tissues without analytical consideration of the differences.