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 ul-
trasound tomograms of the brain which are significant improvements
over previous attempts. Horizontal and coronal images of the ven-
tricles, 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 ul-
trasound tomography has potential for clinical application.

The prototype imaging system uses a linear array of 16 ul-
trasound 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 com-
bining 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 preset 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.14 However, the difficulties associated with acoustic imaging through the calcified skull have hindered the application of ultrasound tomography to the adult brain.15 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.16 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 x 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

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**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.
caused by slight displacements and angulations of individual cerebral vessels.

By utilizing the selectable M-mode feature, illustrated in figure 8, one could measure changes in the diameter and position of arterial structures during the cardiac cycle. In addition, by monitoring ECG and carotid pulse pressure along with the M-mode echo from the individual cephalic vessels, one could compare arterial pulse arrival time in the carotid arteries of the neck versus arrival times in cerebral arteries. Preliminary studies of these arrival times have recently been completed using only an A-mode system. The variable M-mode feature of the real time ultrasound tomographic system will allow precise positioning of the ultrasound beam on the arterial structure of interest. Thus it would be possible to compare the arterial pulse arrival times and variations in vessel diameters of a suspected diseased artery versus a normal artery.

In the future, as the performance of the imaging system is improved to enable resolution of the lumens of small cephalic vessels, it may become possible to measure cerebral arterial blood flow directly by combining the real time tomographic system with ultrasound pulsed Doppler information. Finally, the absence of normal pulsatile echoes in a specific location of the tomographic images could lead to the identification of an occluded vessel. Thus, this non-invasive technique offers potential for the initial diagnosis of cerebrovascular disease as well as the serial evaluation of stroke patients and their response to therapy.

Despite these improvements, trans-skull ultrasonic imaging of the brain still suffers significant limitations. Using the current system the resolution capability and target acquisition is inferior to that of the CT scanner. Although the phased array ultrasonic system can resolve targets 3 mm apart in a water tank, lateral resolution is degraded to 6–8 mm through adult skull as noted above. In addition, reverberant acoustic echoes within the near side of the skull are sometimes displayed as artifacts in the real time two-dimensional images.

The current small field of view makes it impossible to display a tomogram of the entire brain as with the CT scanner. Furthermore, with the 31 mm transducer it is difficult to establish contact on the curved surfaces of the head in some areas which results in reduced image quality. Finally, with the current system design, ultrasound scans have been limited to the thinner regions of skull bone in the temporal and parietal areas.

The limitations discussed here may be overcome in the future, however. Improved system design offers the possibility of a 90° field of view over all areas of the skull. In addition, there is the potential for generating composite ultrasonic images of the entire brain by superimposing several sector scans made at various locations around the head within the same plane. Laboratory experiments in on-line signal processing techniques indicate the potential for achieving 2 mm resolution for ultrasonic imaging of the brain through the intact skull.

The cephalic images presented in this report demonstrate substantial improvement in obtaining ultrasonic tomograms of the brain. An inherent advantage of this ultrasound scanning system over computed tomographic systems arises from the real time feature of the displayed information which permits visualization of dynamic structures. The ability of the current system to detect the pulsations of cerebral arteries offers the potential of non-invasive determination of cerebrovascular patency which is essential in the assessment, treatment and prevention of cerebrovascular accidents.

It should also be noted that most current computed tomographic scanners are capable of generating horizontal, cross-sectional images only. However, the phased array real time ultrasound imaging system produces tomographic images in any desired plane in the temporal and parietal areas of the skull. 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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