SESSION 4:5 ULTRASONIC FIELD MEASUREMENT USING THE SUSPENDED BALL RADIOMETER AND THERMOCOUPLE PROBE

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INTRODUCTION

Precise determination of the acoustic intensity and the intensity distribution in sound fields used to irradiate body organs and tissues is necessary for quantitative studies investigating conditions for eliciting interactive responses and elucidating the basic physical mechanisms involved. Such determinations permit accurate correlations to be made between effects observed at specific sites and the local acoustic conditions. Additionally, quantitative determination of the acoustic propagation parameters of tissue structures are obtained. Implementation of this quantitative characterization of sound field conditions, with reference to various tissues and body organs, and the derivation of acoustic parameters has involved the development of several specific instruments and techniques which are considerably different than those employed for diathermy and diagnostic regimes.

SUSPENDED BALL RADIOMETER

Absolute levels of sound intensity in plane wave fields are determined by a radiation force method which utilizes a small stainless steel sphere (from 1/2 to 1 wavelength in diameter) suspended by a bifilar arrangement in the sound field (*1*, *2*). The radiation force F_r deflects the sphere and the magnitude of this deflection Δ_r (measured by a cathetometer) permits accurate evaluation of the force exerted by the radiation field. For small angular deflections of the suspension from the vertical,

$$F_r = \frac{\Delta_r (m_s - m) g}{L} \qquad (1)$$

where L is the length of the suspension, m_s is the mass of the sphere, m is the mass of the displaced liquid, and g is the gravitational constant. In practice the sound level is varied, for example by changing the voltage across the transducer, and the deflection of the sphere is plotted as a function of the square of the driving voltage, since the latter is proportional to the intensity. The acoustic intensity is expressed in terms of the radiation force as,

$F_r = \frac{I \pi a^2 y}{c}$

$$I = \frac{F_r c}{\pi a^2 y} \qquad (2)$$

where a is the radius of a sphere, c is the speed of sound in the fluid imbedding medium and y is a factor which depends upon the wave number, the densities of the sphere and fluid, and the boundary condition at the sphere-fluid interface, viz., "rigid" or "soft" sphere (*1*, *2*), or elastic spheres (*3*), though there is not universal agreement on computations of the latter (*4*).

This radiation force method has been employed for calibrating appropriate ultrasonic probes over the frequency range of 500 kHz to 10 MHz.

THERMOCOUPLE PROBE

For the determination of detailed configurations of sound fields (either focused or unfocused) the transient thermoelectric method is used (*2*). The thermoelectric probe has some distinct advantages over piezoelectric probes in that it yields directly values of the particle velocity amplitude and pressure amplitude in acoustic fields of any configuration, including both free and standing wave fields. For the traveling plane wave field, the probe yields the acoustic intensity. A most important aspect of this probe is the precision with which results can be obtained: it is possible to obtain values for the pressure amplitude and particle velocity amplitude with an uncertainty of not more than ± 2 percent. Indeed, one can study the fine structure of an ultrasonic field in a liquid in the megahertz frequency range with this instrument.

The following is a brief description of the probe construction (5). A thermocouple junction is imbedded in a liquid sound absorbing medium. The absorbing medium is separated from the medium in which the sound field is to be examined by thin polyethylene sheets (0.1 mm thickness). The thermocouple wire and the polyethylene windows are supported by a stainless steel, cylindrical frame which has an inner diameter (or aperature) large enough to admit the passage of the sound beam through it without producing disturbance to the beam.

The acoustic absorbing material is chosen to have a density and acoustic velocity which closely match those of the liquid in which the sound field is to be examined. For investigations of ultrasonic fields in water and various salt solutions, castor oil and some silicone fluids are suitable imbedding materials since they have the proper combinations of a relatively high acoustic absorption coefficient and a density and sound velocity which closely match those of dilute salt solutions. The percentage of incident sound energy reflected at the interfaces is, therefore, negligibly small. In the neighborhood of the thermocouple junction, the thermocouple wires are etched down to 0.013 mm diameter. For a frequency of 1 MHz in water, the wavelength is approximately 1.5 mm, that is, the thermocouple junction is of the order of one-one hundredth of a wavelength.

The output of the probe, that is, the thermoelectric emf produced by the temperature change at the thermocouple junction resulting from exposure to an acoustic disturbance, can be observed by a number of different methods. For example, the probe may drive a low noise amplifier which is in turn connected to an oscilloscope whose beam deflection is recorded photographically. Alternatively, the probe may drive a magnetic oscillograph whose deflection is also recorded photographically.

The thermocouple probe functions in the following manner. The sound source is excited to produce a single, square-wave acoustic pulse of 1-second duration. A relatively rapid rise occurs just after initiation of the acoustic disturbance, which is followed by an "almost linear" rise for the remainder of the pulse duration. After cessation of the sound, a rapid fall in temperature occurs followed by a slow return of the temperature to its value preceding the disturbance (see fig. 1). The initial, rapid increase in temperature results from the conversion of acoustic energy into heat by the viscous forces acting between the wire and the fluid medium (6). This phase of the temperature sequence approaches equilibrium rapidly. The second phase of the temperature sequence, the "linear" part, is caused by absorption of sound in the body of the fluid medium. The closeness of approach of this phase to linearity during irradiation is dependent upon the acoustic amplitude, the form of the variation of the acoustic absorption coefficients of the fluid and the wires, the duration of the acoustic disturbance and the acoustic field distribution. With a suitably designed probe this second phase enables one to compute the absolute sound intensity for the plane traveling wave case if the absorption coefficient of the imbedding medium is known. If the absolute sound intensity is known the acoustic absorption coefficient can be calculated. The relatively rapid decrease in temperature immediately following termination of the period of radiation results from the removal of the viscous force mechanism which contributed a heat source confined to the immediate neighborhood of the wire. The subsequent slow phase of the decline in temperature is a consequence of the cooling of the imbedding medium, previously heated by absorption in the body of the medium.

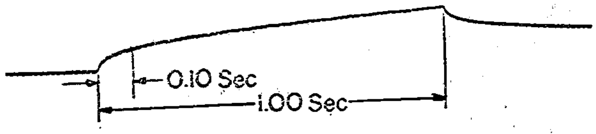

Figure 1. Photographic recording of deflection of oscilloscope beam (or oscillograph) resulting from the thermoelectric emf produced by the temperature change experienced by the thermocouple junction due to an incident acoustic pulse.

The temperature rise of the thermocouple junction, resulting from absorption of sound in the body of the imbedding medium, is, of course, independent of the direction of the wire. However, the temperature rise resulting from the action of the viscous forces between wire and fluid medium is a function of the angle between the direction of propagation of the sound and the direction of the wire (6).

The relation basic to the design and operation of this probe for plane traveling wave fields is

$$\mu I = \rho C \left(\frac{dT}{dt}\right)_0 \qquad (3)$$

where μ designates the acoustic intensity absorption coefficient of the imbedding medium per unit path length, I represents the acoustic intensity, the product ρC designates the heat capacity of the imbedding fluid per unit volume, and $(dT/dt)_o$ indicates that fraction of the time rate of change of the temperature of the imbedding medium resulting from absorption in the body of the medium at the time of initiation of an acoustic disturbance of rectangular envelope. If the thermocouple wire diameter in the neighborhood of the junction is of the order of 0.025 mm or less and if the beam diameter at half intensity is of the order of a few millimeters or more, than it is permissible to identify the quantity $(dT/dt)_o$ of Eq. (3) with the initial time rate of change of the temperature caused by absorption in the body medium.

The probe cannot be used as an absolute measuring device in accordance with Eq. (3) if sufficiently accurate data for the absorption coefficient of the imbedding material are not available. Under such conditions, the radiation force method is adopted for calibrating the probe. The calibration takes place in a free plane wave field and the radiation force detector is the small steel sphere suspended in the sound field discussed above. The undirectional force due to the measured deflection of the sphere is used to compute the acoustic intensity at the position of the sphere, as well as the pressure amplitude and particle velocity amplitude. (This arrangement constitutes an absolute determination of the acoustic intensity.) The thermocouple probe is then placed in the sound field and the thermoelectric response to a 1-second pulse is observed. The deflection amplitudes of the initial response, the linear response and the total response, as observed by the oscillograph camera, can now be related to the previously determined values of the particle velocity amplitude, pressure amplitude and intensity, respectively. This is accomplished, for example, for the intensity by specifying the intensity in watts per square centimeter corresponding to a specified open circuit voltage at the probe terminals.

The second phase (or linear portion) of the thermocouple probe response, deviates from linearity as the acoustic amplitude increases. This is a consequence of thermal conduction, variation of the absorption coefficient of the imbedding medium with temperature, and acoustic streaming. Therefore, in practice, it is convenient to calibrate the overall electro-acoustical system against the thermoelectric probe at relatively low sound levels and then extrapolate to higher sound levels. This requires that the electro-acoustical system possess a component which indicates relative sound levels.

An analysis of the procedure used to determine the sensitivity of the thermocouple probe, based on the method of least squares, yields an uncertainty of 2 percent. A similar analysis of the calibration of an unknown free plane wave sound field yields an uncertainty of 1 percent and thus the overall uncertainty in determining the acoustic intensity for this field is 3 percent. The above uncertainties are the calculated standard deviations (determined by the method of least squares) of the observed points from the straight line of best fit.

Advantages of the thermoelectric probe are: (1) the probe yeilds directly values of the particle velocity amplitude and the pressure amplitude; (2) it is small in size; (3) it is highly stable; (4) it is a primary standard for determining absolute sound levels; (5) it is insensitive to stray rf fields; and (6) it has a low input electrical impedance. The disadvantages are: (1) the sensitivity is low when the temperature sensitive element is a thermocouple constructed from metals commercially available in wire form and (2) it cannot be used for determining wave shapes.

From Eq. (3) it is readily seen that if the acoustic intensity absorption coefficient of the imbedding medium is known accurately enough, the thermocouple probe system constitutes an absolute measurement method for the plane traveling wave case. Conversely, if the sound intensity is known at a thermocouple junction of sufficiently small size, imbedded in an absorbing medium, then the acoustic intensity absorption coefficient of the material can be calculated. The method therefore makes possible the determination of absorption coefficients of minute quantities of material. Hence, the thermocouple method permits the determination of sound field configurations in deep tissue sites and additionally it permits the direct experimental determination of acoustic absorption properties on a restricted regional basis. If the thermocouple wires are sufficiently small in diameter, the initial time rate of change of temperature from the second phase is related to the acoustic intensity absorption coefficient per unit length by Eq. (3) as

$$\mu = (\rho C_\rho K/I)\ (dT/dt)_o, \qquad (4)$$

where I is the known acoustic intensity and K is the mechanical equivalent of heat.

The method has been used extensively to determine the absorption coefficient in tissue as a function of temperature. The young mouse, 24 hours after birth, is a convenient preparation for such a study for a number of reasons, one of the more important being that it is an essentially poikilothermic animal[1] which readily allows temperature cycles to as low as 0° C. to be carried out without producing permanent changes in the animal (7). A remarkable result of this study was the finding that the ultrasonic absorption coefficient in mammalian central nervous system tissue has a positive temperature coefficient.

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[1] Poikilothermy, a condition in which the temperature of the animal body fluctuates according to that of its surroundings. From Gk. Poecil: many coloured. Ed.