Experimental study of high-resolution ultrasound imaging of hemorrhage, bone fragments, and foreign bodies in head trauma

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The accuracy of high-resolution ultrasound scans in detecting foreign bodies and hemorrhage within the brain was evaluated by comparison with computerized tomography (CT) scans and gross pathology. The test lesions were blood and foreign bodies consisting of bone, wood, and metal placed in the brain of an experimental animal. High-resolution ultrasound scans (10 MHz) performed in coronal and sagittal planes accurately delineated the position and spatial orientation of these foreign bodies and hemorrhage. Both hemorrhage and foreign bodies were echogenic compared to normal, hypoechoic brain parenchyma. Metal fragments had a highly characteristic echo pattern caused by sound reverberation within the object. Acute intracerebral hemorrhage produced an ultrasound image consisting of sharply circumscribed homogeneous echoes. The sonographic shape of intracerebral hemorrhage correlated closely with the area of increased density seen on the CT scan. High-resolution ultrasonography accurately delineated experimentally produced components of head trauma and may prove useful as an intraoperative imaging technique to facilitate surgery in head-injured patients.

KEY WORDS • high-resolution ultrasound • hemorrhage • foreign body • head trauma • computerized tomography

COMPUTERIZED tomography (CT) has facilitated the detection of intracranial lesions and has significantly improved their localization. The combination of axial and coronal CT scans can accurately delineate a lesion and its relationship to important surrounding structures. Interfacing a stereotaxic device with the CT scan promises to further refine lesion localization and the neurosurgical approaches to small lesions.\(^1\)\(^,\)\(^17\) Despite all these improvements, it would still be advantageous for the neurosurgeon to have the ability to image lesions during surgery.\(^8\) This capability would prove useful during surgery of head-injured patients for delineating intracerebral hemorrhage and identifying foreign bodies.\(^11\)\(^,\)\(^20\) Direct intraoperative visualization of bone fragments would allow more complete removal while minimizing tissue damage resulting from such debridement.

Ultrasound examination of the adult brain to detect mass lesions and foreign bodies has a sporadic but long history and has involved primarily A-mode ultrasonography.\(^3\)\(^,\)\(^7\)\(^,\)\(^9\)\(^,\)\(^10\)\(^,\)\(^12\)\(^,\)\(^14\)\(^,\)\(^16\)\(^,\)\(^19\) Echoencephalography through the adult calvaria is currently beset by penetration and access problems. A-mode ultrasonography, although accurate, does not provide an image and, therefore, spatial orientation is difficult to achieve. Epidural B-mode ultrasonography has been limited by image quality and spatial resolution. We evaluated a high-resolution ultrasound instrument for localizing intracerebral hemorrhage and foreign bodies in the brain of an experimental animal. We found high-resolution ultrasound to be highly accurate in defining these experimentally produced components of head trauma; demonstrating some advantages over CT. An instrument of this type could be adapted for intraoperative use.

Materials and Methods

Preparation of Experiment

After implantation of foreign bodies, the brains of eight mongrel dogs were studied using both high-resolution ultrasound and CT brain scans. The fol-
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lowing lesions and foreign bodies were investigated: intracerebral hemorrhage (four dogs), metallic fragments (four dogs), wood splinters (three dogs), and bone fragments (one dog).

Intracerebral hemorrhage was produced and foreign bodies were placed in the following manner. The dog, after being sedated with acepromazine maleate (10 mg/5 kg, intramuscularly), was anesthetized with intravenous sodium pentobarbital (16 mg/2.5 kg) and intubated with an endotracheal tube. The dog's head was affixed to a stereotactic device, and a midline scalp incision was made to reflect the temporalis muscle and expose the frontal parietal skull. A craniotomy was performed, producing a skull defect approximately 3 × 5 cm in size. This skull defect was large enough to admit the sound beam of the ultrasound probe. After hemostasis was achieved, the dura and pia were incised for placement of bone fragments, metallic fragments, or wood splinters. The metallic fragments consisted of copper and lead pellets (less than 1 mm in diameter), wire staples (3 to 4 mm in length and less than 0.5 mm diameter), and irregularly shaped fragments of lead pellets (approximately 1 mm in size). An intracerebral hematoma was produced by injecting freshly drawn venous blood into the cerebral hemisphere through a No. 25 needle. The volume of injected whole blood varied from 2 to 3.5 cc. The operative site was vigorously flushed with saline and closed in layers. The bone was not replaced.

Imaging

High-resolution ultrasound scans were obtained in the coronal and sagittal planes during and shortly after surgery while the dogs were still under anesthesia. Ultrasound performed during surgery required the use of a sterile plastic drape and gel for good acoustical contact with the brain surface. Appropriate images were photographed using the instrument's real-time and freeze capability. Images were selected to identify each foreign body and the entire extent of hemorrhage. These scans were compared to scans obtained through the scalp muscles after closure. The informational content between these two types of ultrasound scans did not differ. Within 1 hour of the ultrasound scan, and with the dog still under general anesthesia, coronal CT scans were performed in a serial fashion through the brain at 5-mm intervals. The CT scans were obtained with a bolusing device on a body scanning unit* using the following factors: Kv = 120, mA = 320, pulse width = 3.3 msec, collimator = 5 mm.²

Immediately after CT scanning, the brains were removed and fixed in 4% formaldehyde for 5 weeks.

Conventional radiographs of these brains were obtained in the lateral and vertex projections for comparison with ultrasound and CT scan images. Coronal sections (5 mm in width) of the gross specimen were made to correlate the gross pathological findings with both the ultrasound and CT scans. The ultrasound imaging system† was a B-scanner using a 10-MHz, 64-element linear array. Dynamic focusing was used on both “transmit” and “receive” to provide sub-millimeter resolution in both dimensions over the entire image. A fixed acoustic lens provided focusing in the direction orthogonal to the image plane. The field of view was 3 cm wide and 4 cm deep, and a real-time image was generated at 30 frames/sec. The small ultrasonic transducer housed in an electric shaver-sized enclosure (2.5 × 4.5 × 9 cm), and attached to a coaxial cable, allowed easy manipulation.

Results

Intracerebral hemorrhage, being different from surrounding brain in both density and acoustical impedance, was readily detected by both CT and ultrasound scans. Normal cerebral cortex on the ultrasound scan was hypoechogenic with only the cortical sulci being moderately echogenic. The characteristic location and pattern of cortical sulci allowed easy differentiation from pathological sources of echoes. Intracerebral hemorrhage by ultrasound examination appeared as a well circumscribed, highly echogenic lesion surrounded by hypoechoic brain (Fig. 1). The pattern of echoes was homogeneous and sharply demarcated from adjacent brain. Edema surrounding the hemorrhage, however, could not be defined by ultrasound. The experimental hemorrhage on the CT scan was of increased density, well circumscribed, and surrounded by a narrow halo of low density representing edema (Fig. 1). The echogenic lesion delineated by ultrasound examination corresponded closely to the area of increased density on the CT scan.

The orientation of embedded foreign bodies was such that their longest axis was directed in the same direction as the sound beam from the probe; thus, a relatively disadvantageous orientation was used. Placement of foreign bodies did not cause detectable adjacent hemorrhage. Metallic fragments in the form of staples, pellets, and irregular pieces of lead all produced highly echogenic lesions on the ultrasound scan. In fact, metal produced a very characteristic ultrasound pattern in that a column of echoes was projected beyond the actual metal fragment, resulting from sound reverberation within the metal object (Fig. 2). All metal fragments placed in the brain were detected by ultrasound as discrete structures even when these fragments were in close apposition.

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*Body scanning unit No. 8800 manufactured by General Electric Co., Medical Systems Division, 4855 Electric Avenue, Milwaukee, Wisconsin.

†Ultrasound imaging system developed by SRI International, Menlo Park, California.
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FIG. 1. Coronal computerized tomography (CT) scan (A) and coronal high-resolution ultrasound scan (B) of an experimental intracerebral hemorrhage. Hemorrhage on the CT scan is kidney-shaped and of characteristically increased density. The low-density region medial and inferior to the hemorrhage represents edema. Hemorrhage on the ultrasound scan appears as a homogeneous area of increased echoes. Note the close correlation between the shape of the hemorrhage as depicted by ultrasound and the shape as shown by the high-density area on the CT scan. Surrounding normal brain is hypoechoic; edema adjacent to the hemorrhage could not be visualized by ultrasound. In each ultrasound image, the dense horizontal band of echoes represents the craniotomy defect and dura. The echoes above this band are from scalp musculature (temporalis muscle).

thin wire staple produced a thin, straight band of dense echoes without reverberation. The CT scan easily detected metal, but the image was often degraded by streak artifact (Fig. 2). This artifact often precluded determination of the exact number, location, and orientation of the actual metal fragments. The ultrasound scan proved superior in the ability to distinguish between individual metal objects.

Fragments of bone were readily detected by the ultrasound scan and were characterized by a pattern of increased echoes conforming to the shape of the fragment. The magnitude of the echoes, however, was less than those produced by metal. The echoes accurately delineated the dimensions and the orientation of the bone fragments (Fig. 3). No significant reverberations were noted, and posterior shadowing was not apparent. The CT scan accurately depicted the calcific bone fragments and their orientation (Fig. 3). These fragments produced no CT artifact and thus were clearly differentiated even when closely approximated.

Each sliver of wood was detected by the ultrasound scan. Wood was also characterized by increased

FIG. 2. Coronal computerized tomography (CT) (A) and high-resolution ultrasound scans (B and C) of metallic fragments embedded in the right parietal lobe. Prominent CT artifact from the metallic fragments precludes determination of their number and orientation. Coronal (B) and sagittal (C) ultrasound scans show the characteristic broad band of resonant echoes produced by metallic fragments. The sagittal scan (C) clearly shows two separate fragments only 3 mm apart. The top of each band of echoes has a line of very dense echoes that indicates the actual site of the metallic object.
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Fig. 3. Coronal computerized tomography scan (A) and coronal high-resolution ultrasound scan (B) show two bone fragments embedded in the right parietal lobe. These bone fragments are readily identified by both imaging techniques. The ultrasound scan shows the presence of a cortical sulcus between these two bone plugs as indicated by the thin echogenic line between the broad echogenic bands, representing bone. Bone was highly echogenic but without reverberation.

Echoes that corresponded to the shape and orientation of the object (Fig. 4). The magnitude of this echogenicity, however, was less than that of bone or metal. Fragments of wood were easily differentiated by ultrasound from metal fragments even when they were closely associated. No posterior shadowing was noted. The CT scan imaged wood fragments as areas of decreased density because of air trapped within the wood (Fig. 4). Their orientation was accurately gauged. Wood splinters, however, were obscured by artifact on the CT scan if they were too closely associated with metal fragments.

Although air is an impediment to the transmission of sound, small amounts of air trapped postoperatively did not degrade the ultrasound images. In some instances a reverberant echo appeared at a distance from the transducer twice that of the actual air pocket. In no animals did air result in obscuration of the lesions of interest. The CT scan confirmed the presence of this air and its location (Fig. 1).

Discussion

Echoencephalography has experienced renewed attention as an imaging modality because of recent advances in ultrasound technology. This progress has translated into marked improvements in image quality and, thus, the clinical usefulness of echoencephalography. Intracranial ultrasound imaging has progressed most rapidly in the pediatric age group.

Fig. 4. Coronal computerized tomography (CT) scan (A) and high-resolution ultrasound scans (B and C) of a wood splinter in the right parietal lobe adjacent to the ventricle. A: On the CT scan, the wood splinter (paired arrows) was visualized as a low-density band extending from the lateral ventricle toward the craniotomy defect. The low density is caused by air trapped within the wood. B: On the coronal ultrasound scan, the wood foreign body was imaged as a band of increased echoes (paired arrows). C: The sagittal ultrasound scan shows the piece of wood (paired arrows) separate from a metallic object lying 1 cm posterior to it. The metallic object has the characteristic band of resonant echoes.

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because of the availability of an acoustic window, the anterior fontanel, and because the relatively thin calvaria can be penetrated by low-energy ultrasound beams.\textsuperscript{13,16,18} The high-resolution ultrasound equipment evaluated in our study cannot be utilized through bone because too much ultrasonic energy is absorbed and, therefore, is not available for image formation. It can, however, be used through the anterior fontanel, through a craniotomy defect, epidurally, or directly on the surface of the brain.

This study has demonstrated the accuracy of high-resolution ultrasound in detecting intracerebral hemorrhage and foreign bodies. This imaging technique has direct intraoperative application to patients undergoing surgery for head trauma. Removal of bone fragments is important in reducing the risk of infection and the ultrasound scan could materially aid in this effort. By facilitating identification and localization of bone fragments, it could reduce the time, effort, and tissue damage associated with debridement. In patients with gunshot wounds, it could be useful in detecting individual pieces of shrapnel that may not be defined as distinct objects on a CT scan. Computerized tomography artifact produced by metallic objects can obscure associated pathology; ultrasound scanning can circumvent this problem. Acute hemorrhage may be delineated and evacuated under ultrasound guidance. High-resolution ultrasound scanning has wider application for localization and characterization of lesions unrelated to trauma.

Normal brain parenchyma is of low acoustic impedance and, therefore, hypoechoegenic. Many types of lesions will, therefore, appear hyperechoic in comparison. In this investigation, intracerebral hemorrhage and a number of foreign bodies (metal, bone, wood) were all hyperechoic compared to brain.\textsuperscript{11,14} Each type of lesion was accurately localized, and its echo pattern corresponded closely to the actual size and shape of the object or hemorrhage. Some lesions, such as the metal fragments, may prove to have specific ultrasound characteristics. The prominent echoes produced by sound reverberation within metal may be a specific marker for this material. Bone was highly echogenic without evidence of reverberation. Wood produced moderate echoes. Acute intracerebral hemorrhage appeared to have a characteristic ultrasonic pattern consisting of a well circumscribed, homogeneous, highly echogenic lesion. The echo pattern correlated closely to the size and shape of the hemorrhage as imaged by the CT scan and as seen on gross pathological examination. Edema surrounding the hemorrhage could not be visualized by the ultrasound scan. These findings are consonant with previous A-mode data. Further experience with high-resolution ultrasound will determine whether these patterns will have a degree of specificity.

Although high-resolution ultrasound scanning opens new vistas for brain imaging, it does have limitations. It cannot in its present form be performed through the calvaria. The particular ultrasound probe used in this study furnished only a limited examination of the brain because of a small field of view. This limitation is surmounted to some extent by the real-time capability which allows relatively large areas of interest to be scanned rapidly. Nevertheless, significant portions of the brain are not imaged. Whereas some lesions such as metal or acute hemorrhage may have characteristic and, in some cases, specific ultrasound findings, most lesions in the brain will be of a nonspecific, echogenic character. The tissue signatures of various brain lesions are fertile ground for further investigation.

The CT brain scan will remain the primary modality for evaluating intracranial contents. High-resolution ultrasonography, however, provides an important adjunct to the CT scan and adds breadth and flexibility to the scope of brain imaging. Its major contribution will be in those areas where portability is an important feature, and a limited field of view is not a significant disadvantage. Our results suggest it has application in the operating room for insuring complete removal of foreign bodies in head-injured patients.

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