modality, especially for tissues with varying microwave absorption and thermal expansion properties. The absorption of microwaves in biological materials is governed by dielectric constants, conductivities, and geometrical variables. Further, the acoustic and thermal properties of biological materials depend on the water content of tissues. The spectrum of the microwave-induced thermoelastic pressure waves will be different when the same microwave energy is absorbed by different tissues. Thus, microwave thermoelastic pressure waves appear to possess some unique features that may allow it to become a useful imaging modality for noninvasive imaging of tissue characteristics [11], [16].

II. The Hardware System

Phantom Models

The electromagnetic properties of biological materials in the microwave range have been extensively studied [12]–[15]. The behavior of biological materials in this frequency range varies according to water and electrolyte contents of tissue [15]; therefore, biological materials can be classified into different categories based on their percentage of water content.

The phantom model consisted of a water tank within which were placed test tubes of varying sizes filled with solutions of different contents. Specifically, the four sizes of test tubes were 1.2, 1.5, 1.6, and 2.0 cm in diameter. These test tubes were filled with either water, glycerol, or glycol to simulate body fluid, muscle, or fat. The test tubes were held in stable positions by the use of semicircular grooves machined on a plastic holder. This holder was designed in such a way that the separation between two test tubes was maintained in fixed increments, namely, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 cm.

Microwave Equipment

The pulsed microwave energy (20 kW peak power at 2.45 GHz) was generated by an Epsco PH40k generator under the control of an external pulse source. The pulse controller included a ramp generator (Tektronix RG501), a pulse generator (Tektronix PG505), and a function generator (Tektronix FG501). With this combination, the pulse width (0.1–25 μs) and duty cycle (0.5–10^{-8}) could be varied over a wider range than using the PG505 or PH40k alone. A low duty cycle, 2×10^{-7} (2 μs pulse at interval of 10 s), was used in this study. With this duty cycle, microwave pulses were separated sufficiently in time, so that each induced acoustic signal would not overlap with previous ones. The influence of reflecting water tank boundaries was eliminated by appropriate time gating to simplify the acoustic signal analysis.

Microwave energy was applied to the simulated tissue models through a rectangular waveguide (7.2×3.4 cm). A quarter-wavelength dielectric plate was used to maintain the required impedance matching condition between air and water. A double stub tuner was employed to further reduce the reflection coefficient. A thin absorbing layer of foam plate was attached to the output flange to reduce the multipath effects due to the reflection of excited acoustic waves.

Transducer and Analog Circuitry

A spherical hydrophone (0.7 cm in diameter) was used in all of the experiments. The barium titanate piezoelectric element of the transducer has a response of 81.3 Pa/mV for the pertinent range of frequencies (80–200 kHz). The hydrophone was placed outside the radiating region of the waveguide and perpendicularly to the propagation direction of microwaves (Fig. 1). Its output signal was amplified and displayed on an oscilloscope (Tektronix 5111A) and photographed on Polaroid film. The signal was conditioned using a bandpass filter with cutoff frequencies at 10 kHz and 1 MHz and a high-gain amplifier (Tektronix AM502). The sample/hold (Datel SHM-2) and A/D converter were used to acquire the data for further processing by a computer.

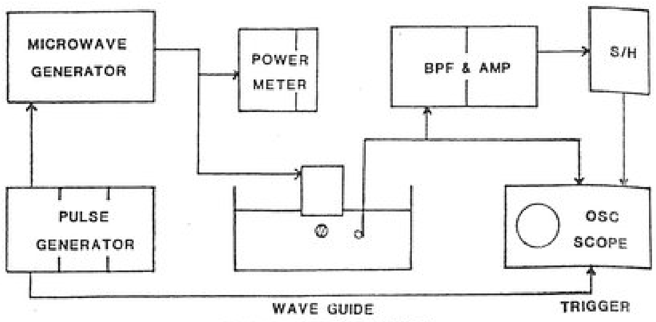

Fig. 1. Schematic representation of the power source, phantom model, and recording configuration.

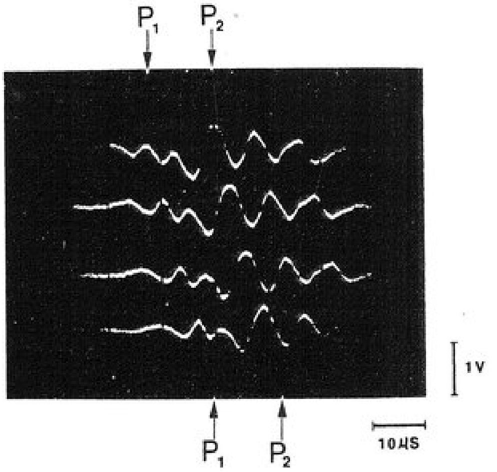

Fig. 2. Successive hydrophone responses after shifting transducer to the right 0.5 cm. P_1 and P_2 correspond to the two sides of a test tube filled with glycol.

III. Software

Measurements were made of the acoustic responses from a single tube and from two test tubes separated by a known distance. Typical hydrophone responses from a single tube filled with glycol are shown in Fig. 2. Note the characteristic dependence of certain wave peaks on the edges of the test tubes and the magnitude of variation with space and/or time. Based on these wave characteristics, a pattern extraction algorithm was developed to analyze the wave. Approximately 60 μs of digitized waves from each experiment were keyed into a computer (IBM 3081D) and stored as a data file. The feature analysis programs were written in Fortran [16].

The technique used to analyze the data is illustrated in Fig. 3, where the basic peak detector is shown. The acoustic wave voltage is denoted by $V(n)$, whose available samples are $V(1)$, $V(2) \cdots$ [see part 1 of Fig. 3(b)]. SLOP(n) and SLOP$(n+1)$ represent the slopes between neighboring points, as defined by

$$\mathrm{SLOP}(n) = V(n) - V(n-1) \tag{1}$$

$$\mathrm{SLOP}(n+1) = V(n+1) - V(n). \tag{2}$$

The peaks $P(n)$ are extracted using the following conditions.

1) If the signs of SLOP(n) and SLOP$(n+1)$ are different, then $P(n) = V(n)$.

2) If SLOP$(n+m) = 0$ for some m, $m = 1, 2, 3 \cdots, M$ and the signs between SLOP(n) and SLOP$(n+m+1)$ are different, then $P(n) = V(n + m/2)$.

The positive peaks are raised by a constant equaling the absolute value of the minimum peak. Part 2 of Fig. 3(b) shows the peaks