AN AUTOMATED SYSTEM FOR MEASUREMEMT OF ABSORPTION COEFFICIENTS USING THE TRANSIENT THERMOELECTRIC TECHNIQUE

D. W. Duback, L. A. Frizzell, and W. D. O'Brien, Jr.

Bioacoustics Research Laboratory
University of Illinois
Urbana, Illinois 61801

Abstract

The transient thermoelectric technique provides the only means currently available to determine the absorption coefficient, as opposed to the attenuation coefficient, in tissue. However, the data acquired over the many years this technique has been available has been limited to some extent by cumbersome and time consuming hand processing of recorded responses. Recently, an automated system for near real-time measurement of absorption coefficients in liquids and biological tissue has been developed. The output of a precision amplifier is presented to the analog interface of a mini-computer and digitized information subsequently processed. A smaller mini-computer is used to control gain, filtering, transducer placement and intensity. This allows real-time processing to a degree sufficient to point to possible anomalies during the course of an experiment. Calibration of the various components of the system has been carried out, and materials of known absorption characteristics measured.

Introduction

Fundamental ultrasonic propagation properties measurements, such as the ultrasonic absorption coefficient, are required to adequately assess the interaction of ultrasound and tissue for such studies as ultrasonic dosimetry[1], tissue characterization[2], etc. The transient thermoelectric technique offers a phase insensitive method for determining the ultrasonic absorption coefficient, as opposed to the attenuation coefficient, in various liquids and solids including tissue[3,4,5]. The technique involves the determination of the initial rate of temperature rise, $(\frac{dT}{dt})_o$ in $^oC/s$, in a sample, measured by a small diameter thermocouple imbedded in the sample, due to the application of ultrasound of known intensity. The absorption coefficient α(Np/cm) is then determined from the relation

$$\alpha = \frac{\rho C}{2I_s} \left(\frac{dT}{dt}\right)_o \quad (1)$$

where ρC is the product of the surrounding medium's density and heat capacity per unit mass at constant pressure (joules/cm^3/^{o}C) and I_s is the ultrasonic intensity at the thermocouple junction (W/cm^2). Until recently the measurement of the rate of temperature rise involved time consuming hand analysis. The thermocouple emf was recorded on photosensitive paper by deflection of a light beam via a mirror attached to a galvanometer and $(\frac{dT}{dt})_o$ was determined graphically from such recordings. This has greatly limited the obtaining and subsequent reporting of ultrasonic absorption coefficient data for biological tissues, an observation which is supported by a recent comprehensive compilation of ultrasonic propagation property data which reported very few absorption data[6].

A system has been developed which utilizes a precision amplifier to increase the thermocouple emf to a level sufficient to permit accurate digitization in the analog-to-digital interface of a large scale mini-computer. The digitized signal is then fit to a polynomial of arbitrary degree using the least-squares criterion. The temperature rise and the slope (rate of temperature rise) can be determined from the fit at any time of interest. In addition, a link has been provided to a smaller mini-computer which previously had been interfaced to equipment which provides on-line automated control of transducer positioning, ultrasonic intensity and irradiation time.

Equipment and Procedures

An automated data acquisition system aimed at the determination of ultrasonic absorption coefficient with the transient thermoelectric technique has been assembled consisting of several elements linked to a Perkin Elmer 7/32 computer which provides system control and data analysis (see Fig.1). An interface has been fabricated which couples the 7/32 to a Digital Equipment Corporation PDP-8 minicomputer so that advantage is taken of the existing automated PDP-8 control of the ultrasonic exposure system. The PDP-8 controls transducer position (3 dimensions), irradiation time and ultrasonic intensity. In addition, it can serve as an "intelligent" driver for an oscilloscope so that temperature vs. time from a given measurement can be quickly displayed together with either theoretical curves or previous results for comparison. The entire memory (8K x 12 bits) of the PDP-8, which is located 30 meters from the 7/32, can be loaded in less than two seconds, leaving the 7/32, which is capable of time shared operation, free for data acquistion and computation for this and other programs.

A thermocouple amplifier shown in Fig. 2, is used to increase the output voltage from the

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thermocouple (typically, 40-60 μV or less - thermoelectric power is 40-60 μV/^{o}C and temperature change is typically 1^{o}C or less) to a level compatible with the input range (0-10.24V) of the analog to digital converter.

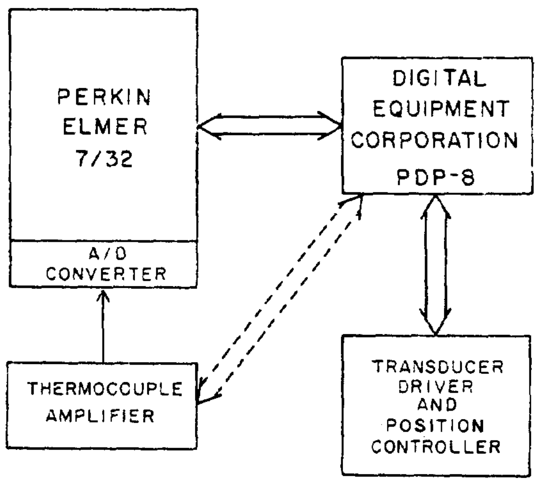

Figure 1. Block Diagram of Automated Data Acquisition System.

The thermocouple amplifier consists of two stages and an active filter to limit noise. (see Fig. 2) The preamp, an Analog Devices Model 606M modular instrumentation amplifier, is configured in this unit with a fixed voltage gain of 10^4 (80dB). The output of the preamp enters the amplifier, an Analog Devices 522B integrated circuit instrumentation amplifier, which has manually selectable voltage gains of 2, 5, 10 and 20 (6, 14, 20 and 26dB, respectively) that are chosen to obtain near full scale voltages at the analog to digital converter. The temperature stability of the preamp and amplifier of the thermocouple amplifier is approximately 30 parts per million per degree Celsius. The active filter has a four-pole, lowpass, Butterworth response with manually selectable corner frequencies of 2, 5, 7.5, 10, 20, 40 and 100 Hz, which allows for the use of the lowest corner frequency which will retain the signal harmonics, and provide for the maximal noise rejection. The high impedence ($10^5 \Omega$ in parallel with 3pF) differential input coupled with the lowpass filter limits noise to the equivalent of 1 microvolt peak-to-peak at the thermocouple amplifier input. Both the second stage of amplification and the filter are being interfaced to provide program control of gain and filter corner frequency.

The analog to digital converter samples at a rate slightly above 20 kHz and has an input range of 0-10.24 volts divided into 1024 levels so that the signal is digitized to 10 millivolt steps. If chromel-constantan thermocouples are used with the maximum gain of the thermocouple amplifier, then one A/D step corresponds to less than 1 millidegree Celsius; however, noise in the amplifier will typically limit resolution to about 15 millidegrees Celsius. On the other hand, at the lowest amplifier gain the system can measure a maximum temperature change on the order of 8.5^{o}C.

The procedure for data acquisition and analysis is implemented by a program which provides control of (1) the ultrasonic intensity, and irradiation time via the PDP-8; (2) the digitization of the thermocouple emf (temperature data) during the ultrasound pulse via the thermocouple amplifier; (3) the fit to a selectable number of the temperature-time data points with a polynomial of desired degree using the least squares criterion; and (4) the calculation of the absorption coefficient utilizing the appropriate fit. The control of ultrasound parameters and data acquisition systems have been described above. A subroutine takes the specified number of values (temperature data at a selected time interval) from among the greater than 20,000 data points stored in the 7/32 and returns an array of constants which specify a set of orthogonal "best fit" polynomials up to the degree, n, requested[7] in the form

$$T = A_o + A_1 t + A_2 t^2 + \ldots + A_n t^n \qquad (2)$$

where T is temperature, t is time and the A_i are polynomial coefficients. The A_n coefficients are not given directly but instead the above mentioned array is used to evaluate a set of recursive functions which, because of the limited precision of machine arithmetic, yield a better fit than would be possible by a direct determination

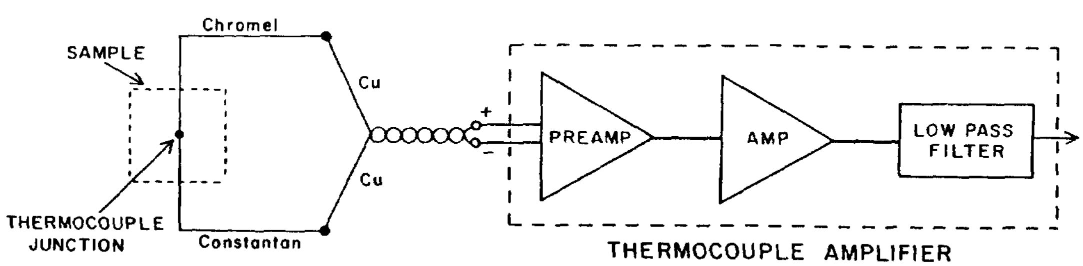

Figure 2. Sketch of Thermocouple Configuration and Block Diagram of Thermocouple Amplifier.

TABLE I

Comparison of Absorption Coefficients (Np/cm) Obtained with the Two Systems of Measurement at 1MHz and 37°C.

	Previous System		Automated System		Difference
Material	Number of Measurements	Mean + Standard Deviation	Number of Measurements	Mean + Standard Deviation	between Means
Dow Corning 710 Silicone Oil	6	0.0525 ± 0.0087	19	0.0499 ± 0.0042	5%
Fresh Beef Liver	8	0.0234 ± 0.0020	19	0.0230 ± 0.0033	1.7%

of the A_n coefficients. In addition, the same array is used to determine the derivatives of the fitted function, using another recursive definition. The value of the fitted function and all its derivatives, for a desired value of the independent variable (time), are returned by a routine which operates only on an array of size 3n, where n is the degree of the fit.

The value of the slope of the temperature-time curve at 0.5 seconds (given by the fit) is used for the value of $(\frac{dT}{dt})_o$ of Equation 1. This choice of time is a compromise which minimizes the errors arising from viscous heating due to relative motion between the thermocouple wire and the surrounding medium and heat diffusion from the ultrasonic beam[5]. The viscous heating is transient and contributes little to the temperature rise after 0.5 seconds, whereas the heat diffusion increasingly affects the temperature rise with time.

Results and Discussion

Comparisons of measured absorption coefficients at 1MHz and 37°C have been made between the system described above and the previous technique involving photo recording and hand analysis of emf outputs (see Table I). Two rather different materials have been measured, and the results show excellent agreement between the two systems of measurement. In the Dow Corning 710 silicone oil the means of a series of measurements with each system agreed to 5%. The results with both systems were high because the viscous heating due to relative motion between the wire and oil is very large for this viscous oil[5] and because streaming can occur in the liquid. The means of results of measurements on fresh beef liver with each system agree to 1.7%, and are the same as reported for this tissue by Goss et al[8].

Preliminary evaluation indicates little difference in the measurements between fits with second and third degree polynomials (see Table II). On the other hand, the fit and results obtained for the absorption coefficient are seriously affected if the number of points used for the fit is decreased much below 100-200 samples per second. More work is being done to determine the appropriate number of points for optimum results and the effect of the filter corner frequency.

In addition to the automation provided to absorption measurements by the new system, a number of other measurement procedures are being implemented. Among these are systems to determine free field variables in 3 spatial dimensions using thermocouple and hydrophone probes and to determine *in vivo* energy distribution within an experimental animal using the thermocouple probe.

TABLE II

Comparison of Results with Various Fit Parameters

Sample	Measurement Number	Degree of Polynomial	Number of Points Used	Absorption Coefficient (Np/cm)
Beef Liver	1	3	200	0.0233
		2	200	0.0233
		3	100	0.0231
		2	100	0.0231
		3	50	0.0214
		2	50	0.0214
Beef Liver	2	3	200	0.0257
		2	200	0.0257
		3	100	0.0258
		3	50	0.0255
Dow Corning 710 Silicone Oil	1	5	100	0.0488
		3	200	0.0488
		3	100	0.0488
		2	100	0.0488
		3	50	0.0486
		3	25	0.0423

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References

1. W. D. O'Brien, Jr., "Ultrasonic Dosimetry," in Ultrasound: Its Application in Medicine and Biology, ed F. J. Fry, pp 343-391, Elsevier Scientific Pub. Co., NY, (1978).

2. R. L. Johnston, S. A. Goss, V. Maynard, J. K. Brady, L. A. Frizzell, W. D. O'Brien, Jr. and F. Dunn, "Elements of Tissue Characterization. Part I. Ultrasonic Propagation Properties," in Ultrasonic Tissue Characterization II, NBS Special Publication 525, pp 19-27, U.S. Government Printing Office, Washington, D.C.,(1979).

3. W. J. Fry, and R. B. Fry,"Determination of Absolute Sound Levels and Acoustic Absorption Coefficients by Thermocouple Probes--Theory," J. Acoust. Soc. Am. 26, 294-310 (1954).

4. W. J. Fry and R. B. Fry, "Determination of Absolute Sound Levels and Acoustic Absorption Coefficients by Thermocouple Probes--Experiment," J.Acoust. Soc. Am. 26, 311-317 (1954).

5. S. A. Goss, J. W. Cobb, and L. A. Frizzell, "Effect of Beam Width and Thermocouple Size on the Measurement of Ultrasonic Absorption Using the Thermoelectric Technique," 1977 Ultrasonics Symposium Proceedings, IEEE Cat. No. 77CH 1264 -1SU, 206-211 (1977).

6. S. A. Goss, R. L. Johnston, and F. Dunn, "Comprehensive Compilation of Empirical Ultrasonic Properties of Mammalian Tissues," J. Acoust. Soc. Am. 64, 423-457 (1978).

7. L. F. Shampine and R. C. Allen, Jr., Numerical Computing: An Introduction, W. B. Saunders Co., Philadelphia, pp 43-51 and 230-234 (1973).

8. S. A. Goss, L. A. Frizzell, and F. Dunn, "Ultrasonic Absorption and Attenuation in Mammalian Tissues," Ultrasound Med. Biol. (in press) .