LETTERS TO THE EDITOR

Attenuation and speed of ultrasound in lung: Dependence upon frequency and inflation

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The dependence of the speed of sound and the attenuation coefficient upon exposure frequency, in the range of 1–5 MHz, and upon level of inflation, in the range of mass density 0.35–0.7 g/cm^3, are reported. The speed of sound decreases linearly and the attenuation coefficient increases exponentially, for all levels of inflation studied.

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The attenuation and speed of ultrasound in freshly excised lung tissue, in the frequency range of 1–5 MHz and inflated to a density of 0.4 g/cm^3, has been reported (Dunn and Fry, 1961; Dunn, 1974). It was found that the attenuation coefficient increases exponentially with frequency and that the speed of propagation increases linearly with frequency. These results are in general agreement with similar measurements on formalin fixed preparations (Bauld and Schwan, 1974). Measurements have now been made on freshly excised canine lung for which the inflation has been varied, and this is an initial reporting of these results.

The measurement methods employed have been discussed previously (Dunn and Fry, 1961). Briefly, a lobe of the freshly excised lung was inflated to the desired level and ligated at the bronchial tube to maintain the selected density, determined from measurements of weight and volume. As preselected density values were sought, each inflation level was achieved only after a series of weight and volume determinations. Continued experience led to increased efficiency, i.e., fewer determinations were needed to achieve the selected density value, with an accuracy of approximately 1%. The preparation was then positioned in the physiological saline transmitting medium between the source of ultrasound and an absorption medium such that standing waves beyond the specimen were reduced to insignificance. The temperature was maintained at 35.0° $\pm$ 0.1 °C. The transient thermoelectric probe (Fry and Dunn, 1962) was employed as the acoustic detector. The acoustic field between the sound source and the specimen was investigated to obtain the axial standing wave pattern, from which the reflection coefficient, and finally the speed of sound in the lung, were determined. Determination of the standing wave ratio limits the speed of sound to an uncertainty of about 10^3 cm/s. The field beyond the specimen, i.e., between the specimen and the sound absorption medium, was investigated to obtain the amplitude of the sound wave traversing the lung, enabling the attenuation to be determined. Herein, infinitesimal wave acoustics was assumed to prevail. It was further assumed that the specimen attenuation was so great that multiple reflections within the lung could be ignored in the calculations. The attenuation is thus considered to be determined with an uncertainty of about 10%, ascertained by the least counts of the amplitude of the signal transmitted through the specimen.

The results of these observations are shown in Table I. Figure 1 shows the apparent speed of sound in freshly excised lung tissue, as a function of exposure frequency, with the parameter from curve-to-curve being the level of inflation, expressed as the mass density of the specimen. The observed ranges of values for the three exposure frequencies for the 0.7-g/cm^3 measurements only are shown, to avoid cluttering the figure, since these exhibited the greatest range, probably because of the least standing wave ratios. Also shown in the figure is the mean ultrasonic speed of sound among 21 mammalian tissues (Goss *et al.*, 1978, 1980); data for high-collagen tissues, to which lung tissue may better compare, are not as numerous. It is seen that a nearly linear relation exists for the dependence of the speed of ultrasound

TABLE I. Tabulation of results.

Density (g/cm^3)	Exposure frequency (MHz)	Apparent speed of sound (m/s)	Attenuation coefficient (cm^{-1})
0.35	1	604	4.8
	3	866	8.5
	5	1155	13.2
0.4	1	644	4.2
	3	916	6.6
	5	1196	11.4
	7	1472	...
0.45	1	697	3.9
	3	968	6.3
	5	1231	10.3
0.5	1	787	3.3
	3	1027	5.6
	5	1266	8.6
0.7	1	976	1.6
	3	1218	2.9
	5	1414	4.9

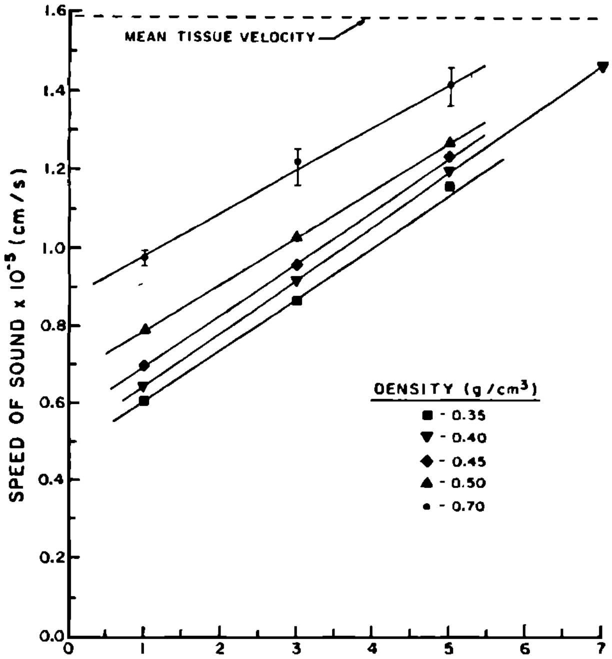

FIG. 1. Speed of sound in lung as a function of exposure frequency and level of inflation. The dashed curve represents the mean value of 21 mammalian tissues, shown for comparison.

of lung in the inflation range of densities from 0.35–0.7 g/cm^3.

Figure 2 shows the (exposure) frequency dependence of the attenuation coefficient A (defined by $I = I_0 e^{-2Al}$, where

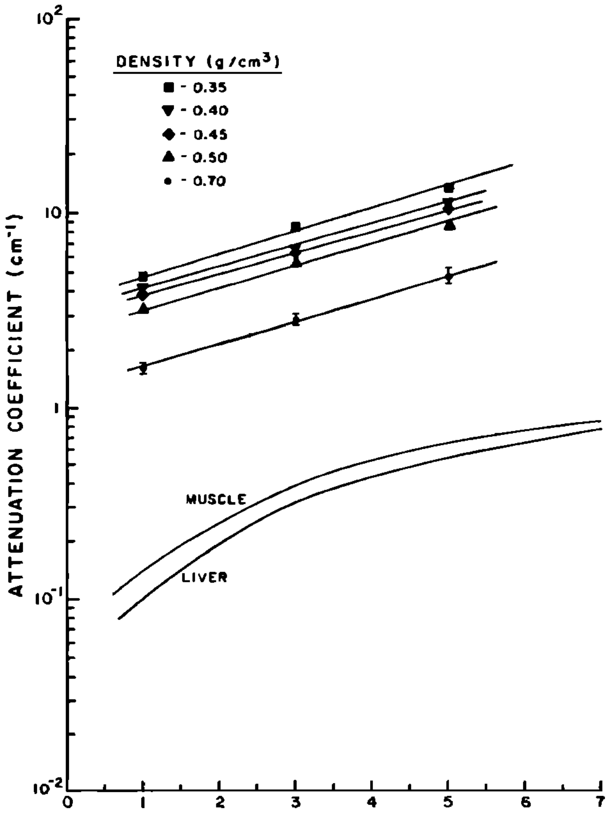

FIG. 2. Ultrasonic attenuation coefficient per unit path length as a function of exposure frequency and level of inflation. The attenuation of muscle and liver is shown for comparison.

I_0 and I are, respectively, the acoustic intensities at the lung–saline interfaces nearest to and farthest from the source for a specimen thickness l). Again, the parameter from curve-to-curve is the inflation level. The error bars, shown only for the 0.7-g/cm^3 data to eliminate clutter, are typical for all inflation levels and show the range of experimental values obtained with nine specimens. The exponential behavior observed earlier is largely maintained for all inflation levels studied. The attenuation of liver ($A = 0.1F^{1.05}$) and muscle ($A = 0.14F^{0.93}$), where F is frequency in megahertz, is shown for comparison (Dunn and Goss, 1984). Figures 3 and 4 show the dependence of the speed of sound and the attenuation, respectively, upon the density of the lung; also upon the volume fraction of the lung tissue since the density of lung tissue is so much greater than that of the air contained.

Note added in revision: Since submission of the above material, the paper by Pedersen and Ozcan (1986) dealing with the ultrasound properties of frozen-sliced-and-sealed-in-plastic bovine lung specimens, in the frequency range of 10–800 kHz, has appeared. It is encouraging to observe that their determinations of phase velocity compare favorably with extrapolations to lower frequencies of the data reported herein. Thus there is confidence that the speed of sound in lung, over a significant range of inflation levels, is known over the frequency range of 10 kHz to 7 MHz. The attenuation data are more difficult to compare since the Pedersen and Ozcan results are approximately an order of magnitude greater, suggesting artifact possibly introduced in specimen preparation, and appear to exhibit a minimum in the neighborhood of 600 kHz. Such a minimum in the attenuation versus frequency behavior of lung was, in fact, predicted on the basis of a decrease with frequency of the attenuation due

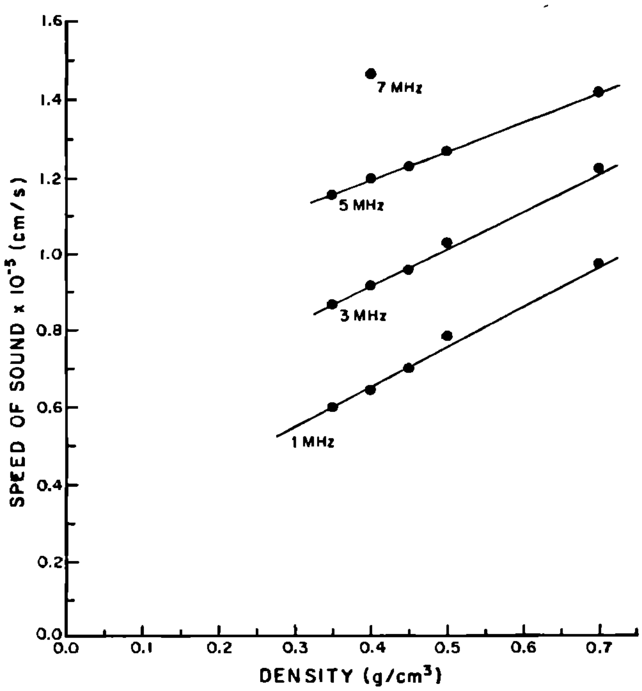

FIG. 3. Speed of sound as a function of lung specimen density (also volume fraction of lung tissue).

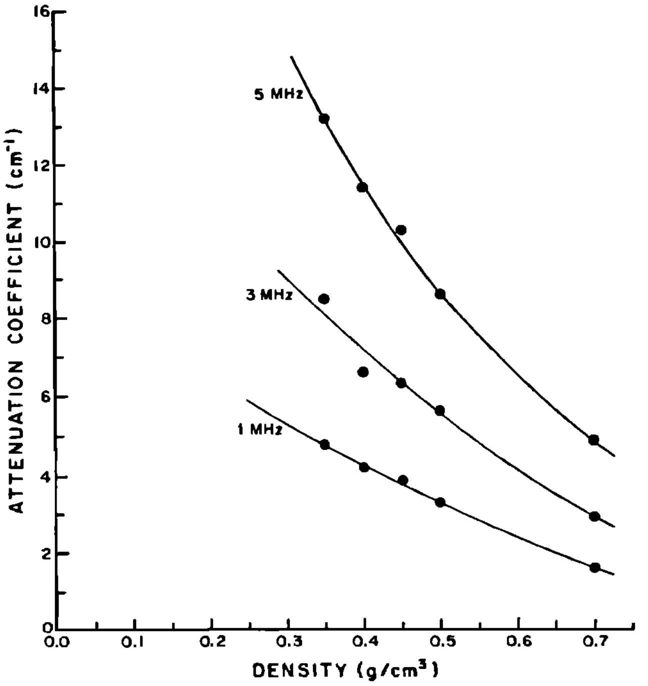

FIG. 4. Ultrasonic attenuation coefficient per unit path length as a function of lung specimen density (also volume fraction of lung tissue).

to the gaseous inclusions radiating spherical sound waves and an increase with frequency due to absorption of acoustic energy in the lung tissue (Dunn and Fry, 1961). However, the dimensions and values of the physical parameters selected for that earlier discussion led to a minimum in the attenuation at about 6 MHz, which was not found (Dunn, 1974).

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Discrimination and response bias for CV syllables differing in voice onset time among children and adults

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A previous experiment demonstrated age-related differences in voice-onset-time (VOT) discrimination when an adaptive procedure was used and trials were concentrated among pairs of stimuli that were discriminated 50% of the time. The major purpose of this experiment was to determine whether the same types of age effects would be replicated for new groups of subjects and a different task in which *all* stimuli were presented equal numbers of times. An eight-item, five-formant consonant–vowel (CV) continuum in which VOT ranged from 0–35 ms was used. The same–different task presented all possible pairs of CV syllables in which VOT differed by 10 and 20 ms and an equal number of catch trials that contained identical CVs. Results showed that children displayed poorer discrimination than adults for CV pairs differing by both time intervals. Adults displayed a somewhat greater tendency to respond "same" than children. The outcomes supported results of the previous study and were interpreted as representing true age-related differences in VOT discrimination.

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INTRODUCTION

Developmental changes in speech perception have been related to stimulus intensity and frequency (Elliott and Katz, 1980; Elliott *et al.*, 1981a,b, 1985). More recently, Elliott *et al.* (1986) demonstrated age-related differences in voice-onset-time (VOT) discrimination, using a same–different, simple adaptive procedure (Levitt, 1971) with trial-by-trial visual feedback/reinforcement and "catch" trials.