First Experience With Postoperative Transcranial Ultrasound Through Sonolucent Burr Hole Covers in Adult Hydrocephalus Patients

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BACKGROUND: Managing patients with hydrocephalus and cerebrospinal fluid (CSF) disorders requires repeated head imaging. In adults, it is typically computed tomography (CT) or less commonly magnetic resonance imaging (MRI). However, CT poses cumulative radiation risks and MRI is costly. Ultrasound is a radiation-free, relatively inexpensive, and optionally point-of-care alternative, but is prohibited by very limited windows through an intact skull.

OBJECTIVE: To describe our initial experience with transcutaneous transcranial ultrasound through sonolucent burr hole covers in postoperative hydrocephalus and CSF disorder patients.

METHODS: Using cohort study design, infection and revision rates were compared between patients who underwent sonolucent burr hole cover placement during new ventriculoperitoneal shunt placement and endoscopic third ventriculostomy over the 1-year study time period and controls from the period 1 year before. Postoperatively, trans-burr hole ultrasound was performed in the clinic, at bedside inpatient, and in the radiology suite to assess ventricular anatomy.

RESULTS: Thirty-seven patients with sonolucent burr hole cover were compared with 57 historical control patients. There was no statistically significant difference in infection rates between the sonolucent burr hole cover group (1/37, 2.7%) and the control group (0/57, $P = .394$). Revision rates were 13.5% vs 15.8% ($P = 1.000$), but no revisions were related to the burr hole or cranial hardware.

CONCLUSION: Trans-burr hole ultrasound is feasible for gross evaluation of ventricular caliber postoperatively in patients with sonolucent burr hole covers. There was no increase in infection rate or revision rate. This imaging technique may serve as an alternative to CT and MRI in the management of select patients with hydrocephalus and CSF disorders.

KEY WORDS: Hydrocephalus, CSF disorder, Shunt, ETV, Ultrasound, Sonolucent, Cranioplasty, NPH, Imaging, Radiology, Endoscopic third ventriculostomy

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The management of hydrocephalus requires repeated head imaging. At present, computed tomography (CT) is the predominant modality in adults, given speed, cost, and availability. However, each acquisition exposes the patient to ionizing radiation. Cumulative exposures increase the risk of tumorigenesis, particularly with exposures in childhood.[1-5] Improved survival of hydrocephalus patients both increases total exposures and increases the chance of living to an extended age where this risk is realized. Alternatively, magnetic resonance imaging (MRI) spares radiation, but is more expensive, requires a longer acquisition, and is less available. Patients with comorbidities may have prohibitive metal implants or hardware that may cause artifact. In the case of inpatients, both modalities require transporting. In critically ill patients, this can increase risk.[6-9] Patients must be flat, and longer acquisition times of MRI are often intolerable or may further increase risk.

For the above reasons, there has been renewed attention to transcranial ultrasound as an alternative to CT and MRI in neurosurgical patients. Although transcranial Doppler ultrasound is common, anatomic imaging is mostly prohibited by the intact calvarium. The bone removed during

ABBREVIATIONS: CT, computed tomography; **ETV,** endoscopic third ventriculostomy; **GE,** General Electric; **LL,** left lateral ventricle; **MRI,** magnetic resonance imaging; **NPH,** normal pressure hydrocephalus; **PMMA,** polymethyl methacrylate; **RL,** right lateral ventricle; **TCCD,** transcranial color-coded duplex; **VP,** ventriculoperitoneal routine cranial neurosurgery serves as a potential window. Recent reports have shown feasibility of transcranioplasty ultrasound through sonolucent cranioplasty material, and similar rates of complication and infection in patients undergoing elective cranioplasty with this material.[10-14] In hydrocephalus patients specifically, a candidate window for transcranial ultrasound is created when patients undergo burr hole placement for ventricular shunting or endoscopic third ventriculostomy (ETV). We sought to assess the safety of using sonolucent burr hole cover implants in routine hydrocephalus procedures and the feasibility of postoperative transcranial ultrasound for assessment of ventricular anatomy.

METHODS

Study Population

FDA-approved clear 2-cm polymethyl methacrylate (PMMA) burr hole covers (Longeviti) were used. All patients who had these placed during new insertions of ventriculoperitoneal (VP) shunt or first ETV performed between September 1, 2020, and August 31, 2021, were included (n = 37). Revisions of an existing shunt were excluded. A historical control cohort was composed of all new VP shunt insertions and ETVs performed by the senior author during the same date range of the previous year: September 1, 2019, to August 31, 2020. Only patients with at least 90 days of follow-up were included. Institutional review board approval was obtained for review and analysis of clinical data. Consent was not required by the institutional review board. In a cohort study design, the sonolucent burr hole group was compared with the historical control for baseline clinical variables, infection rate, and revision rate. Statistical analysis was performed in SPSS (IBM) and reviewed by a biostatistician at the Johns Hopkins Institute of Clinical and Translational Research. Fisher's exact test was used to compare proportions and independent-samples t test was used to compare means, with $P < .05$ denoting significance.

Surgical Technique

After creation of a burr hole at Kocher's point with a standard 14-mm perforator, a 4-mm round cutting burr was used to widen the burr hole to 20 mm. Undercutting the burr hole is helpful to ensure the widest possible field of view for postoperative ultrasound. When finished with ETV or shunt insertion, the sonolucent burr hole cover was fixed to the skull with standard cranial plating screws (Figures 1 and 2). Vancomycin power was left in the surgical site. Twenty-four hours of postoperative antibiotics were administered, in addition to a preincision dose.

Performing Ultrasound

In addition to standard imaging with CT and MRI, patients underwent transcutaneous trans-burr hole ultrasound for evaluation of their ventricular anatomy throughout their follow-up periods. Representative ultrasound images are included with contemporary slices of cross-sectional imaging (Figures 3-6). In patients with frontal burr holes, the image is standardized by maintaining the probe in a coronal orientation and aiming at the ipsilateral foramen of Monroe (Figure 7). Attempt is made to wholly include the ipsilateral lateral ventricle cross-section in the frame, and ideally the contralateral lateral ventricle and third ventricle as well. Quantitation can be performed by measuring the area of the ipsilateral lateral ventricle cross-section. Reconstruction of contemporary CT or MRI by creating a coronal plane image through both the frontal burr hole and ipsilateral foramen of Monroe creates a comparable anatomy. Area of the ipsilateral lateral ventricle was measured on the standard coronal ultrasound view by 2 neurosurgeon authors (R.L. and M.M.) independently in Vue PACS (v.12.6.2, Philips Healthcare Information Solutions). Interobserver reliability was determined by calculating a 2-way, absolute agreement intraclass correlation coefficient on 13 area measurements.

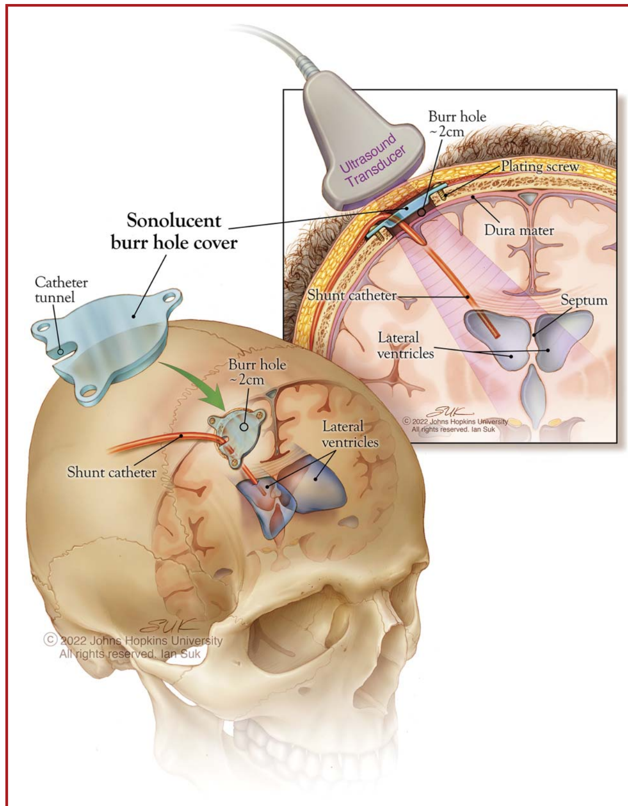

FIGURE 1. *Graphical representation of a sonolucent cover used in a right frontal burr hole for placement of ventriculoperitoneal shunt. This allows for a cone of visualization of the lateral ventricles and third ventricle with transcutaneous postoperative ultrasound. Printed with permission. ©2022 JHU Neurosurgery–Ian Suk.*

RESULTS

We identified 37 patients with sonolucent burr hole covers and 57 historical controls. Baseline characteristics were not significantly different (Table 1, $P = .09$). There was no statistically significant difference in the infection rate (1/37, 2.7% vs 0/57, $P = .39$; Table 2). There were 5 total revisions in the sonolucent burr hole cover group (13.5%, 5/37) compared with 8 in the control group (14.0%, 8/57, $P = 1.00$). No revision in either cohort was a cranial wound revision thought related to the burr hole cover or hardware.

We successfully performed point-of-care ultrasound in the inpatient units and in the outpatient clinic, in addition to formal ultrasound in the radiology suite. The edges of the burr hole define the visualized intracranial contents to a "cone," as depicted in Figure

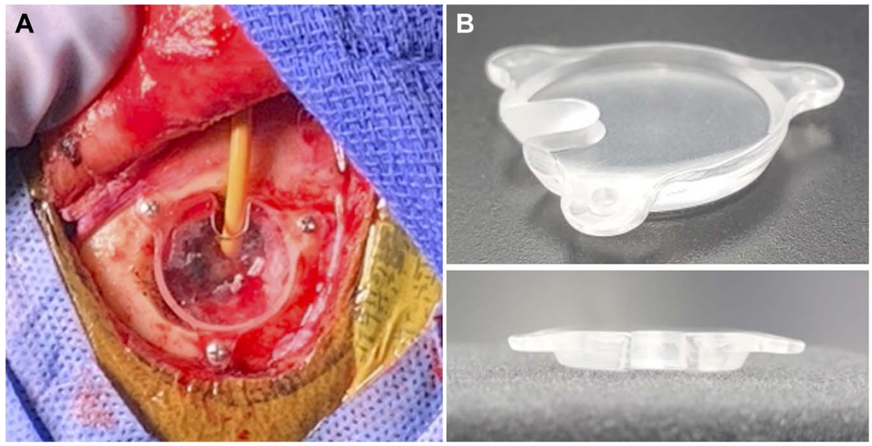

FIGURE 2. *Images of the sonolucent burr hole cover in situ* **A**, *during placement of a right frontal ventriculoperitoneal shunt and* **B**, *preimplantation demonstrating overall low profile. Fixed to the skull with standard cranial plating screws. Optional notch for proximal shunt catheter.*

1. This was sufficient to obtain a gross evaluation of ventricular size, with most information gleaned from a coronal view through the frontal burr hole. Diagnostic imaging could be obtained formally in the radiology suite with the Philips Epiq (Figure 3) without neurosurgery provider involvement. Outpatient clinic point-of-care ultrasound was performed with the General Electric (GE) Venue Go (Figures 4 and 5) and SonoSite X-Porte by neurosurgery physician providers, mid-level providers, and nursing staff. Diagnostic imaging could even be obtained with the ultraportable handheld, iPhone-powered (Apple) Butterfly ultrasound (Figure 6). Standard coronal plane ultrasound captures were compared with prior ultrasound images from the same patient and also to reconstructed contemporary CT images using the technique described (Figure 7). Area measurements of the ipsilateral lateral ventricle compared between 2 neurosurgeons indicated excellent interobserver reliability (intraclass correlation coefficient = 0.992).

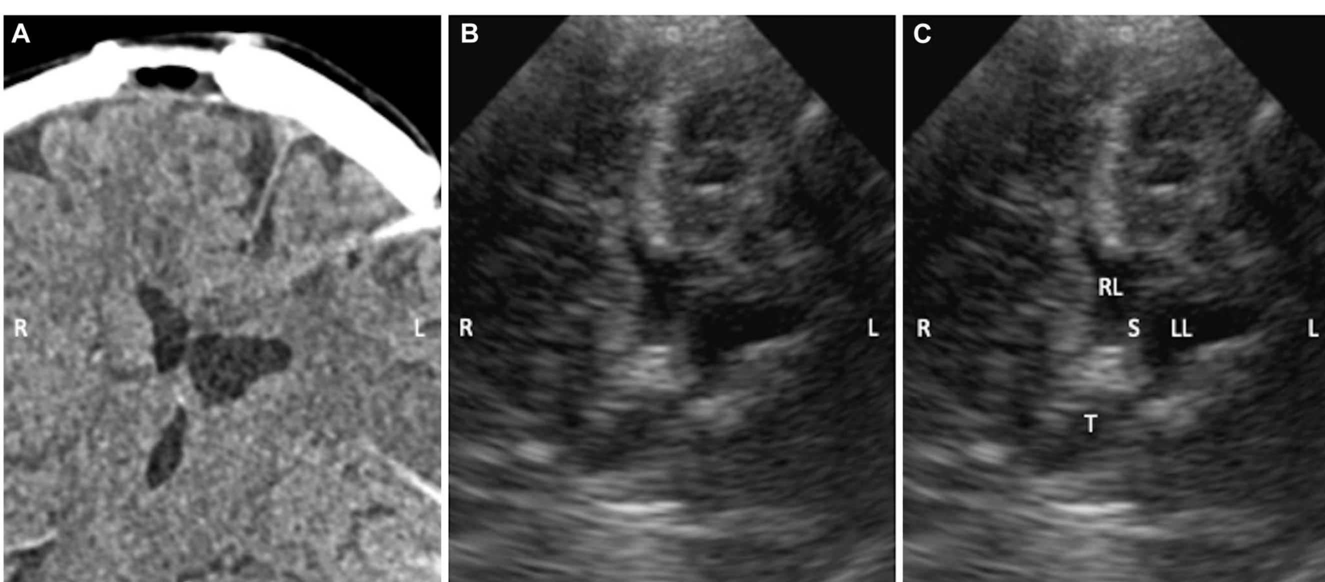

FIGURE 3. *Formal transcranial ultrasound: a 25-year-old woman with congenital hydrocephalus 1 month after endoscopic third ventriculostomy.* **A**, *Coronal computed tomography of the head, same week.* **B**, *Unlabeled coronal plane transcranial ultrasound obtained in the radiology suite with the Philips Epiq.* **C**, *Labeled ultrasound. LL, left lateral ventricle; RL, right lateral ventricle; S, septum; T, third ventricle.*

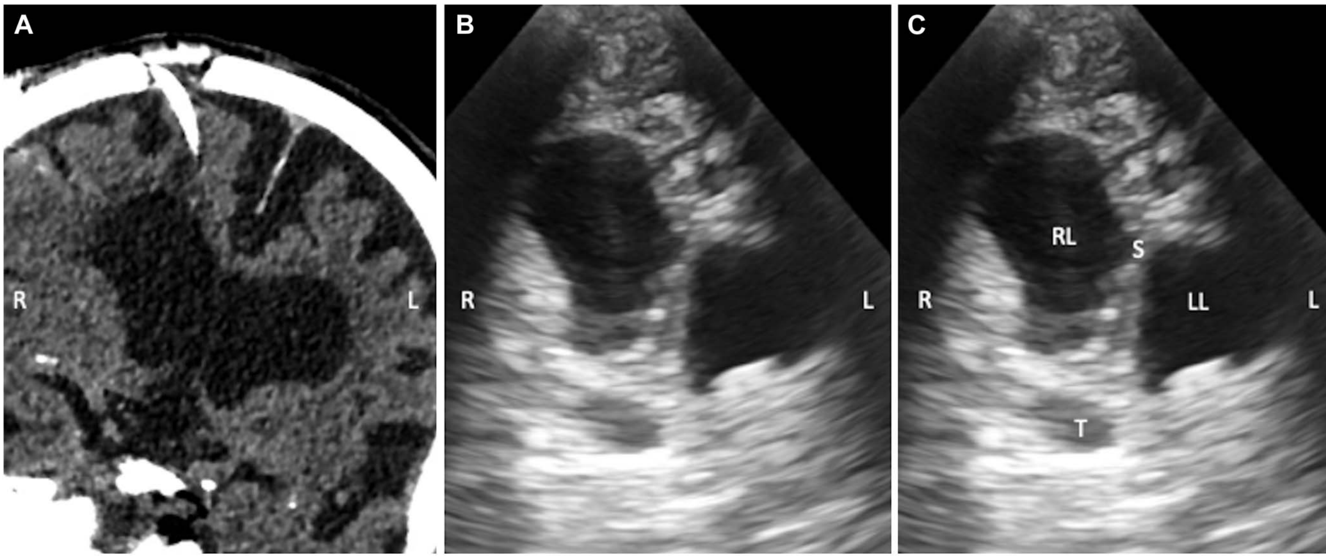

FIGURE 4. *Point-of-care ultrasound in clinic: a 76-year-old man with normal pressure hydrocephalus 4 months after right frontal ventriculoperitoneal shunt.* **A**, *Coronal computed tomography of the head, same day.* **B**, *Unlabeled coronal plane transcranial ultrasound obtained in the neurosurgery clinic with the GE Venue Go.* **C**, *Labeled ultrasound. LL, left lateral ventricle; RL, right lateral ventricle; S, septum; T, third ventricle.*

DISCUSSION

Ultrasound in Neurosurgery

Transcranial Doppler is used commonly for monitoring of vasospasm, although it does not portray anatomy. "B-mode" (anatomic) ultrasound is used in the operating room after surgical bony removal. Transcranial ultrasound is also commonly used for brain imaging in neonates with open fontanelles. However, intact adult cranial and spinal bony anatomy has historically prohibited diagnostic anatomic ultrasound. As a result, CT and MR imaging is the standard.

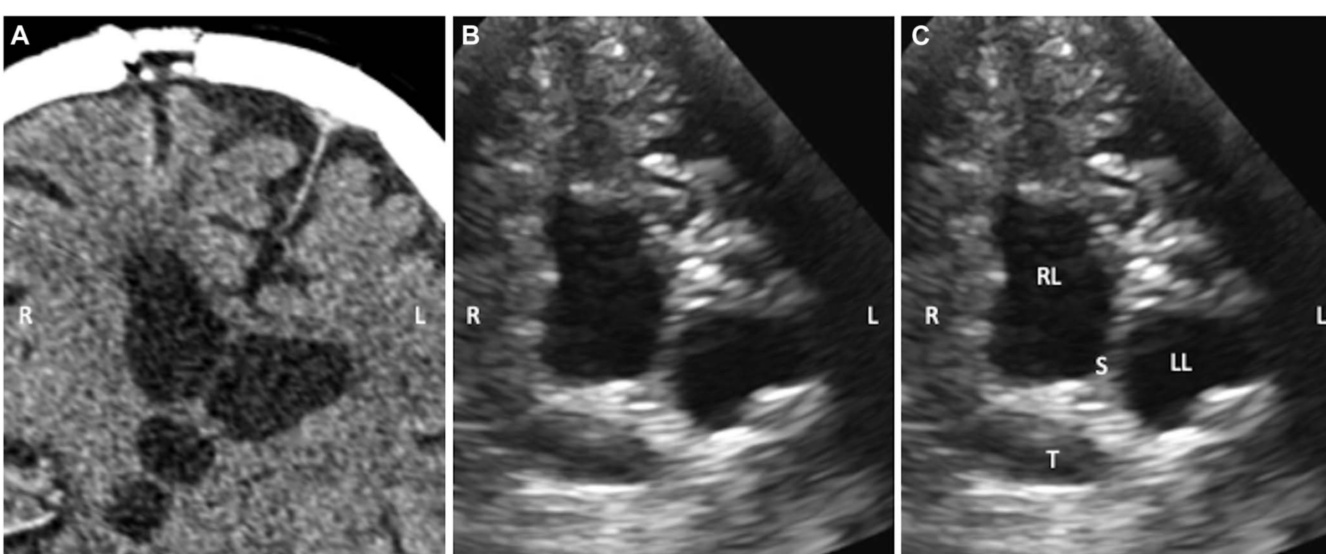

FIGURE 5. *Point-of-care ultrasound in clinic: an 80-year-old man with normal pressure hydrocephalus 3 months after right frontal ventriculoperitoneal shunt.* **A**, *Coronal computed tomography of the head, same week.* **B**, *Unlabeled coronal plane transcranial ultrasound obtained in the neurosurgery clinic with the GE Venue Go.* **C**, *Labeled ultrasound. LL, left lateral ventricle; RL, right lateral ventricle; S, septum; T, third ventricle.*

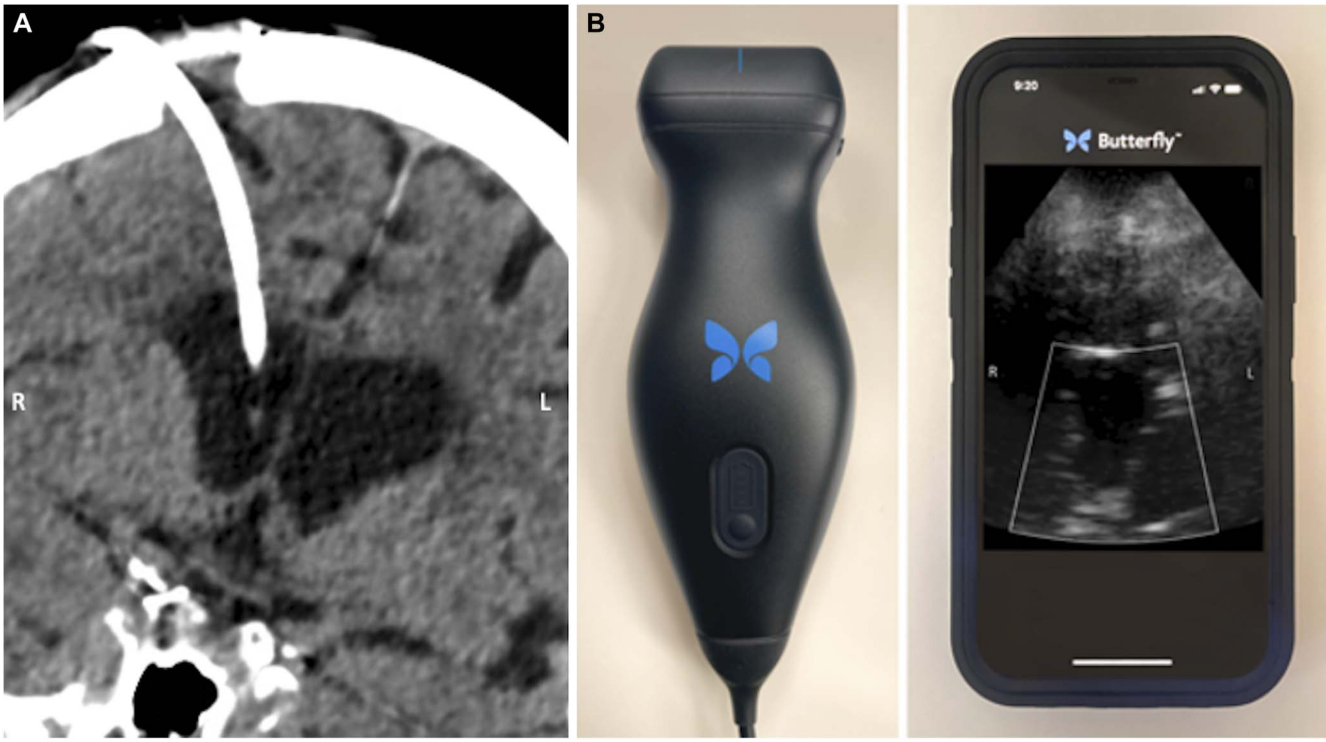

FIGURE 6. *Smartphone-powered handheld ultrasound in clinic: a patient with normal pressure hydrocephalus 3 months after ventriculoperitoneal shunt.* **A**, *Coronal computed tomography of the head, same day.* **B**, *Coronal plane transcranial ultrasound obtained with the handheld iPhone-powered Butterfly probe in the neurosurgery clinic.*

In populations that warrant repeated imaging, such as those with hydrocephalus and cerebrospinal fluid (CSF) disorders, CT imaging poses cumulative radiation risks.[1-5] MRI is radiation-free but presents a larger cost burden, has more limited availability, and is not possible in patients with some implants. Neither is point of care. Critically ill patients require transport, which increases risk of adverse events.[6-9] For these reasons, there is renewed interest in ultrasound techniques for intracranial imaging. Transcranial color-coded duplex (TCCD) sonography is a newer method gaining traction as technology improves. With TCCD,

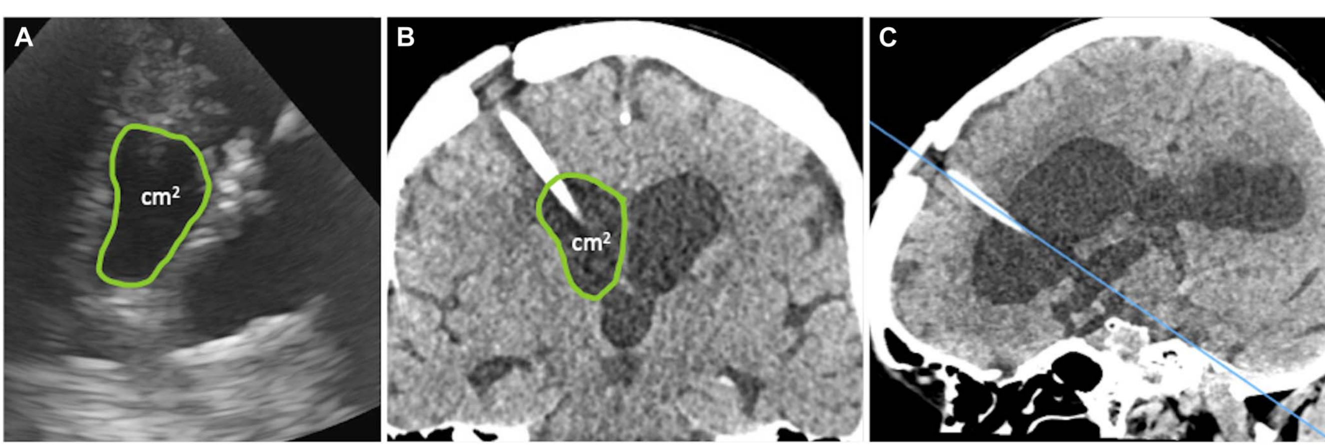

FIGURE 7. *Coronal images for measurement showing* **A**, *"standard" coronal view ultrasound and* **B**, *reconstructed analogous coronal computed tomography.* **C**, *a reference line in the sagittal view of the coronal plane used in* **B**. *Example area tracings are shown of the ipsilateral lateral ventricle cross-section.*

TABLE 1. Basic Demographics, Reason for Surgical Intervention, and Follow-up

	Sonolucent burr hole cover	Controls	*P* value
Total patients	37	57	
Reason for intervention			.09
IIH/venous outflow obstruction	2 (5%)	12 (21%)	
NPH/communicating hydrocephalus	28 (76%)	36 (63%)	
Congenital hydrocephalus	2 (5%)	0	
Aqueductal stenosis	2 (5%)	6 (11%)	
Tumor-related hydrocephalus	3 (8%)	2 (4%)	
CSF leak	0	1 (2%)	
Male gender	19 (51%)	23 (40%)	.40
Age (y)	66	59	.06
Mean follow-up (d)	247.8	468.1	5×10^{-11}

CSF, cerebrospinal fluid; IIH, idiopathic intracranial hypertension; NPH, normal pressure hydrocephalus.
Demographic and clinical variables are compared between the cohort of patients with the sonolucent burr hole cover and historical controls. Statistical comparisons are made, showing similarity between the groups, except as noted.

anatomic parenchymal and ventricular imaging can be obtained through a transtemporal window owing to the relative thinness of bone in that area. This has been reviewed recently and several reports have correlated transtemporal TCCD assessment of ventricular size, intracranial hematomas, and midline shift with CT.[15-21] Despite its promise, TCCD ultrasound has not been widely adopted because of technical and anatomic challenges.[22] Many patients do not have an adequate transtemporal window, and anatomic imaging is nondiagnostic.[20,23] Even with an adequate window, the field of visualization is incomplete.

The Sonolucent Burr Hole Cover Technique

Large craniectomy defects, such as after decompressive craniectomy, allow for very good ultrasound visualization. In this setting, ultrasound has been shown to be comparable with CT in measuring ventricular diameter, midline shift, and acute parenchymal hemorrhages.[24-26] Several authors have described the feasibility of using sonolucent cranioplasty material for reconstruction to allow for anatomic transcranial sonography.[10-14]

The circumstances for cranioplasty of a solitary burr hole—such as in shunt and ETV procedures—are somewhat different. For a standard 14-mm burr hole, a cover is not always needed. However, scalp depressions at these sites can occur and many surgeons do place covers for this reason. Our technique describes widening the burr hole to approximately 20 mm to improve ultrasound visualization. In our experience, a burr hole of this size warrants a cover for cosmesis, making the sonolucent cover valuable in this circumstance.

Certainly, leaving additional foreign material in a patient with a permanent ventricular shunt is reason to hesitate. Overall adult infection rates range from 1.6% to 12.9%.[27-34] Adults without prior cranial surgery or high-risk comorbidities are generally thought to be low risk.[28] In our control cohort, there were no infections in 57 procedures, lending support to this point. Adding a sonolucent burr hole cover did not statistically significantly increase the infection rate in this low-risk population.

Cost Considerations

The extra costs of the sonolucent burr hole cover technique should be considered. The implant itself is an additional cost, as are the fixation screws. In the 2 study hospitals, this was comparable to about one-third to half the cost of a programmable valve and a similar cost to the disposable supplies needed for Axiem navigation (Medtronic). Of course, this is not directly charged to the patient, and every hospital will have different implant costs negotiated. The additional surgery and anesthesia time needed in

TABLE 2. Comparison of Infection and Revision Rates

	Sonolucent burr hole cover	Controls	*P* value
Total patients	37	57	
Prior central nervous system surgery	3 (8%)	4 (7%)	1.00
General surgery assistance	8 (24%)	11 (23%)	.80
Infections	1 (2.7%)	0	.39
Revisions	5 (13.5%)	8 (14%)	1.00

Comparisons are made to show no difference in rate of prior central nervous system surgery or general surgery assistance with shunt implantation between patients with sonolucent burr hole cover and historical controls. There was no statistically significant difference in infection rate or revision rate between groups.

our experience is low—about 5 minutes once the surgeon has practice.

There are many notable benefits of transcranial ultrasound that may present longer-term cost-saving potential. For one, if ultrasound can be performed point-of-care in clinic or bedside inpatient, this can obviate the need for a CT or MR image and the resultant facility and professional fees. If the neurosurgeon or his team bills, then this revenue is captured by the neurosurgery rather than radiology department. Although ultrasound is generally considered less expensive than CT and certainly MRI, true cost comparisons are quite difficult and are specific to institutions and payers. Even if the costs of US and CT are similar at the time of acquisition, US spares radiation and the potential downstream costs—monetary and otherwise—of treating secondary tumors. In the outpatient setting, patients may value the convenience of not having to coordinate extra scans, and the increased interaction with the neurosurgery provider performing the ultrasound. If done point-of-care inpatient, transport of unstable patients can be avoided, thus mitigating risk of transport-related adverse events. This may be particularly relevant if sonolucent cranioplasty is used after situations like subdural hematoma evacuation and patients are relatively unstable afterward.[11] If formal ultrasound is done in the radiology suite, there is a tradeoff of a transport but for improved image quality and performance by a technologist and interpretation by a radiologist. In our experience, independent performance and interpretation of burr hole ultrasound thus far by the radiology team has been efficient and informative.

Standardizing Image Capture and Measurement

For the hydrocephalus patient with a sonolucent frontal burr hole, we propose a standard ultrasound imaging technique (Figure 7). Given the typical cone of visualization defined by the frontal burr hole location and size, the most consistently visualized structure is the ipsilateral lateral ventricle cross-section. Based on our experience, this is best appreciated and most orienting when viewed in the coronal plane as opposed to sagittal. Often at least part of the contralateral lateral ventricle cross-section can be visualized in the same frame. The standardized view should include the ipsilateral foramen of Monroe. This, then, yields a view of the same cross-section of the lateral ventricle for each acquisition across providers and time points, as opposed to a cross-section more anterior or posterior. In other words, given that the starting point (the burr hole) and target (the ipsilateral foramen of Monroe) are fixed, then a standardized view is obtained on every acquisition for that patient.

In the case of hydrocephalus, one of the main goals of serial imaging is to evaluate gross ventricular size. Without loculated or compartmentalized hydrocephalus, this is achievable even with the limited view from the frontal burr hole, as all ventricles should increase and decrease together. Therefore, noting change in size of the ipsilateral lateral ventricle should be sufficient in these patients. Although interpretation of CT or MR imaging—both new diagnosis and comparison between time points—is often done qualitatively, there is frequently a need for quantitative measures. In this particular case, the most consistently available measure is cross-sectional area of the ipsilateral lateral ventricle in the standard frame that includes the ipsilateral foramen of Monroe. This technique allows for measurements to be compared between ultrasounds of the same patient at different time points. CT or MR imaging can also be reconstructed to create a coronal plane image that passes through both the burr hole and ipsilateral foramen of Monroe. Measurement of cross-sectional area of the ipsilateral lateral ventricle was consistent among providers that measured. Further data are needed to calculate the precise sensitivity and specificity of this measurement technique for changes in ventricular caliber. Next steps also include defining a conversion factor for ultrasound area compared with CT, as ultrasound appears preliminarily to underestimate exact ventricular size, given lower resolution at the interface of parenchyma and CSF. We hope that reporting on positive initial safety and efficacy will encourage others to join the effort to explore these questions in parallel with our group.

Future Directions

Larger sample sizes and longer follow-up times are needed for additional safety data, but initial results with these sonolucent burr hole covers—along with clear PMMA implants in general—are very promising. Accumulated experience with using the data from ultrasound imaging in these patients will help better define in what circumstances it can safely replace cross-sectional imaging. This is a new workflow for the neurosurgery clinic, requiring decisions on who performs the scan (eg, physician, mid-level, nurse), how it affects timing of patient visits, billing, and storage and interpretation of data.

Undoubtedly, new quantitative measures of ventricular and parenchymal anatomy are needed. This will help compare US to cross-sectional imaging, and will also help compare between images on a single patient at different time points. Although the cone of visualization is limited with a burr hole, the cone is consistent every time you scan that patient, thereby standardizing the angle and view of the ventricular and parenchymal structures visualized. Ultrasound hardware will naturally continue to advance, which will likely improve visualization as a result, making the future of this technique very promising. At present, there are no specific ultrasound protocols for transcranioplasty imaging, which is also a limitation likely to be overcome soon, thus improving diagnostic yield.

Limitations

The first limitation of our comparison between the 2 cohorts is that there is no randomization or blinding. There are no strict criteria by which patients were chosen for sonolucent burr hole implantation, other than that they were new ventricular shunt or ETV patients without significant prior cranial surgical history. Patients with prior cranial surgical incisions, who are thought to be higher risk for infection or wound breakdown, were excluded. Also, patients with very small ventricles expected to be poorly visualized on ultrasound were not typically candidates. This accounts for the smaller proportion of idiopathic intracranial hypertension patients in the experimental group.

Although this is a biased sample population, at present, this is the population that we consider to be appropriate for sonolucent burr hole cover. The historical control group is less selective but serves as a very similar baseline population of also only new ventricular shunts and ETVs by the same surgeon with identical technique aside from the sonolucent burr hole cover placement. Although there was less mean follow-up time for the sonolucent cover group, all patients had at least 90 days of confirmed follow-up. The majority of shunt infections have been shown to present during this time frame.[35]

CONCLUSION

Utilization of a sonolucent polymethyl methacrylate burr hole cover in new adult VP shunt and ETV procedures did not increase infection rate or revision rate in our study, although longer follow-up times and larger sample sizes are needed for further evaluation. Transcutaneous trans-burr hole ultrasound is feasible for gross evaluation of ventricular caliber postoperatively in patients with sonolucent burr hole covers. This imaging technique may serve as an alternative to CT and MRI in the management of select patients with hydrocephalus and CSF disorders. It will be strengthened by the application of objective quantitative metrics of measurement to compare between modalities and at different time points longitudinally in individual patients.

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Disclosures

Under a licensing agreement between Longeviti Neuro Solutions, LLC, and the Johns Hopkins University, the university and Dr Gordon are entitled to royalty distributions on technologies described in this publication. Dr Gordon is a cofounder of Longeviti Neuro Solutions, LLC, and owns equity in the company. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict of interest policies. Dr Gordon also has financial relationships with Stryker, DePuy Synthes of Johnson & Johnson, and Acumed/OsteoMed. Dr Huang is a stockholder in Longeviti Neuro Solutions. Dr Brem is a paid consultant to Insightec and chairman of the company's Medical Advisory Board. Insightec is developing focused ultrasound treatments for brain tumors. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict-of-interest policies. Dr Brem is a consultant for CraniUS, Candel Therepeutics, Inc., InSightec*, Accelerating Combination Therapies*, Catalio Nexus Fund II, LLC*, LikeMinds, Inc*, Galen Robotics, Inc.*, and Nurami Medical* (*includes equity or options). A colleague of Dr Luciano's in the Department of Neurosurgery and in Plastic Surgery has a financial interest through investment in Longeviti, Inc, the company that produces the ClearFit burr hole cover. However, this work was conceived, performed, and analyzed by the lead author and Dr Luciano and performed on his own patients. The other authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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COMMENTS

This paper presents an interesting preliminary experience using ultrasound and a sonolucent burr hole cover to monitor ventricular size in hydrocephalus. The authors were able to demonstrate safety of ventricular shunt catheter implantation in a cohort of 37 patients. A variety of ultrasound machines, including a portable smartphone-based device, were used with acceptable results. Although not specifically investigated, this combination of technologies may allow avoidance of postoperative CT scanning to document shunt placement. It may also be possible to quickly assess ventricular size in an outpatient setting. The authors deserve credit for expanding the neurosurgical applications for ultrasound.

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This is a retrospective review of 37 ETV patients who were followed with ultrasound through a burr hole to monitor hydrocephalus. A sonolucent burr hole cover was used. There were no adverse outcomes when compared with historical controls. Patients were followed for at least 90 days.

The follow-up might seem to be too short but this is mitigated by the focus of the article on a technique rather than the outcome. The idea that a technical change at the time of ETV surgery, using a novel burr hole cover, facilitates a less costly and less morbid follow-up is refreshing and patient-centered innovation for this patient population.

Neurosurgery is known for effectively embracing cutting edge technology; however, when it comes to ultrasound, we have lagged behind other specialties. Obtaining high-quality ultrasound imaging requires that neurosurgeons acquire the requisite skills in addition to the requisite technology. ETV obviously is relevant for only a portion of the hydrocephalus population. As a community, we can be grateful that work such as this is leading us to new opportunities for improved patient care, and we can expect that this technology will be brought to bear on other etiologies of hydrocephalus and ultimately to other neurosurgical disease processes as well.

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