TABLE I.

α/β	5.75	λ	0.024
S'	1.044	θ	0.523
S	0.047	P	1.476
a	0.64	Q	0.311
b	1.52	α	0.52
Δr	0.001	β	0.09

current takes place. As Δr and λ are determined experimentally, θ is known, and hence the values of P and Q for the previous values of α and β are known. The value of σ corresponds to that position where a 70 percent fall of the peak value is taken. Hence values of both sides of Eq. (2) are determined. Thus only that value of α is taken for which Eq. (2) holds.

Figure 1 shows the plot of i against r, which is called the reaction curve.

Values of the various constants as well as the values of attenuation coefficient and the reflection coefficient for the above particular case are shown in Table I.

Similar sets of observations were taken in air at different humidities.

RESULTS AND DISCUSSION

Table II gives the measured values of the attenuation in air at 1.46 Mc at different relative humidities.

It will be noticed from Table II that the attenuation at first rises from 0.32 with the increase in humidity, reaches a maximum value $\alpha=0.52$ at 46 percent humidity and again falls to 0.39 at 84 percent humidity.

The classical value of absorption, that is, absorption

TABLE II.

Gas	Humidity	Temp.	α cm^{-1}
Air	Dry	19.6°C	0.32
	33%	21°C	0.40
	46%	20.4°C	0.52
	65%	20°C	0.43
	84%	21.2°C	0.39

caused by viscosity and heat conduction is given by

$$\alpha=\frac{2\pi^2N^2}{v^3\rho}\left(\frac{4}{3}\eta+\frac{\gamma-1}{C_p}\cdot K\right),$$

where v is the velocity of sound waves, ρ the density of the medium, η the coefficient of viscosity, γ ratio of specific heats and K the coefficient of thermal conductivity. For dry air this yields $\alpha=1.45N^2\times10^{-13}$ cm^{-1}, or 0.31 cm^{-1}, at 1.46 Mc, which is in close agreement with the observed experimental value.

The excess of absorption is probably due to the influence of water vapor on the oxygen molecules which decreases the average lifetime of a quantum of vibrational energy of the oxygen molecules.

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The Velocity of Sound through Tissues and the Acoustic Impedance of Tissues

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The velocity of sound through various animal organ tissues and through living human tissues is measured, using an ultrasonic pulse method, at 1.25 and 2.5 Mc. The effect of anisotropy (fiber direction) on velocity is determined with beef muscle. Values obtained with the beam traversing the tissue perpendicularly to the long axis of the muscle bundles do not differ significantly from those found with the energy directed parallel with the muscle fibers.

Velocity through living human tissues, consisting mostly of muscle, is measured by transmitting the ultrasound through various thicknesses of the arm, leg, and thigh.

Specific gravities of the tissues are measured. The characteristic acoustic impedances (ρc values), calculated from the density and velocity data, vary between 1.5×10^5 and 1.7×10^5 g/cm^2/sec. The imaginary component of tissue impedance is calculated and found to be negligible at the frequencies at which these measurements are made.

THE successful application of ultrasonic pulse techniques and the echo-ranging principle to underwater detection and ranging and to the localization of flaws in metals[1] prompted an investigation of the use of an analogous technique for diagnostic purposes in medicine and surgery.[2] The development of ultrasonic

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[1] F. A. Firestone, J. Acous. Soc. Am. **17**, 287 (1946).

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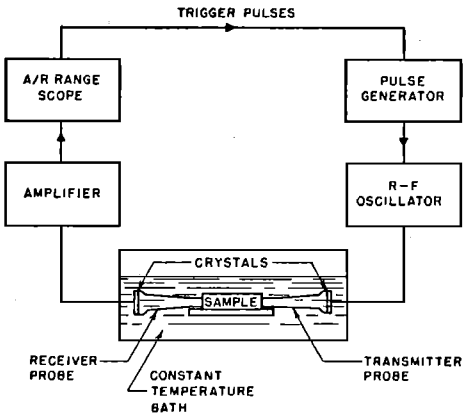

FIG. 1. Schematic diagram of apparatus for measuring velocity of sound through tissues.

instruments and techniques for medical applications requires a knowledge of some of the acoustic propagation characteristics of tissue. Values of the characteristic acoustic impedance of various tissues are needed to calculate reflection coefficients at interfaces such as those between dissimilar tissues, and between foreign bodies and tissue.

Sound velocity and attenuation measurements have been made through certain human and animal tissues. The specific gravity of each tissue was measured and the characteristic acoustic impedance (ρc values) calculated from the velocity and density data. This paper deals with the velocity and acoustic impedance data, some of which have been reported in an earlier paper.[2] The data on the attenuation of sound in tissue will be published in a subsequent paper.

When this work was begun, the literature contained no actual data on the velocity of sound through tissues or acoustic impedances. Pohlman reported measurements of the attenuation of sound in tissue[3] but gave only estimates of velocity and impedance.[4]

EXPERIMENTAL METHOD

For the velocity measurements an ultrasonic pulse technique similar to that described by Pellam and Galt[5] and used by Nolle and Mowry[6] is employed. Instead of a single transducer with a reflector, however, two transducers are used, one to transmit and the other to receive. Each contains an x-cut quartz crystal with the same resonant frequency. The time required for the pulse to travel through various thicknesses of each type of tissue is measured and the velocity is then calculated.

A schematic illustration of the apparatus is given in Fig. 1. The A/R range scope produces trigger pulses at the rate of several hundred per second. Each pulse initiates a new sweep of the oscilloscope and simultaneously triggers the external pulse generator which in turn delivers an r-f pulse to the crystal transducer. The ultrasonic pulse thus generated passes through the sample and is received by the second transducer whose output voltage is amplified and displayed on the oscilloscope screen. The scope is equipped with a delayed sweep that allows the received signal to be placed at the left-hand edge of the oscilloscope trace and the transmission time in "radar yards" to be read from a direct-reading dial. The dial is calibrated with respect to time by an internal crystal that places signal markers on the scope screen at precise intervals. Dial readings are converted to time (in microseconds) to obtain a plot of distance (thickness in centimeters) *vs.* time.

Various types of crystal holders were fashioned in an effort to achieve maximal transfer of the ultrasonic energy into tissue. Best results have been obtained with a hollow plastic probe. The crystal is mounted at one end. The probe is filled with water and the tip, which measures 1.5 cm in diameter, is closed by a Nylon diaphragm 3 mils thick.

The transducer probes are mounted in the lens holders of a standard optical bench. Movable supports are thus provided which maintain the probes in parallel alignment when they are moved in a horizontal plane. For the measurements on animal organ tissues the optical bench is inverted over a constant-temperature water tank. The transducers and the sample under investigation are immersed in the bath and the sample is supported on a movable tray. Good contact between the probes and the tissue sample is secured. Temperatures of the tissue samples are taken before and after each determination. For these particular experiments the temperature of the bath was maintained at 24°C and the tissue temperatures did not vary from this value by more than 1°C.

The choice of frequency for medical purposes involves many considerations. Since the attenuation in tissues is so great at higher frequencies, the frequency must be maintained low enough or the intensity increased to achieve deep penetration. The danger of tissue damage imposes an upper limit of intensity. Therefore, the frequency must be decreased to allow the desired amount of tissue penetration. However, lowering the frequency increases the wave-length with a resultant decrease in resolving power and beam directivity. In diagnostic applications, where resolution is of great importance, the choice of frequency must be a compromise, low enough to offset the increasing attenuation with increase in frequency and high enough to provide sufficient resolution. Previous experiments[2] had shown that the most desirable frequency range for a diagnostic instrument capable of detecting foreign bodies of the order of 0.5 cm diameter or larger at tissue depths up to 15 cm, is 1.0 to 2.5 Mc. Therefore, the velocity measurements reported here were made at frequencies in this range, namely 1.25 and 2.5 Mc.

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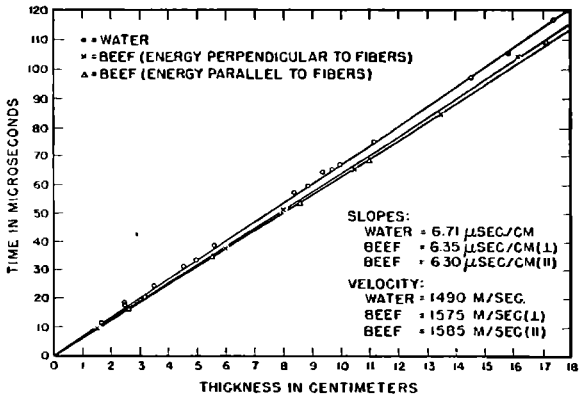

FIG. 2. Transmission time *vs.* thickness for distilled water and for beef. The velocity values calculated from the slopes of the lines are given in the lower right corner.

EXPERIMENTAL PROCEDURE

Zero time was determined by placing the transmitting and receiving probes in direct contact. A dial reading was taken with the leading edge of the received signal adjusted to coincide with the start of the oscilloscope trace. Samples of tissue of various thicknesses were successively interposed between the probes. The receiving probe position was adjustable to accomodate each sample while the transmitting probe remained fixed. For each sample thickness the received signal was adjusted to the start of the scope trace and a reading taken. The difference in readings between zero time and each sample reading was converted to time. A direct reading of the thickness was obtained from the amount of separation of the lens holders.

The transmission times through the various thicknesses of each tissue were measured and plotted against thickness. The velocity was calculated from the reciprocal of the slope of the line best fitting these data, determined by the method of least squares.

The specific gravity of each tissue was determined by means of the copper sulfate method.[7] Using an appropriate temperature factor, these values were converted to density values. The specific gravity of the test solutions varied between 1.000 and 1.100 in steps of 0.001. The specific gravity of representative sample bottles was checked from time to time on a specific gravity balance.

The characteristic acoustic impedance (ρc value) was calculated from the velocity and density data. The product of the velocity and density expresses the real (resistive) component of the impedance. In order to find the order of magnitude of the imaginary component of the impedance, measurements of the attenuation of sound in various tissues were made at 1.25 and 2.5 Mc. The methods used and the complete data will be reported at a later date. Suffice it to say that the attenuation values obtained ranged between 1.0 and 3.0 db/cm. The absorption coefficients calculated from these data agree closely with values reported by Hueter[8] and Hueter and Pohlman[9] who used an optical method. From these absorption values the imaginary component of the impedance has been calculated for tissues and has been found to be negligible. Therefore, in this paper all characteristic acoustic impedances of tissues are expressed as the ρc values.

The absolute accuracy of the velocity measurement is limited by the measurement of sample thickness. With the larger samples of animal tissues the ultrasonic path length in the tissue could be determined to about one part in 200 on the optical bench. The time measurements were accurate to approximately one part in 400 on the radar range scope. The probable error in the final results averaged from measurements on several samples is estimated to be one part in 200.

A check on the method was made by measuring the velocity through distilled water (Fig. 2). A value of 1490 m/sec. ($\pm$0.7 percent) at 25°C was obtained. This agrees within $\pm$0.5 percent with the values given by Bergmann[10] and the *International Critical Tables*,[11] and with a value obtained at the Naval Research Laboratory with an interferometric method.[12]

EXPERIMENTAL RESULTS

The velocity through sections of boneless beef was measured at 1.25 and 2.5 Mc. The blocks consisted almost entirely of muscle and were cut from quarters of refrigerated beef so that the muscle fibers were oriented in one direction. To determine the effect of the fiber direction (anisotropy), measurements were made with the ultrasonic beam directed parallel to the axis of the muscle bundles and then perpendicular to their long axis. The transmission time through the largest dimension was measured first. Each succeeding measurement was made by cutting a few centimeters from the large block; the ultrasonic beam was directed through the same portion of the block as its thickness was decreased.

The data for the beef are given in Fig. 2 in which the values are compared with the data for distilled water. Average values of 1575 and 1585 m/sec. (temperature 24 to 25°C) were obtained for the transverse (perpendicular to fiber direction) and longitudinal (parallel to fiber direction) irradiations, respectively. These values are not significantly different and are within the experimental error of the method. These data are for 2.5 Mc;

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[10] L. Bergmann, *Ultrasonics and their Scientific and Technical Applications* (John Wiley and Sons, Inc., New York, 1938), Hatfield translation.

[11] *International Critical Tables* (McGraw-Hill Book Company, Inc., New York, 1926), Vol. VI, p. 464, National Research Council.

[12] R. J. Urick, unpublished data, Naval Research Laboratory (1948).

data obtained at 1.25 Mc give approximately the same values and are not included.

In a similar fashion measurements were made of the velocity of sound through various organ tissues of dog and hog. Immediately the animal was killed the organs were removed and placed in normal saline solution. Measurements were made as soon as the temperature of the tissue came to equilibrium with room temperature (24 to 25°C). The temperature of the sample was held constant at 24 to 25°C during measurements by means of the large constant-temperature bath.

The data for brain, liver, spleen, and kidney are given in Fig. 3 and the velocity values are given in column 1 of Table II. The velocity value for dog and hog brain are approximately equal.

Average values of velocity through certain living human tissues were also obtained. The ultrasonic beam was directed through various thicknesses of calf muscles, thigh and biceps muscles. All these measurements were made with the beam perpendicular to the long axis of the muscles with care being taken to avoid the long bones. The data are given in Table I.

The data are more variable with this type of tissue than with water or beef. For the most part, this is probably attributable to the fact that variable amounts of fat, muscle, connective tissue, blood vessels, and nerves are traversed by the ultrasonic beam as it passes through the calf, thigh, or arm at different points. However, some of the variability can be attributed to the decreased accuracy of measurement of thickness of the living tissues.

TABLE I. Sound velocity at 2.5 Mc through living human tissues consisting mostly of muscle. The standard deviation for each value is approximately two percent.

Tissue	Transmission time μsec./cm	Velocity m/sec.
Leg (calf)		
G.L.	6.20	1610
R.U.	6.35	1575
T.C.	6.66	1500
J.B.	6.36	1565
Arm (biceps)		
G.L.	6.49	1540
R.U.	6.33	1580
T.C.	6.49	1540
J.B.	6.56	1515
A.L.	6.30	1587
Thigh (quadriceps)		
G.L.	6.40	1563
R.U.	6.51	1536
T.C.	6.64	1506
J.B.	6.65	1504
Mean value for human tissue (mostly muscle)	6.49	1540

A mean value for human tissue consisting principally of muscle was found by plotting all the data from measurements on the arms, legs, and thighs (Fig. 4); the best straight-line fit was determined by the method of least squares. The mean velocity, calculated from the

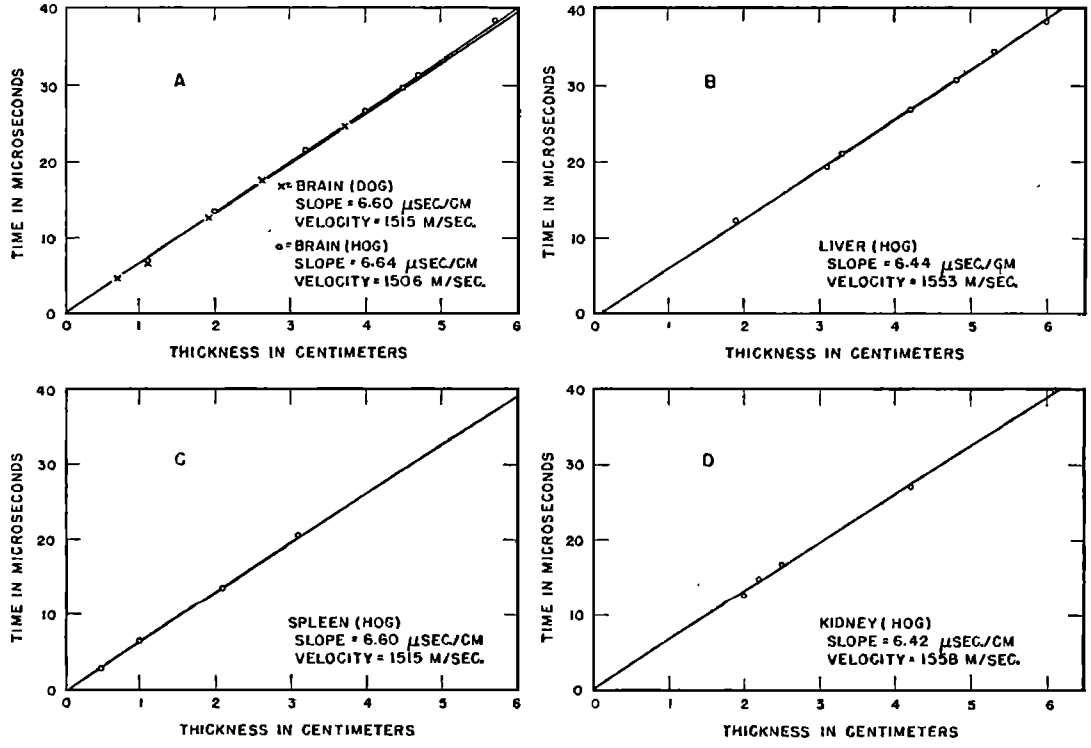

FIG. 3. Transmission time *vs.* thickness for various animal organ tissues.

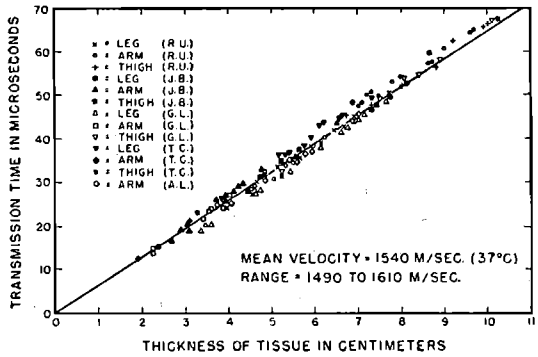

FIG. 4. Transmission time *vs.* thickness for living human tissue consisting principally of muscle. The line is the best straight-line fit of all data taken on living human tissues.

slope of the line, was 1540 m/sec. Temperature for all the human tissue measurements was that of body temperature (37°C).

Ten small pieces, each approximately 1 mm³, were cut from each block of beef and organ tissue. The specific gravity of each was determined and a mean value obtained which was converted to a density value by appropriate temperature corrections. The density values agree closely with those obtained by other investigators.[13,14] Behnke[15] gives 1.06 for the over-all average specific gravity of human tissue. This was used in computing the characteristic acoustic impedance of living human tissue. The values for beef, organs and living tissue, are given in column 2 of Table II. The characteristic acoustic impedance of these tissues are given in column 3 of Table II.

TABLE II. Velocity (c), density (ρ), and acoustic impedance (ρc) of tissue. The standard deviation in values for the animal tissues is ±1 percent.

Tissue	Velocity m/sec.	Density g/cm³	Acoustic impedance g/cm²/sec. ×10⁶
Brain (dog)	1515	1.028	1.56
Brain (hog)	1506	1.026	1.55
Spleen (hog)	1515	1.059	1.60
Liver (hog)	1553	1.064	1.65
Kidney (hog)	1558	1.040	1.62
Beef	1575–1585	1.068	1.68–1.69
Human tissue	1490–1610	1.06	1.58–1.70
(mean value)	1540	1.06	1.63
Water	1490	1.00	1.49

SUMMARY

Sound velocity through tissues has been measured at frequencies of 1.25 and 2.5 Mc, using a pulse method. Values obtained at these frequencies are identical indicating that dispersion does not occur, at least in this range.

The effect of the anisotropy (fiber direction) of the tissue on the sound velocity was investigated with beef muscle. Values obtained with the energy traversing the tissue perpendicularly to the long axis of the muscle bundles do not differ significantly from those found with the irradiation directed parallel with the muscle bundles.

Values for brain, liver, kidney, and spleen of the dog and hog and for beef muscle vary between 1506 and 1585 m/sec. (24 to 25°C).

The velocity through living human tissue has been measured by transmitting the ultrasonic beam through the muscles of the leg, arm, and thigh of different individuals. A range of values between 1490 and 1610 m/sec. with a mean value of 1540 m/sec. is obtained.

The specific gravities of the animal tissues were measured; the values ranging from 1.026 to 1.068.

The characteristic acoustic impedances of these tissues were calculated. Values for impedance vary between 1.5×10^5 and 1.7×10^5 g/cm²/sec. These values, which were calculated from the velocity and density data express only the real component of the impedance. The imaginary component was calculated by utilizing data on the absorption of sound in tissue. In each case, the reactive component of the impedance has been found to be negligible, at the frequencies at which the measurements were made.

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