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Transcranioplasty Ultrasound Through a Sonolucent Cranial Implant Made of Polymethyl Methacrylate: Phantom Study Comparing Ultrasound, Computed Tomography, and Magnetic Resonance Imaging

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Background: Current methods of transcranial diagnostic ultrasound imaging are limited by the skull's acoustic properties. Craniotomy, craniectomy, and cranioplasty procedures present opportunities to circumvent these limitations by substituting autologous bone with synthetic cranial implants composed of sonolucent biomaterials.
Objective: This study examined the potential to image the brain using transcranioplasty ultrasound (TCU) through a sonolucent cranial implant.
Materials and Methods: A validated adult brain phantom was imaged using computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound without an implant. Next, for experimental comparison, TCU was performed through a sonolucent implant composed of clear polymethyl methacrylate.
Results: All imaging modalities successfully revealed elements of the brain phantom, including the bilateral ventricular system, the falx cerebri, and a deep hyperdense mass representing a brain tumor or hematoma. In addition, ultrasound images were captured which closely resembled axial images obtained with both CT and MRI.
Conclusion: The results obtained in this first-ever, preclinical, phantom study suggest TCU is now a viable immediate and long-term diagnostic imaging modality deserving of further clinical investigation.

Key Words: Cranioplasty, CT, implant, MRI, PMMA, sonolucent, ultrasound

Unlike other superficial tissues surrounding the brain, cranial bone attenuates, scatters, and absorbs ultrasonic waves.[1] This distortion significantly limits emerging transcranial diagnostic and therapeutic ultrasound applications.[2–5] Neurocranial surgeries with bone replacement (following craniotomy/craniectomy) present opportunities to replace autologous bone with implants composed of novel synthetic biomaterials. Synthetic implants offer several advantages compared with large bone flaps reimplanted after periods of prolonged storage, including lower complication rates and the ability to correct coexisting soft and hard tissue volume deficiencies.[6–9] In addition, synthetic cranial implants made of novel, clear-colored polymethyl methacrylate (PMMA) offer new-found advantages of transparencies to visible light, electromagnetic waves, and potentially ultrasonic waves.[10,11]

In the setting of adult cranioplasty, where complication rates approach 40%, sonolucent cranial implants may permit diagnostic imaging using a new, noninvasive modality termed here as "transcranioplasty ultrasound" (TCU).[12–14] Interestingly, ultrasound investigation of intracranial pathologies is widely accepted and often preferred in neonates, where open fontanelles act as naturally occurring acoustic windows.[15] Therefore, to explore the potential for TCU, we performed a preclinical phantom study comparing standard computed tomography (CT) and magnetic resonance imaging (MRI) images against TCU images obtained through a synthetic cranial implant composed of clear PMMA.

MATERIALS AND METHODS

Imaging was conducted using a validated adult brain phantom (True Phantom Solutions, Windsor, ON, Canada) containing an internal cavity approximating the shape of the bilateral cerebral ventricular system, a hyperdense midline falx cerebri, and a deep hyperdense intracranial mass simulating a parenchymal tumor or hematoma. For accuracy, an experienced pediatric neuroradiologist oversaw study design and performed results interpretation. The ventricular cavities were filled with saline to simulate cerebrospinal fluid (CSF). Control CT and MRI images were obtained using a Siemens Somatom Force CT system and a Siemens Magnetom Verio 3 Tesla MRI, respectively. Both CT and MRI scanning were conducted using standard neuroimaging protocols and executed by experienced radiology technicians.

Ultrasound imaging was performed by an experienced sonographer using a 1 to 5 MHz Philips S5-1 sector array transducer on a Philips EPIQ 7G ultrasound system. Control images without the implant present were first captured by ultrasound. The points along the phantom surface at which the transducer was placed were recorded for later use. In addition to a position directly above

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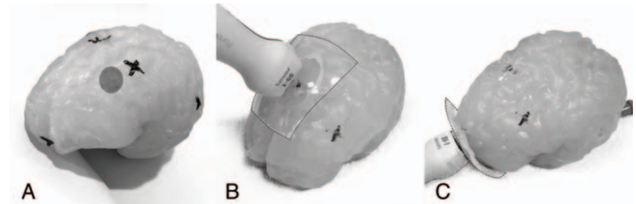

FIGURE 1. Ultrasound experimental setup is shown. A brain phantom was imaged using 1 to 5 MHz Philips S5-1 sector array transducer on a Philips EPIQ 7G ultrasound system without and with a sonolucent skull implant composed of clear PMMA. Transducer positions were recorded to standardize probe locations. In addition to placement at the imagined anterior fontanelle (B) and over the hyperdense mass lesion (dark circle in A), the probe was positioned (A) to create images similar to the axial images obtained with CT and MRI.

the deep brain mass, the transducer was placed both at the anterior fontanel and in positions to capture images most closely resembling axial images seen with MRI and CT.

Following ultrasound imaging without an implant present, TCU was performed through an 8 × 6 cm cranial implant composed of clear PMMA (Longeviti Neuro Solutions, Hunt Valley, MD) with a thickness of 4 mm (typical thickness of adult cranial bone) and a curvature mirroring the phantom's contour. A copious amount of ultrasound gel was placed both beneath and over the implant to displace air. The implant and transducer were moved to each recorded point and all resultant imaging captured for later comparison. Ultrasound gel was reapplied at each point. Additional probes were also tested, but then abandoned as insufficient contact between transducer footprints and the curved implant surface limited TCU efficacy. All images and interpretations were supplied by an experienced pediatric neuroradiologist to confirm accurate reporting of findings. Methodology is summarized in Figure 1.

RESULTS

Computed tomography and MRI of the brain phantom revealed lateral ventricles, the midline falx, and the hyperdense intracranial mass. As expected, ultrasound of the phantom in the absence of a cranial implant revealed similar findings. Transcranioplasty ultrasound through the clear PMMA implant also revealed the ventricular system, the hyperdense midline, the hyperdense parenchymal mass, and the full depth of the phantom in coronal, axial, and sagittal views. Measurements of the intracranial mass were comparable across all imaging modalities. Axial images obtained using TCU were directly comparable to CT and MRI. Of note, TCU through the implant demonstrated increased edge shadowing artifacts, which reduced image clarity compared with ultrasound imaging with no implant present. However, with transducer manipulation, shadows and interference could be strategically localized away from the region of interest, thereby allowing TCU to remain effective. Results are summarized in Figure 2.

DISCUSSION

Ultrasonic waves are distorted and degraded when transmitted through scalp, skull, and various underlying structures. Bone density and speed of sound differ significantly from surrounding soft tissues. Within the cranium, heterogeneities in the acoustic properties of inner trabecular (diploe) and outer cortical bone layers severely attenuate wave propagation.[16] In fact, cranial bone reflects approximately half the energy of incident ultrasonic waves and absorbs most of the residual wave energy.[17–19] Wave transmission is further limited by high acoustic impedance mismatches at both the scalp-skull and skull-dura interfaces. Compounding these issues, acoustic properties vary significantly between patients due to differences in their cranial bone composition.[20]

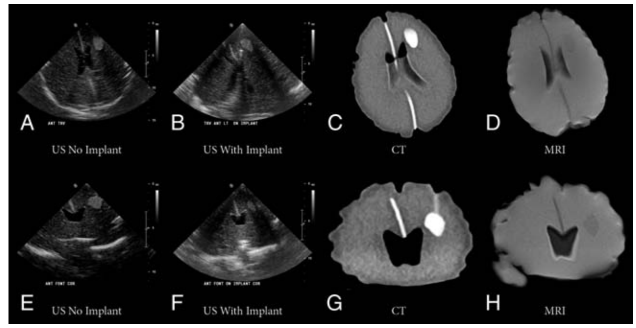

FIGURE 2. Radiographic results are presented. A 1 to 5 MHz Philips S5-1 sector array transducer on a Philips EPIQ 7G ultrasound system successfully generated images through a sonolucent, clear-colored cranial implant (made of PMMA) (B and F) which are similar to images obtained with ultrasound in the absence of a skull implant (A and E) and axial images obtained with CT and MRI (C, D, G and H). Edge shadowing was present during ultrasound through and in the absence of the implant. The interference and shadowing were greater during TCU through the implant but with transducer manipulation, this artifact could be strategically positioned away from the region of interest.

Phased ultrasound arrays, algorithmic software, and real-time MRI feedback correction have all improved the ability to circumvent the acoustic properties of cranial bone. These developments have allowed high-frequency, transcranial therapeutic ultrasound to successfully treat certain neuropathologies. [2,21,22] Despite similar advances in diagnostic ultrasound, the use of transcranial B-mode sonography and transcranial Doppler ultrasound remains limited in adults.[23-25]

Attenuation experienced by an ultrasound beam is related to its frequency. As expressed by the attenuation coefficient equation $\alpha = \propto \cdot fn$ (where α is attenuation, $\propto$ is a constant, f is the frequency, and n a positive integer), acoustic attenuation increases with increasing frequency.[26] For ultrasonic waves to penetrate cranial bone with limited attenuation, lower frequencies are needed.[19] Although low frequencies generally reduce attenuation, they also reduce image quality and spatial resolution. High-frequency (and hence high-resolution) ultrasound consoles in the laboratory have been reported to achieve spatial resolution comparable to MRI, but again this technology remains restricted by the acoustic properties of bone.[27,28]

Complications following cranioplasty, including instances of epidural bleeding and CSF leak, may approach 40%.[12–14] Over 100 adult cranioplasty procedures are performed each year at our institution, with the vast majority using synthetic biomaterials.[29] In the pediatric population, cranioplasty with synthetic implants is increasingly common; however, controversy persists regarding the appropriate skeletal development stage at which synthetic implants may be used.[30,31] Pediatric cranioplasty case series with opaque PMMA have reported high patient satisfaction with no complications.[31] Synthetic implants in both adult and pediatric populations offer several advantages over autologous bone, including reduced complication rates, reduced resorption, and design flexibility to correct soft tissue deficiencies such as temporal hollowing.[6–9,30–32] Regardless of implant material type, postcranioplasty complication rates >26% have been reported in both adults and children.[33] In the adult population specifically, cranioplasty complications, including instances of epidural bleeding and CSF leak, may approach 40%.[12–14,33] As such, TCU through sonolucent cranial implants may represent a newfound opportunity, in adults and developmentally appropriate children, for both immediate postoperative and long-term diagnostic examination of intracranial pathologies, including hematomas, brain edema, tumor recurrence, hydrocephalus, and midline shift.[2–4,19] Furthermore, TCU could be readily available at the bedside. With this in mind, we chose to examine the potential of diagnostic TCU, and employed a validated adult brain phantom imaged with CT, MRI, ultrasound (in the absence of an implant) (ie, all 3 imaging scenarios serving as controls), and then experimented with TCU through a sonolucent clear PMMA implant for direct comparison.

In all imaging modalities including TCU, the ventricular system, the falx, and the hyperdense mass could be identified. In addition, intracranial mass measurements were comparable across all modalities, suggesting the potential for TCU in solid tumor surveillance. By extension, intracranial measurements with TCU may also be used to assess ventricles in hydrocephalus, aneurysms, brain edema, midline shift, tumor recurrence, and fluid collections such as hematomas or hygromas.

By positioning the transducer at 'extreme' positions—such as the anterior frontal lobe or posterior occiput—images were generated which resembled the axial images seen with CT and MRI. These preliminary results are encouraging and suggest TCU through sonolucent implants is a viable modality and could be used for both immediate postoperative and long-term diagnostic imaging. However, the limitations of ultrasound present several challenges which must be overcome before TCU becomes well accepted and considered equivocal.

For example, in neonates, ultrasound imaging is a common and validated tool for diagnosing intracranial pathologies such as hydrocephalus, hemorrhages, cerebral edema, infarction, hematomas, tumors, and cysts.[15] As a neonatal imaging modality, ultrasound presents numerous advantages over CT and MRI, including reduced cost, no ionizing radiation, no sedation, portability (thereby leaving the neonate within the incubator), and enables 'interactive' image acquisition and 'live' diagnostic investigation.[15,34,35] However, when compared with MRI and CT, ultrasound remains less sensitive in detecting certain pathologies such as acute ischemia.[36,37] In addition, ultrasound is subject to signal attenuation, perspective distortion, shadowing, and is significantly impacted by sonographer proficiency, transducer geometry, probe frequency, and the relationship of the acoustic window to the imaging target.[1]

However, emerging technologies, such as robot-guided diagnostic probe placement, three-dimensional neurosonography, novel concave transducers, and distortion reducing computer algorithms, may help to overcome these limitations.[38-41]

As observed in this study, an increased number of vantage points to position a transducer improves ultrasound examination. Therefore, larger cranial implants would be more advantageous for TCU because they provide the sonographer a greater amount of surface area to work with. In all probe positions, TCU signal attenuation within the validated adult phantom brain did not limit visualization of the entire phantom depth, suggesting TCU may be utilized in macrocephalic patients.

Although TCU generated results which approximated the axial images obtained in CT and MRI, these results required the transducer (and consequently the implant) to be positioned at specific regions. Without a cranial implant in these regions, axial images would be challenging to obtain. However, as neonatal neuroradiologists readily use ultrasound to diagnose intracranial pathologies, axial TCU images may not always be required for certain diagnoses.

The implant used was of standard curvature and thickness consistent to those frequently used by the senior author for standard adult cranioplasty reconstruction (CG). As the adult brain phantom lacked a skull, no reference was available to perfect an implant shape with computer design and fabrication. Instead, the implant selected approximated the curvature of the brain phantom surface based on a standard reference skull atlas. To limit the potential discordance in shape between the phantom and implant, imaging was restricted to the center most portion of the implant—as the greatest mismatch was found along the periphery. Despite these efforts, some air accumulation may still have occurred, which has the potential to negatively alter the true value of our findings.

Resolution of the ultrasound images was limited by the curvature/geometry of available transducers. Edge shadowing observed with TCU appeared as a consequence of poor contact between the flat transducer face and the curved implant surface, or due to refraction of the sound beam caused by the oblique incident angle at the edges of the image. These limitations could be improved using an alternative concave transducer shape made specifically for TCU, but to our knowledge, such a diagnostic transducer is not commercially available at this time. In addition, a gel pad was tested as a possible solution to achieve better contact between the transducer and the implant, but the pad introduced reverberation artifacts that further deteriorated image quality.

All diagnostic imaging is subject to imaging technologist or operator proficiency. However, ultrasound is particularly user dependent as image acquisition is an interactive process. Our results were obtained by a trained sonographer with experience in neurosonography. Consequently, clinicians attempting TCU may require familiarization or training in sonography to acquire appropriate diagnostic quality TCU imaging.

CONCLUSION

The incidence and significance of postcranioplasty bleeding complications and postcraniotomy tumor recurrences suggests a critical need for noninvasive bedside imaging. In this preclinical brain phantom study, TCU successfully revealed the ventricular system, the 2 hemispheres, the midline, and a hyperdense mass simulating a parenchymal lesion/hematoma. Most notably, these results were comparable to CT and MRI. Although axial ultrasound images were similar to CT and MRI, these results required frequent probe position changes and adjustments which may not be possible in certain clinical scenarios. Regardless, these results are highly encouraging and suggest TCU—through sonolucent cranial implants—may be developed for immediate postoperative and long-term intracranial imaging. Future investigations will validate postoperative TCU and explore its potential to transform clinical practice.

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Strategy of Mandibular Central Arch Reconstruction After Firearm Injury

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Abstract: Gunshot wounds can cause extensive destruction of soft tissue and bone, and the maxillofacial region is often affected. The

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