merged sea lion uses intensity cues to localize underwater sound sources, but the results do offer previously lacking behavioral evidence that this is a viable acoustic cue available to the sea lion underwater.

Unfortunately, only a limited amount of information exists regarding this sensory capability in other marine mammals. Evans,[11] in a review of the literature, reports comparative discrimination performance, in an echolocation task, for the Bottlenose porpoise (*Tursiops truncatus*) and for the Amazon-River dolphin (*Inia geoffrenisis*) using submerged targets of varying reflective signal strengths. Inspection of this data suggests that both delphinids could detect (at 70% correct responses) a reflective signal difference of about 1.0 dB. One should expect both *Tursiops* and *Inia* to exhibit a smaller DL for intensity than the sea lion since both species are known to possess a sophisticated echolocation system.

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[1]P. W. B. Moore and W. W. L. Au "Underwater localization of pulsed pure tones by the California sea lion (*Zalopus californianus*)," J. Acoust. Soc. Am. 58, 721–727 (1975).

[2]P. W. B. Moore, "Underwater localization of click and pulsed pure-tone signals by the California sea lion (*Zalophus californianus*), J. Acoust. Soc. Am. 57, 406–410 (1975).

[3]R. J. Schusterman, "Low false-alarm rates in signal detection by marine mammals," J. Acoust. Soc. Am. 55, 845–848 (1974).

[4]R. J. Schusterman and B. W. Johnson, "Signal probability and response bias in California sea lions," Psychol. Rec. 25, 39–45 (1975).

[5]R. J. Schusterman, B. Barrett, and P. Moore, "Detection of underwater signals by a California sea lion and a bottlenose porpoise: variation in the payoff matrix," J. Acoust. Soc. Am. 57, 1526–1632 (1975).

[6]R. J. Schusterman, "Vocal Communication in Pinnipeds," in *Studies of Captive Wild Animals*, edited by H. Markowitz and V. Stevens (Nelson-Hall, Chicago, 1977) (in press).

[7]R. J. Schusterman, R. F. Balliet, and J. Nixon, "Underwater audiogram of the California sea lion by the conditioned vocalization technique," J. Exp. Anal. Behav. 17, 339–350 (1972).

[8]W. J. McGill and J. P. Goldberg, "Pure-tone intensity discrimination and energy detection," J. Acoust. Soc. Am. 44, 576–581 (1968).

[9]J. A. Swets, "The relative operating characteristic in psychology," Science 182, 990–1000 (1973).

[10]T. Engren, "Psychophysics: I. Discrimination and Detection," in *Woodworth and Schlosberg's Experimental Psychology*, edited by J. W. Kling and L. A. Riggs (Holt, Rinehart and Winston, New York, 1971), pp. 11–46.

[11]W. E. Evans, "Echolocation by marine delphinids and one species of fresh-water dolphin," J. Acoust. Soc. Am. 54, 191–199 (1973).

# Ultrasonic propagation properties of mammalian testes*

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The ultrasonic absorption and reflection properties of sexually mature, freshly excised mouse, rabbit, cat, and dog testes have been investigated at 37°C in the frequency range 0.5–7 MHz by the transient thermoelectric absorption, the pulse-reflection, and the pulse-transmission methods. The absorption coefficient is found to exhibit values considerably less than those of other parenchymal tissues and to possess a frequency dependence mimicking a simple relaxation process of characteristic frequency approximately 0.9 MHz.

Subject Classification: [43]80.20; [43]35.26, [43]35.80.

## INTRODUCTION

An ultrasonic toxicity study, utilizing the reproductive system of the mouse, has been undertaken to identify exposure conditions potentially hazardous to patients and thus to be avoided in clinical practice.[1] Pregnant females are exposed to 1-MHz cw ultrasound for a variety of conditions of acoustic intensity and exposure, at various times during gestation, and the fetuses are subsequently examined for abnormal development at autopsy prior to parturition. Also, male and female gonads of sexually proven animals are exposed with subsequent observations of libido, fertility, and fecundity of the adults and histological examination of the gonadal tissues. An early observation, viz., that relatively high ultrasonic dosages were required to produce functional impairment, or demonstrable lesions, in testicular tissue, suggested departure of the ultrasonic propagation properties of this tissue from that of other parenchymal tissues, and this note constitutes an initial reporting of these results.

The ultrasonic absorption coefficient per unit pathlength was determined by the transient thermoelectric method, which has been described in detail elsewhere.[2] Briefly, the amplitude absorption coefficient is computed from

$$\alpha = (\rho C J/2I)(dT/dt)_0 , \tag{1}$$

where $\rho C$ is the heat capacity per unit volume of the tissue, $J$ is the mechanical equivalent of heat, $I$ is the acoustic intensity at the junction of the thermocouple imbedded in the specimen tissue, and $(dT/dt)_0$ is the observed initial time rate of change of temperature at the junction associated with the phase of the response resulting from acoustic energy converted into heat by absorption in the surrounding (embedding) tissue. The method yields absolute uncertainties in the absorption

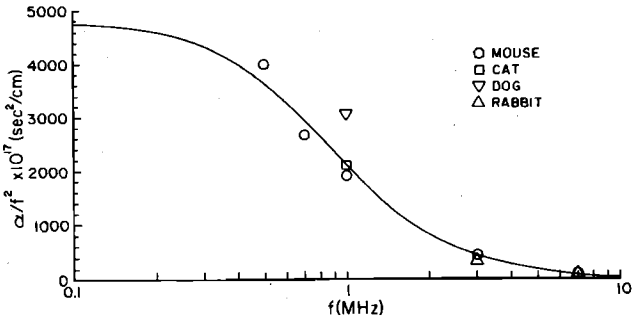


FIG. 1. Ultrasonic frequency-free absorption versus frequency for testes of mouse, rabbit, cat, and dog.

coefficient of less than ± 10% for frequencies in the neighborhood of 1 MHz and below. Insertion of the butt-soldered copper–Constantan thermocouple junctions, fabricated from 0.003-in. diam wire, was facilitated by small (30 gauge) hypodermic needles. The specimen organ was suspended in the sound field by a supporting frame which did not interfere with the propagating sound beam. The value of 0.84 cal/cm$^3$ °C was used for the heat capacity per unit volume in the calculations.[3,4] An average of ten measurements in each testis was made.

The specimens were removed surgically, all surrounding tissue being dissected away, leaving the tunica albuginea intact. The tissue was immersed in degassed Ringer's solution, maintained at 37 °C ± 0.5 °C, which served as the acoustical coupling medium. All mouse and rabbit specimens and one cat specimen were measured within one hour of excision. The other specimens were cooled in Ringer's solution immediately after excision and measured within four hours.

## ABSORPTION AND REFLECTION OBSERVATIONS

A first consideration was that of substantial reflection of energy occurring, possibly at the boundary of the organ, which thereby reduces the amplitude of the acoustic wave able to penetrate to the interior. The fact that the tough outer layer of testis, i.e., the tunica albuginea, is comprised largely of connective tissue, and likely to have acoustic properties significantly different than the bounding media, gave credence to this view. Two different measuring schemes were employed, both utilizing freshly excised mouse and rabbit testes. The first method involved a pulse–echo technique providing a working range that would have permitted an amplitude reflection coefficient of 0.08 to be resolved. However, the reflected signals were below such level. The acoustical coupling medium was distilled water at room temperature, i.e., about 20 °C. The second scheme consisted of a transmission method which yielded the value of less than 0.1 for the intensity reflection coefficient per reflective surface. Here, the coupling medium was degassed Ringer's solution at 37° ± 0.5 °C. It thus emerged that the acoustic impedence of testis was not unusually different than that of other soft tissues.

Scattering of the incident wave, out of the main beam by the testis, was also considered as a possible mechanism limiting the energy entering the organ. However, the difference in the acoustic field distribution observed with the specimen present, and again with the specimen removed, failed to exhibit either significant amplitude or geometric disturbance necessary to account for the substantial fraction of the incident energy needed to be deflected out of the main beam and becoming unavailable, thereby, to affect the tissue.

Figure 1 shows the frequency-free absorption parameter $\alpha/f^2$ as a function of frequency for mouse, rabbit, cat, and dog testes, though data are available only for the mouse testes at each of the exposure frequencies, viz., 0.5, 0.7, 1, 3, and 7 MHz. Table I contains the amplitude absorption values for these tissues. Two remarkable findings emerge from these data. Firstly, it is seen that the magnitude of the absorption coefficient of testis is markedly less than that of other parenchymal tissues. For example, brain, liver, and kidney have values ranging, approximately, from 0.1 to 0.3 cm$^{-1}$ at 1 MHz,[5] while testicular tissue is seen to be in range 0.02–0.04 cm$^{-1}$, a factor of approximately ten lower. Explanation for this low value of absorption may be obtained from water content of testis, which is known to be substantially greater than most tissues.[6] The suggestion that decrease in ultrasonic absorption of tissues and organs attends increasing water content[7] may be applicable here.

The second remarkable finding is associated with the frequency dependence of the mouse testicular tissue absorption coefficient. The curve through the data of Fig. 1 describes a single relaxation process:

$$\frac{\alpha}{f^2} = A + \frac{B}{1+(f/f_r)^2}\ , \qquad (2)$$

where the term $A$ represents the classical absorption processes which follow quadratic frequency relationships, $B$ represents the strength of the relaxation process, and $f_r$ is the relaxation frequency. The data of Fig. 1 are seen, particularly for the mouse, to follow well the description for which $f_r = 0.88$ MHz and $B = 4840 \times 10^{-7}$ sec$^2$/cm. For convenience in plotting, it was considered that $A = 0$, and it is seen that serious discrepancy is not introduced since $\alpha/f^2 = 15 \times 10^{-17}$ sec$^2$/cm for water. Explanation is presently unavailable for this relatively simple frequency behavior.

TABLE I. Ultrasonic amplitude absorption coefficient of various mammalian testes.

| $f$(MHz) | $\alpha$(cm$^{-1}$) | No. of specimens | Animal |
|---|---|---|---|
| 0.5 | 0.010 | 3 | Mouse |
| 0.7 | 0.013 | 6 | |
| 1 | 0.019 | 3 | |
| 3 | 0.040 | 5 | |
| 7 | 0.042 | 5 | |
| 3 | 0.032 | 1 | Rabbit |
| 7 | 0.039 | 1 | |
| 1 | 0.034[a] | 2 | Cat |
| 1 | 0.021 | 1 | |
| 1 | 0.038[a] | 2 | Dog |

[a]Stored in cooled Ringers after excision.

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[1]F. J. Fry, F. Dunn, J. Brady, W. D. Erdman, P. Strang, R. Kohn, I. Baird, and J. Cobb, "Ultrasonic Toxicity Study of the Mouse Reproductive System and the Pregnant Uterus," in *Ultrasound in Medicine*, edited by D. White and R. Barnes (Plenum, New York, 1976), Vol. II, p. 533.

[2]F. Dunn, P. D. Edmonds, and W. J. Fry, "Absorption and Dispersion of Ultrasound in Biological Media," in *Biological Engineering*, edited by H. P. Schwan (McGraw-Hill, New York, 1969), pp. 205–332.

[3]W. Güttner, "Die Energieverteilung im Menschlichen Korper bei Ultraschall-Einstrahlung," Acustica 4, 547–554 (1954).

[4]F. Dunn, "Temperature and Amplitude Dependence of Acoustic Absorption in Tissue," J. Acoust. Soc. Am. 34, 1545–1547 (1962).

[5]D. E. Goldman and T. F. Hueter, "Tabular Data of the Velocity and Absorption of High-Frequency Sound in Mammalian Tissue," J. Acoust. Soc. Am. 28, 35–37 (1956).

[6]See for example, J. E. Logan and W. A. Himwich, "Animal Tissues and Organs: Water Content," in *Biology Data Book*, compiled and edited by P. L. Altman and D. S. Dittman (Federation of American Societies Experimental Biology, Bethesda, 1972), 2nd ed., Vol. I, pp. 392–398.

[7]F. Dunn, "Ultrasonic Velocity and Attenuation in Tissues and Organs," in *Proceedings of Seminar on Ultrasonic Tissue Characterization*, NBS Special Publication 453, edited by M. Linger (U.S. GPO, Washington, DC, 1976), pp. 21–28.

# Shear properties of mammalian tissues at low megahertz frequencies*

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Rough values for the transverse-wave specific acoustic impedance $Z_s = R_s + jX_s$, transverse velocity of sound $c_s$, and transverse absorption coefficient $\alpha_s$ have been measured for canine liver, kidney, muscle tissues, and for packed red blood cells in the frequency range from 2 to 14 MHz at 25°C. The ranges of the results are $R_s = 700$–$3000\ \Omega_{mech}/cm^2$, $X_s = 400$–$4000\ \Omega_{mech}/cm^2$, $c_s = 900$–$10000$ cm/sec, and $\alpha_s = 2000$–$30000$ np/cm. The corresponding results for shear stiffness $\mu_1$ and viscosity $\mu_2$ are $\mu_1 < 10^7$ dyn/cm$^2$ and $\mu_2 = 4$–$30$ centipoise. At these frequencies the viscosities are orders of magnitude less than those reported at 0.5–5 kHz by Oestreicher (1951). The low impedances (viscosities) correspond to low velocities and extremely high absorption coefficients for shear waves in tissue.

Subject Classification: [43]80.20, [43]80.30; [43]35.26; [43]85.20.

## INTRODUCTION

It has been recognized for many years that transverse waves may play an important part in the interaction of ultrasound with tissue (Carstensen, 1960). For lack of data, however, only speculations have been possible (Schwan and Carstensen, 1952; Lehmann, 1953; Baldes *et al.*, 1958; Taylor and Connolly, 1969; O'Brien *et al.*, 1972). For some insight into these phenomena, rough measurements of the shear acoustic impedance of several mammalian tissues have been made at low megahertz frequencies. Transverse acoustic properties of tissue at these frequencies appear to be determined primarily by the stiffnesses and viscosities of the subcellular constituents.

## I. EXPERIMENTAL METHOD

### A. Equipment

A pulse superposition technique as developed by McSkimin (1961) was used to measure the complex shear specific acoustic impedance. The technique involved measurement of the magnitude and phase angle of the reflection coefficient of a shear wave impinging on a quartz-sample interface. This was compared with total reflection from a quartz–air interface. From a knowledge of the impedance of the quartz, one then obtained the complex impedance of the sample being investigated (McSkimin, 1961). From the shear impedance and density, it was possible to calculate the dynamic shear stiffness $\mu_1$, dynamic shear viscosity $\mu_2$, shear velocity $c_s$, and shear absorption coefficient $\alpha_s$ as shown in the following relationships:

$$\mu_1 = (R_s^2 - X_s^2)/\rho\,, \tag{1}$$

$$\mu_2 = 2R_sX_s/\omega\rho\,, \tag{2}$$

$$c_s = (R_s^2 + X_s^2)/\rho R_s\,, \tag{3}$$

$$\alpha_s = \rho\omega X_s/(R_s^2 + X_s^2)\,, \tag{4}$$

where $\rho$ is the density, $\omega$ is the angular frequency, $R_s$ is the real part of the specific shear acoustic impedance