Real Time Ultrasound Tomography of the Adult Brain

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SUMMARY Initial clinical results are reported from a new real time, 2-dimensional ultrasound scanner modified for adult cephalic applications. An optimized transducer design and the use of the dynamically focused phased array imaging system have resulted in ultrasound tomograms of the brain which are significant improvements over previous attempts. Horizontal and coronal images of the ventricles, the corpus callosum and other midline structures are routinely displayed in a 45° sector format. In addition, pulsating cerebral arteries are displayed in real time. Quantitative information can be obtained concerning cerebral vascular patency by using the selectable M-mode feature of this system. The results indicate that real time ultrasound tomography has potential for clinical application.

A-MODE ECHOENCEPHALOGRAPHY has been accepted as a routine clinical tool of proven value in neurology.1-4 Unfortunately, this widely available ultrasound technique does not provide 2-dimensional information about anatomical or pathological structures. Since the initial development of B-mode ultrasonography, there have been a number of attempts5-9 to apply this imaging modality to the generation of tomographic images of the brain. As the ultrasonic beam passes through the adult skull, it is seriously degraded so that previous attempts at cephalic imaging proved to be only marginally useful. This report represents the initial clinical results from a new, real time, 2-dimensional ultrasound scanner modified for adult cephalic applications. An optimized transducer design and the use of the dynamically focused phased array imaging system have resulted in ultrasound tomograms of the brain which are significant improvements over previous attempts.

METHODS

Instrumentation

Echoencephalographic studies were performed using a 2-dimensional imaging system originally designed for cardiac applications.5-9 This system, developed in the Duke University Biomedical Engineering Department, relies on phased array principles to rapidly steer the ultrasonic beam through the target volume and is capable of producing high-resolution tomographic images of the brain in real time. This approach does not require that the ultrasound transducer be moved in the image formation process.

The prototype imaging system uses a linear array of 16 ultrasonic transducers in both the transmit and receive operations. The fundamental frequency of each individual array element is 1.0 MHz and the array measures 31 mm × 14 mm at the site of contact. The latter dimension corresponds to the height of each of the active elements.

In this system the entire ultrasonic linear array transducer is excited to produce a wave-front which propagates at any desired azimuth angle as illustrated in figure 1A. For simplicity only a 5-element linear array is indicated. In this figure, the time sequence of excitation pulses to each of the elements is indicated on the left side of the array. First, the top element is excited which produces a circular wave front which propagates toward the right into the tissue. A short time later, the next element is excited resulting in a second acoustic pulse which propagates into the tissue. This process continues until the last element has been pulsed. In the tissue all of the individual acoustic wave fronts will add to produce a maximum acoustic intensity along the direction indicated by the solid line in figure 1A. The direction of propagation of the effective transmit insonification is directly related to the time excitation sequence of the array elements, so that the acoustic beam may be reoriented to any azimuth angle merely by altering the timing sequence of the excitation pulses.

The concept of beam formation is extended in the imaging system to include focusing of the transmitted beam by combining a spherical timing relationship with a linear one to produce a beam which is focused at a given range and propagates at a specific azimuth angle. This combination of steering in azimuth and focusing is illustrated in figure 1B.

Figure 1C illustrates the electronic processing of received signals in the phased array system. Echoes arise from scatterers in the tissue on the right side of the array and propagate back toward the elements where they arrive at differing times, as indicated by the small pulses to the left of the array. The delay lines included in the receiver assure that only echoes from a certain azimuth direction will add to produce a maximum, while discriminating against echoes originating from other directions.
Image quality is also improved by focusing during the receive mode. Provisions are made to alter rapidly the delay times in each of the received channels so that the receiver focus can be synchronized to the range of returning echoes. This method ensures that all targets within the field of view will be in focus, resulting in improved image resolution. Thus, the system utilizes an electronic lens, focused in both transmit and receive.

The architecture of the prototype imaging system currently under clinical evaluation is diagrammatically illustrated in figure 2. The computer in association with the appropriate timing logic controls the entire scan sequence but is not utilized for computations or image processing. The tomographic B-mode images produced by this system are displayed on a Hewlett-Packard 1311A monitor oscilloscope. Normally, the acoustic image frame rates are synchronized to standard television rates of 30 frames/second.

The system also permits the display of echo amplitude and position, the well known time-motion mode, along a pre-selected line of the image. In this way the presence and location of arterial pulsations within the brain may be shown on a second monitor. The patient's ECG, carotid pulse waveforms and other physiological data may be also displayed simultaneously on this second monitor. Both monitors are viewed by television cameras and a permanent video tape recording of this simultaneous information is made of each examination for later review of frame by frame analysis.

Examination Techniques

Images presented in this manuscript are from the first 30 patients examined with this system at the Duke University Medical Center. In the present system design 2 operators are necessary to perform an ultrasound examination. The first operator manipulates the hand-held transducer while the second operator adjusts the image variables (time gain control, overall gain and range) and manages the video tape recording system.

The contact transducer array is initially positioned approximately 3 cm superior to the external auditory canal to produce a real time horizontal tomographic image of a portion of the brain. From this position the transducer can be moved posteriorly or anteriorly to complete the examination of one horizontal plane. At each location, a short segment of the real time ultrasonic images is recorded on video tape. Successive horizontal planes spaced 1 cm apart are examined in the same fashion. At the completion of this procedure the transducer array is rotated 90° and placed 3 cm superior to the external auditory canal to produce a coronal scan. Again, the transducer may be moved anteriorly or posteriorly to obtain successive coronal scans at 1 cm increments.

After the routine examination the transducer is positioned so as to record image areas of special interest such as arterial structures or lesions. The hand-held transducer can then be rotated to record an image of any desired plane in an effort to obtain maximum diagnostic information.

Results

Instrumentation

This new ultrasound imaging system produces improved resolution B-mode tomograms in real time. These images are generated in a circular sector format with a maximum sector scan angle of 45° as illustrated in figure 3. The plane of the scan is parallel to the long axis of the linear array of transducer elements.

Images are generated synchronously with standard television rates (i.e., at 30 per second). For a typical maximum range selection of 15 cm each tomographic image frame is composed of 128 individual B-mode lines. The azimuthal resolution capability of this system has been determined experimentally in water tank measurements to be 3–5 mm throughout the field of view. The range resolution was determined to be 3 mm. Resolution in the dimension perpendicular to the tomographic plane corresponds to values predicted for an unfocused slit aperture (—6 dB beam width is 7.5 mm at 70 mm range). Thus the thickness of each image slice is less than 1 cm.

Logarithmic compression of the received echo informa-
tion allows 60 dB of echo amplitude information to be presented in the approximately 10 to 1 brightness range of the primary display oscilloscope. Flexibility during operation is an intrinsic characteristic of this system. Since the entire image formation process of scan sequence is under computer control, various scan parameters can be changed readily. Facility in clinical use is assured through the use of a hand-held transducer in direct skin contact. This allows rapid visualization of various cephalic structures by simply reorienting or repositioning the transducer.

The images presented in this manuscript are Polaroid photo recordings of single frame images from the display. There is significant degradation in image quality produced by the photographic process required in recording single frame images from the television monitor video tape recording. An individual frame from the TV monitor represents only 1/30th of a second. Additional diagnostic information can be seen in the real time images due to moving targets or slight angulations of the transducer.

Representative images using the real time phased array B-scan system with a 1 MHz, 31 mm linear array transducer are shown in figures 4–7. In figure 4, a horizontal tomogram through the skull of a 34-year-old female is compared to an anatomical cross section. One can see the far skull, the mid-cerebral fissure, the posterior portions of the lateral ventricles, midline structures and echoes from the Sylvian fissure. The splenium of corpus callosum appears as the relatively echo-free band between the mid-cerebral fissure and the posterior horns of the lateral ventricles.

In figure 5 a coronal ultrasound scan through the skull of a 24-year-old male, a few centimeters anterior to the auditory canal, is compared to an anatomical cross section. Here again the far skull, the mid-cerebral fissure, the anterior portions of the lateral ventricles and septum pellucidum are visualized. The corpus callosum from this view is again a relatively echo-free band. In figure 6 a coronal scan through the skull of a 30-year-old male in a plane 3 cm posterior to the auditory canal is compared to an anatomical cross section. In this image, one sees the far skull, the mid-cerebral fissure, the corpus callosum and the posterior region of the lateral ventricles. In addition, the calcified pineal gland and the inferior colliculus are seen as bright targets in the center of the scan. Echoes arising from the tentorium cerebellae and cerebellum are also shown. In figure 7 the ultrasound coronal scan of a 26-year-old female taken 4 cm anterior to the auditory canal is compared to an EMI computed tomographic scan at 0 degrees in the 2A plane. A 45° sector angle has been superimposed on the CT scan to illustrate a field of view analogous to the ultrasound image. Both imaging techniques reveal the presence and midline location of a large mass diagnosed at surgery to be a glioma-ependymoma.

In addition to the display of these static cephalic images we routinely record images of pulsating cerebral vessels. In coronal scans both posterior cerebral arteries are seen...
pulsating synchronously. Branches of the middle cerebral artery internal to the Sylvian fissure and the anterior cerebral artery in the mid-cerebral fissure have been displayed. The internal carotid arteries are routinely seen in the approximate area of the circle of Willis.

In the assessment of vascular patency and cerebrovascular disease, a valuable adjunct to cross-sectional imaging is the selectable M-mode feature. When a pulsating arterial structure is visualized in the image, the M-mode line can be adjusted over the artery to provide arterial pulse information as a function of time. The arrival times of the cerebral arterial pulsations can be plotted with respect to ECG and carotid pulse.

Figure 8 shows a composite time-motion trace of 1 selected line from the real-time tomographic image. The line was chosen to intersect the image of both posterior cerebral arteries in a coronal scan of a 24-year-old normal male subject. Timing markers and an ECG trace are also included in the chart record. Variations in echo amplitude (darkness of trace) and small changes in echo positions are seen during each cardiac cycle. In similar manner such M-mode recordings can be obtained from other cerebral arteries.

Discussion

Since first clinically used in 1955,13 A-mode echoencephalography has justifiably enjoyed wide clinical application in the diagnosis of a variety of neurological disorders. Recently, clinically useful ultrasound tomograms of the brain have been demonstrated in neonates. However, the difficulties associated with acoustic imaging through the calcified skull have hindered the application of ultrasound tomography to the adult brain.24 The intervening presence of the calcified skull results in poor signal-to-noise ratio, limited dynamic range in the images, and reduced image resolution. Two characteristics of skull bone are responsible for poor quality brain images: (1) substantial attenuation of diagnostic ultrasound by the skull bone; (2) the variation in thickness of the inner table of skull bone. This thickness variation acts as a distorting lens in front of a transducer, degrading the quality of the ultrasonic image. Both of these skull characteristics rapidly become more severe as the ultrasonic frequency increases. As a result, traditional B-mode imaging systems operating at 2.25 MHz have not been able to overcome the effects of the skull. However, through the use of a phased array ultrasound system and by the proper
choice of transducer frequency and size, significant improvement may be achieved in ultrasound tomograms of the brain. Extensive analysis of skull thickness and attenuation data have indicated that a large phased array transducer operating at 1 MHz is able to overcome partially the degrading effects of adult skull bone. The present report concerns results from the initial cephalic application of a phased array ultrasonic imaging system using a 31 mm × 14 mm, 1 MHz transducer array. The ultrasound beam is steered over a 45° sector and focused throughout the field of view to develop 2-dimensional high resolution images of the brain in real time. Improved lateral resolution, on the order of 6-8 mm, has been obtained in imaging through adult skull. Previous attempts at trans-skull imaging indicates the resolution achieved was in the range of 1-2 cm.

In addition, the real time aspect of these tomographic images permits the display of pulsating cephalic arterial structures without the use of contrast media or ionizing radiation. The presence and diagnostic relevance of intracranial echo pulsations using A-mode echoencephalography has been the subject of some discussion in the past. In the real time ultrasound tomographic images, localized pulsatile variations of the amplitude and position of the targets are evidently

![Image](https://example.com/image.png)

**Figure 6.** Comparison of a coronal ultrasound tomogram through the skull of a 30-year-old normal male in a plane 3 cm posterior to the auditory canal versus an anatomical cross section. The far skull, the mid-cerebral fissure, the corpus callosum, the posterior regions of the lateral ventricles, the calcified pineal gland, and the tentorium cerebellae are visualized.

**Figure 7.** Comparison of a coronal ultrasound tomogram of a 26-year-old female in a plane 4 cm anterior to the auditory canal versus an EMI 0 degree computed tomogram in the plane 2A. A large midline mass measuring 4 cm in diameter is visualized in each image.

**Figure 8.** A composite time-motion trace of a selected line from a real time ultrasound coronal tomogram of the brain. Amplitude and position variations are seen in echoes from the 2 posterior cerebral arteries of a 24-year-old normal male. Half-second timing marks and an ECG trace have been included in the image.
would be possible to compare the arterial pulse arrival times of the brain. An inherent advantage of this ultra-
sound technique offers potential for the initial diagnosis of possibilities of a 90° field of view over all areas of the skull. In the freedom of movement of the hand-held transducer coupled with the real time display provides for the rapid identification and localization of intracranial lesions. Therefore, real time ultrasound tomography represents a non-invasive imaging modality capable of rapid examinations with little patient discomfort, thus providing the possibility for serial evaluation of pathological processes. The results presented here are still preliminary. However, the improvements which have been noted are encouraging and it seems evident that real time ultrasound tomography has significant potential for clinical application in neurological diagnosis.

References

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Stroke. 1978;9:117-122
doi: 10.1161/01.STR.9.2.117

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