Ultrasonic Visualization of Soft-Tissue Structure, Based on Gradients in Absorption Characteristics

WILLIAM J. FRY AND FRANCIS J. FRY

Interscience Research Institute, Champaign, Illinois
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Experimental support is presented for the feasibility of detecting structural features of soft tissue by a method previously proposed and treated analytically by one of the authors. The method is based on locating regions in which the tissue is characterized by gradients in the value of the ultrasonic absorption coefficient. Two beams of sound are employed—one to induce transient localized nondamaging temperature changes in tissue volumes, thus resulting in gradients of acoustic impedance at sites where ultrasonic absorption-coefficient differences exist, and a second beam to detect and localize the sites of such gradients.

PRESENTLY employed ultrasonic instruments designed for detecting, and in some cases visualizing, features of soft-tissue structure reveal those structural interfaces at which the characteristic acoustic impedance undergoes changes large enough to result in the reflection of detectable acoustic energy to the receiving transducer. Pioneering work in establishing and developing this method was accomplished by Wild and collaborators[1] and by Howry and associates.[2] It is now receiving considerable attention throughout the world, and many groups of investigators are applying it to the study and routine examination of soft tissue structures *in vivo*.[3] Since the early work, much progress has been made, including the demonstration of feasible areas of clinical application, the evolution of improved scanning methods, the development of practical presentation techniques, and the design of more-elaborate transducers. However, there has been no development based on new acoustic-detection principles during this period of time.

Approximately two years ago, one of the authors (WJF) formulated a basically new way to employ ultrasonic energy to disclose structural features of soft tissue.[3,4] This method is based on the detection of differences in the value of the acoustic absorption coefficient that occur, in general, at tissue interfaces rather than on differences in acoustic impedance. The method promises to furnish structural information that cannot be detected at all and other information that can be obtained only with considerable ambiguity by the older method employed up to the present time. This conclusion is based partially on the observation that the magnitude of the absorption coefficient is generally more sensitive to differences in structure than is the value of the speed of sound. This viewpoint can also be supported by an example of considerable importance to basic and applied neurology. Specifically, the ultrasonic-visualization method based on obtaining detectable reflections from tissue interfaces at which impedance changes occur does not furnish useful information concerning the location of the major anatomic structures of the brain—that is, position information on the interfaces between the gray- and white-matter masses. However, since dense white matter exhibits an ultrasonic absorption-coefficient value approximately one and one-half times that characteristic of gray matter (at least at frequencies near 1 mc/sec at which measurements have been made[5]), it is feasible to consider locating the major anatomic structures of the

[1] J. J. Wild and J. M. Reid, in *Ultrasound in Biology and Medicine*, edited by E. Kelly (American Institute of Biological Sciences, Washington, 1957). This paper contains references to the early work of these investigators.

[2] D. H. Howry, in *Ultrasound in Biology and Medicine*, edited by E. Kelly (American Institute of Biological Sciences, Washington, 1957). This paper contains references to the early work of this investigator.

[3] See, for example, W. J. Fry, Proc. IRE **50**, 1393 (1962) for a partial list of references to the literature.

[4] This method was also presented and discussed at the last Symposium on Ultrasound in Biology and Medicine, held in Urbana, Illinois, June 1962.

[5] J. W. Barnard, W. J. Fry, F. J. Fry, and R. F. Krumins, J. Comp. Neurol. **103**, 459 (1955).

brain by the method based on detecting gradients in the absorption characteristics.

The basic principle underlying the method of detecting structural features of tissue by determining the loci of gradients in the value of the absorption coefficient is illustrated in Fig. 1. Two pulsed, synchronized, scanning beams of focused ultrasound are employed. The one, designated the inducer, is of relatively long pulse duration and the other, designated the examiner, consists of a series of pulses, each very short as compared to the first. The inducer and examiner transducers operate, in general, at different frequencies. The energy content of a single pulse of the inducer beam is chosen so that, in the relatively small volume of tissue at the focus, a transient increase in temperature of several degrees is produced by conversion of a fraction of the acoustic energy into heat. The duration of the inducer pulse is chosen so that heat conduction from the region is relatively unimportant during its temporal extent. In boundary regions between structures characterized by different values of the ultrasonic absorption coefficient, transient gradients of temperature are thus produced when the focus is placed in such locations. Since the speed of sound is temperature-dependent, corresponding temporary gradients in the sound speed (and, consequently, in the acoustic impedance) are induced. The acoustic energy of the examining beam is then partially reflected from these regions. Analytic treatment of the method and calculations based on measured values of ultrasonic absorption coefficients for brain indicate that practically useful acoustic echoes can be obtained for temperature increases that do not result in tissue damage.

It should be noted that this new method is particularly appropriate to the centering of attention on a chosen small volume of tissue to realize enhancement of echoes from the region, as compared to those from surrounding or embedding structure. This effect is achieved since the temperature gradients that induce the acoustic-impedance differences at boundaries are much greater in magnitude in the region of the focus of the inducing beam than outside this region.

Fig. 1. Schematic diagram of ultrasonic method of visualizing soft-tissue structure (e.g., boundaries between gray- and white-matter masses of the brain), based on locating regions characterized by gradients in the value of the acoustic absorption coefficient.
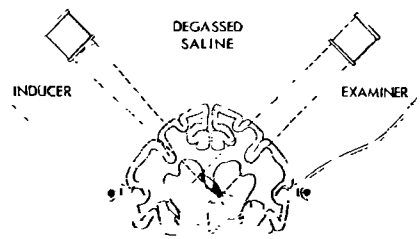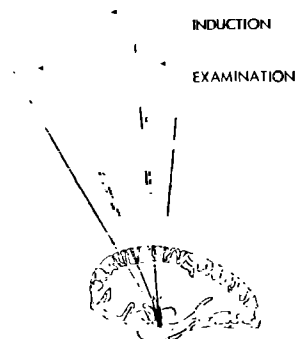

Fig. 2. Configuration of equipment for demonstrating ultrasonic detection of ultrasonically induced acoustic-impedance gradients in brain.

The purpose of this note is to place on record in the technical literature some observations that *experimentally* demonstrate the feasibility of detecting the presence of transiently induced nonlesion-producing temperature gradients in tissue (brain) by ultrasound, in accordance with the principle of the method described here.[3] The ultrasonic detection of the presence of ultrasonically induced lesions in brain immediately after production is also demonstrated. The *existence* of the analytically predicted effects can be demonstrated with a relatively simple arrangement of apparatus, such as that illustrated in Fig. 2. However, it should be emphasized that the development of a system to supply *quantitatively useful* information is dependent on an extensive development program. With the configuration of transducers illustrated in the figure—beam axes at right angles—it is readily possible to obtain ultrasonic echoes from the site of the focus of the high-intensity beam in the tissue. Of course, the arrangement shown is not the best for the localization of tissue interfaces, since with this orientation echoes can be obtained from homogeneous tissue from the positions of the relatively steep thermal gradients that occur in directions radial to the axis of the focused high-intensity beam. In practice, a coaxial design or an arrangement in which the axes of the inducer and examiner deviate from parallelism by only a few degrees represents a much better choice, because the shape of the focal region of the inducer beam can be designed so that the temperature gradient in homogeneous tissue in the direction of sound propagation is so small that a negligible fraction of the acoustic energy of the examining pulses is reflected as compared to that which is reflected at tissue interfaces characterized by changes in the value of the absorption coefficient.

The configuration shown schematically in Fig. 2—cat brain with portion of skull bone removed, pan supporting degassed saline as transmitting medium, transducer operating at a frequency of 1.0 mc/sec and a pulse duration of one second to induce a temperature gradient in a deep brain site, and a standard commerical pulse-reflection unit (unfocused beam, operating frequency 5 mc/sec)—was employed to obtain the following results. It should be noted that the axes of the inducing
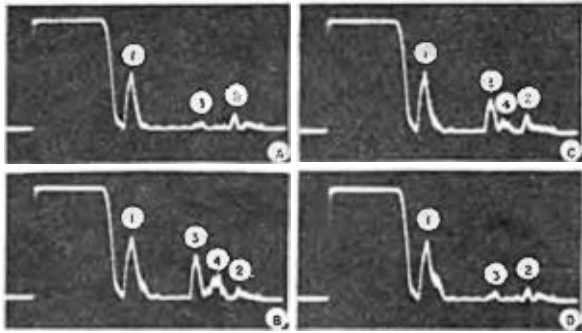
Fig. 3. Echo pattern received by examining transducer, (a) preceding, (b) 2 sec following, (c) 5–6 sec following, and (d) 1½ min after the induction of a transient-temperature distribution deep in cat brain by a 1.0-sec pulse of focused ultrasound.

and examining beams were oriented approximately mutually perpendicular and individually at about 45° with respect to the horizontal plane. Figure 3(a) shows the echo pattern received in the absence of an induced temperature gradient—reflected energy is received from the brain surface at the port of entry (1) of the sound and from the surface diametrically opposite the port of entry (2) where the brain abuts intact cranial bone. A single intervening echo (3), which was just detectable under the operating conditions employed, also appears
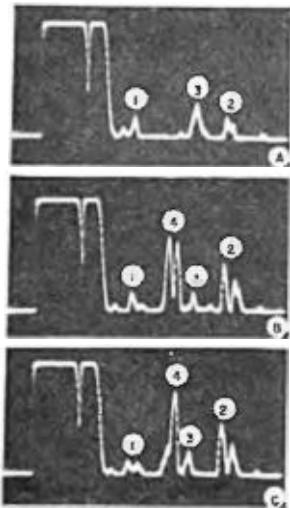

Fig. 4. Echo pattern received by examining transducer, (a) preceding, (b) 15 sec after the induction of a lesion deep in cat brain by a 6-sec pulse of focused ultrasound. The pattern subsequently changed to that illustrated in (c), which then persisted throughout the period of observation.

on the trace. The echo pattern seen approximately 2 sec after termination of the pulse that induces the localized temperature gradient is shown in Fig. 3(b). A large enhancement (factor of eight) of the just-detectable echo of Fig. 3(a) is apparent (3), and echo, (4) from a structural site not exhibited in Fig. 3(a) is present. Between five and six seconds after generation of the temperature gradient, both the enhanced (3) and the induced (4) echoes are present at reduced amplitude [Fig. 3(c)], and, 1½ min later, Fig. 3(d) demonstrates that the echo pattern had returned to its original form.

By contrast with the completely reversible results just described, a different sequence of results is observed when the dosage level of the inducing beam is increased so that a permanent lesion is produced [Figs. 4(a)–(c)]. Figure 4(a) shows a typical echo pattern before irradiation—the individual echoes corresponding to the brain interface at the port of entry (1) of the examining beam, the brain surface diametrically opposite the port of entry (2), and an intermediate-reflection probably from a ventricular interface (3). The echo pattern present 15 sec after termination of the 6-sec lesion-producing pulse is illustrated in Fig. 4(b). In addition to the new echoes (4) reflected from the lesion, the record shows a modification of the echo pattern (2) that is received from the brain interface diametrically opposite the port of entry of the examining beam. The two distinct echoes that are received at this time from this latter interface region could be the result of slight movement of the brain relative to the encasing bone. The form of the echo pattern (4) from the permanent lesion changed subsequently into that seen in Fig. 4(c), which persisted throughout the period of observation.

As already indicated, it is not the intent to demonstrate here the full capability of the ultrasonic method of soft-tissue-structure visualization based on detecting differences in absorption coefficient values, nor to present data obtained on a system of practical utility. Rather, it is the objective of this note to show, by direct experimental observation, that the method proposed and previously analyzed by one of us is feasible. Development of a system to place this new method in a form suitable for routine use will be initiated in the immediate future.