Application and Feasibility of Bedside Cranial Ultrasound in Patients with a Translucent Cranial Implant: A Potential Path for an Introduction of a "Neurosurgical Stethoscope"

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Research Article

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Abstract

Background: Imaging is the cornerstone of management of neurosurgical patients. The use of ultrasound (US) in neurosurgery can potentially avoid some of the disadvantages of computed tomography (CT), including the need for patient transport, and radiation exposure. Traditionally limited in neurosurgical patients due to lack of skull penetrance, the recent introduction of translucent cranial implants can facilitate acoustic-based imaging.

Objective: In this study, we sought to examine the feasibility of a bed-side US done post-operatively in patients with translucent cranial implants, and to qualitatively compare the accuracy of this modality in diagnosing basic neurosurgical “red flags” on imaging, to a head CT.

Methods: We reviewed 5 cases operated in our institution which underwent implantation of sonolucent cranial implants. Implant size ranged from a burr hole cover to a fronto-temporo-parietal cranioplasty implant (2 – 15cm). Indications for surgery included: normal pressure hydrocephalus, complex hydrocephalus, superficial temporal artery to middle cerebral artery bypass, resection of a falcine meningioma and cranioplasty after decompressive hemicraniectomy. Patients were scanned by ultrasound between post-operative days 1 and 3, immediately prior to a CT scan ordered for a change in clinical status based on attending neurosurgeon’s decision.

Results: Relevant anatomy correlated between US and CT in all cases. This included: ventricles contour and size, midline shift, the presence of a mass or mass effect, and catheter tip position when available. Bedside US evaluations were all obtained within 5 minutes (range: 2:00 – 5:30 minutes:seconds) using a handheld probe with standard sonication settings and minimal patient discomfort.

Conclusion: Cranial sonolucent implants create an opportunity to use bedside US as a non-invasive imaging modality capable of enhancing the post-operative neurosurgical exam in an acute setting. Further study is needed to refine the use of this modality and characterize the relative advantages it may offer for neurosurgical patients.

Introduction

Brain imaging is the cornerstone of the diagnosis and management of neurosurgical patients [(Kirkman 2015; Preul and Feindel 2001)]. Imaging is particularly important in the post-operative setting to confirm the achievement of operative goals and to diagnose complications. Brain imaging becomes critical in the setting of acute alterations in the level of consciousness in the post-operative setting where patients may be suffering from life threatening complications [(Haber et al. 2019)].

Computerized tomography (CT) answers most questions in the acute setting as it can rapidly and reliably confirm the presence or absence of life-threatening complications, such as a post-operative hematoma causing brain shift, diffuse brain edema, CSF outflow obstruction leading to hydrocephalus, or other causes of neurologic decline [(P.A. et al. 2019; Qoqandi et al. 2020)].

Despite being readily available within a hospital, CT requires patient transportation and may incur time delays, which can be dangerous in the setting of acute life-threatening complications such as brain herniation. Morever, radiation is a concern especially with repeat imaging in patients with fluctuating level of consciousness [(Alkhorayef et al. 2019; Pearce et al. 2012; Smith-Bindman et al. 2009)].

Ultrasound is a safe, inexpensive imaging modality that is potentially suited to negate most of the aforementioned disadvantages [(Gargani and Picano 2015)]. It is frequently performed as a quick bedside test devoid of harmful radiation and is used in many medical fields [(Lu et al. 2020; Roque et al. 2014; Turner et al. 2015)].

In neurosurgical patients, the use of US in the preoperative and post-operative setting has always been limited by a lack of skull penetrance, which precludes its ability to accurately assess structures beyond the bone.

Recently, translucent bone flaps, which do not attenuate acoustic signals as much as native bone or traditional implants, have been developed [(Belzberg, Shalom, Yuhanna, et al. 2019; Shay et al. 2020)]. Translucent bone flaps permit penetrance of ultrasonic waves and may “unlock” the skull, thereby allowing for US imaging to play a role in the assessment of post-operative neurosurgical patients.

We have begun incorporating custom-made or standard translucent bone flaps (Longeviti Inc.) in select cases. These cases include cranial reconstruction procedures, craniotomies, and other procedures in which burr holes are drilled to cover small skull defects.

In this study, we examine the feasibility of a bed-side US done post-operatively in patients with translucent cranial implants. Moreover, we explore the accuracy of this modality in diagnosing, or ruling out, basic neurosurgical “red flags” on imaging when compared to a head CT scan obtained as a gold standard.

Materials And Methods

We retrospectively analyzed cases in which translucent cranial implants (ClearFit®, Longeviti Neuro Solutions LLC, Hunt Valley, MD, USA) were used at our department between June and September 2021 to identify cases in which clinical changes prompted urgent CT imaging between post-operative day 1 and 3.

In all cases, implants were affixed to the skull using the Stryker cranial plating system (Stryker, Kalamazoo, Michigan, USA). Postoperative ultrasound was performed by the senior author (DL). The cases described here were those in which clinical changes were reported by the ICU or floor team during hospitalization. Prior to obtaining the CT scans, without delaying the natural work flow, an ultrasound bed-side scan was performed and recorded (Fig. 1).

Ultrasound scans used for the bed-side assessment were obtained using a hand-held probe (Butterfly iQ (Butterfly Network, Guilford, Connecticut, USA) with a probe size of 185 *56* 35 mm and 2-dimensional array, 9000 micromachined sensors curved and linear features; an abdominal window for cranial images and a vascular window for pulsed-doppler based images. Importantly, in cases where the planes of US scans didn't match exactly the conventional axial/sagittal/coronal CT scan planes, representative images were chosen in as close an orientation as possible.

Case Descriptions

Complex Hydrocephalus

A 17 y.o male with a known recurrent right optic glioma, diagnosed in early childhood, underwent several prior craniotomies for partial mass resection, as well as placement of a left ommaya reservoir and a right frontal ventriculoperitoneal shunt. Most recently, following repeat resection of the known optic nerve glioma, the patient was noted to have persistent hydrocephalus and underwent shunt revision and endoscopic septum-pellucidotomy in order to improve communication between the lateral ventricles. During shunt revision, a translucent implant was utilized within the craniotomy flap.

After a mental status alteration occurring on post-operative day 1, bedside US and urgent non-contrast head CT were performed (Fig. 2). Both modalities demonstrated distorted ventricles that were unchanged compared with his baseline ventricular morphology. Catheter position and midline shift were noted and followed up on in multiple sequential days (along with CT scans), as can be seen in Fig. 2, with excellent correlation.

The patient regained consciousness and was transferred to a rehabilitation facility at his neurologic baseline.

Normal Pressure Hydrocephalus

An 85-y.o male presented with progressive cognitive decline and abnormal gait and was diagnosed with normal pressure hydrocephalus. After successful diagnostic large volume lumbar puncture, the patient underwent elective ventriculoperitoneal shunt placement. Using standard techniques, a ventriculoperitoneal shunt (Certas™, Integra Lifesciences) was placed at the frontal horn of the right lateral ventricle. A translucent burr hole cover size implant was used to cover the burr hole. The procedure was uncomplicated, but the patient developed a severe headache on post-operative day 1. Urgent bedside ultrasound was performed and easily demonstrated the tip of the shunt located within the lateral ventricle, with a preserved midline and no signs of hemorrhage. These findings were later confirmed on non-contrast head CT scan **(**Fig. 3**).**

Cranioplasty After Evacuation Of Subdural Hematoma

A 70 y.o female with recurrent cerebrovascular accidents (CVAs) presented for evaluation of intermittent speech disturbances and decreased right hand dexterity and was diagnosed with severe intracranial atherosclerosis with pressure-dependent neurologic exam unresponsive to maximal medical therapy. Ultimately, the patient underwent revascularization with superficial temporal artery (STA) to middle cerebral artery (MCA) bypass, complicated by left frontal intracerebral hemorrhage for which the patient underwent left sided decompressive hemicraniectomy. The patient made a significant functional recovery and two weeks later underwent early cranioplasty using a customized translucent bone flap. The procedure was well-tolerated. On POD 1, the patient complained of subjective worsening right sided weakness and bedside ultrasound and urgent CT were performed. Ultrasound demonstrated a lack of midline shift and a stable, chronic type, liquefied hematoma, confirmed ultimately by a CT scan. (Fig. 4). This patient underwent serial sonication which demonstrated progressive complete fluid resorption and no midline shift, confirmed on serial CT scan. These findings correlated clinically with the patient who was ultimately discharged to rehab.

Cranial Bypass Surgery

A 58 y.o female suffering from recurrent right hemisphere strokes was referred to our institution with critical MCA stenosis (M1 segment). Cerebrovascular workup demonstrated significant pressure-dependent brain ischemia and the patient underwent revascularization via a direct STA to MCA bypass.

Following an uneventful surgery, the patient was noted to be disoriented on POD 1. At the bedside, an ultrasound scan using a hand-held probe was performed. No parenchymal nor subdural hematoma were identified. The ventricles were symmetric and no midline shift was appreciated. Using doppler feature of the ultrasound, a robust signal was detected adjacent to graft location underneath the flap (Fig. 5). A CT scan was done showing no midline shift, followed by a diagnostic cerebral angiography revealing a widely patent graft. The patient's mental status improved over time and she was discharged later that week.

Post Tumor Resection

An 80 y.o male presented for evaluation of a progressive, recurrent left-sided parafalcine meningioma with significant mass effect. The patient underwent an uneventful reoperation and removal of the lesion. On POD 1, the patient demonstrated confusion and word-finding difficulty and underwent bedside US prior to an urgent non-contrast head CT. Figure 6 compares the bedside ultrasound to the urgent CT. The ultrasound image clearly shows no epidural/subdural collections, hematoma within the surgical bed, or midline shift which was corroborated on subsequent CT. Symptoms spontaneously resolved and improved and the patient was discharged on POD 4 at his neurologic baseline.

Discussion

Postoperative change in neurological function may herald the onset of hydrocephalus, be indicative of an intracranial hemorrhage or be due to ischemic stroke or seizure. Specifically, the presence or absence of midline shift, intracranial hematoma, ventricular size and visible and stable catheter tip position in implant cases provides essential insights into most acute neurosurgical complications[15–18].

Post-operative cranial imaging—specifically CT scan—are the cornerstone of decision-making protocols guiding treatment in the post-operative setting. However, in many scenarios there is little need for detailed total brain imaging and the ability to rule out major reversable complications such as acute hydrocephalus, hemorrhage or mass effect can be either confirmed or ameliorated by specific imaging features. Furthermore, while CT scan provides a comprehensive view of the head and is still very much essential for the evaluation of pre- and post-operative neurosurgical patients, the threshold for obtaining a CT scan, especially in the acute stage post-surgery in the ICU, is controversial, and subjective [(Gunnarsson and Hillman 2000; Wen et al. 2016),(Karanci and Oktay 2021; El Khoury et al. 2000),(Zimmermann et al. 2016),(Benveniste, Ferraro, and Tsimpas 2014)]. As a result, it may be over-used. Obtaining a head CT also consumes time while subjecting patients to unnecessary transport, radiation, and other possible complications [(D., S., and A. 2010; Sheppard et al. 2020)].

Assuming skull penetrance can be achieved, ultrasound-based imaging modalities can identify each of these potentially reversible post-operative events and contribute to post-operative patient management. This is exemplified in neonates who have open fontanelles that serve as natural acoustic windows for sonication [(Franco and Lewis 2013)]. However, the use of ultrasound as a diagnostic tool has been otherwise limited as ultrasound doesn't travel well through air or bone due to ultrasonic wave attenuation, scattering and absorption [(Estrada et al. 2018; Robertson et al. 2018),(Pinton et al. 2012)].

Previous pre-clinical studies [(Belzberg, Shalom, Yuhanna, et al. 2019)] explored the sonolucency of native cranial bone compared to synthetic implants such as clear PMMA, PEEK, porous-polyethylene, and opaque PMMA using a 2- to 4-MHz US transducer. While cranial bone and porous-polyethylene were not sonolucent, clear PMMA, PEEK, and opaque PMMA cranial implants were found to be sonolucent, as imaging through each material displayed different tissue echogenicities.

Recently, cranial customized implants (CCIs) fabricated with translucent/clear PMMA became approved by the Food and Drug Administration within the United States, with the inherent benefits of visible transparency and sonolucent transmission via trans cranial ultrasound (ClearFit® Longeviti Neuro Solutions, Hunt Valley, MD, USA) [(Belzberg, Shalom, Lu, et al. 2019)].

In most neurosurgical procedures, an opportunity exists for the operator to create a synthetic acoustic window by replacing normal bone, or covering a missing drilled bone, with a cranial implant composed of sonolucent biomaterial, thus facilitating trans cranial ultrasound use. As implants can be customized, and can be as small as a burr-hole cover, the introduction of an ultrasonic-based imaging modalities into the neurosurgical arena may be realized beyond cranioplasties.

In this study we sought to characterize a number of post-operative settings where urgent ultrasound based imaging through novel sonolucent implants could be performed with diagnostic accuracy and clinical ease. We evaluated the clinical utility of bedside ultrasound coupled with sonolucent implants in a variety of representative pathologies encountered in our department.

As an imaging modality, ultrasound has been historically underused in neurosurgery [(Harary et al. 2018)]. As a result, it is not a tool routinely used during training and most aren't comfortable interpreting or performing brain US scans as compared with MRI and CT [(Giussani et al. 2017; Müns et al. 2014)]. While bedside ultrasound was useful in the above series to rapidly and reliably rule out major post-operative complications, the potential introduction of ultrasound as a viable and readily available option in neurosurgical patients in the acute post-operative state is dependent on use of a sonolucent implant.

Additional challenges, such as scalp closure, drain placement, subgleal swelling and irrigation of blood and air underneath a sonolucent flap, all impact the image quality obtained by a bed-side US and should be taken account during interpretation.

Clinical judgment should still dictate treatment decisions and CT scan timing, but clinicians should be encouraged to use US handheld probe at the bedside as part of a routine neuro-focused exam. While concern over fresh incisions remains real, care should be used to place the sonolucent plate under uninterrupted skin, as well as to use sterile lubrication and gentle touch to avoid infections or pain.

Lastly, ultrasounds come in a variety of makes and models with various features. The US probe definitions that were used in this study were either abdominal or vascular for doppler purposes. This, however, may not be ideal, as specific brain tissue characteristics may require a more sub-specialized probe setting with specific settings for the cranium and the brain [(Selbekk et al. 2013)]. Future studies should help characterize the combination of flap/ultrasound/brain tissue in both normal and pathological states such as hydrocephalus or brain edema, in order to define best acoustic properties and implant shape.

Limitations

This study has several limitations. First, most patients didn't undergo an ultrasound follow-up exam to assess longitudinally changes in the initial scan obtained. Second, the overall number of cases is not large enough to derive a definite conclusion about the use of ultrasound in a bedside setting. Lastly, in this small case series, although anatomical properties were well correlated with CT findings, no pathological situations with scans necessitating intervention were encountered.

Conclusions

Cranial sonolucent implants can potentially pave the way for the introduction of ultrasound as a non-invasive, bedside imaging modality. The limited nature of the neurological exam in neurosurgical patients, especially post-operatively and in an acute setting, can be significantly enhanced by insights gained from the rapid and easy use of acoustic-based imaging tools. Thus, just as clinicians harnessed the stethoscope to assess heart sounds at the bedside centuries ago, ultrasound-based imaging can be used as an important bedside diagnostic aid serving as a “neurosurgical stethoscope.” Future larger studies are needed to refine the use of this modality and characterize the relative advantages it may offer for neurosurgical patients.

Conflicts of interest/Competing interests:

Dr Langer serves as the chief medical officer of Longeviti Neurosolutions Inc., and is a share holder in the company. No conflict of interest exists for any of the other authors.

Disclosure

of Funding: None

Declarations

Conflicts of interest/Competing interests: Dr Langer serves as the chief medical officer of Longeviti Neurosolutions Inc. , and is a share holder in the company. No conflict of interest exists for any of the other authors.

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Figures

Figure 1

Left, patient at the bedside scanned by an US hand held probe. Right, US probe connected to a smartphone immediately captures and record US images.

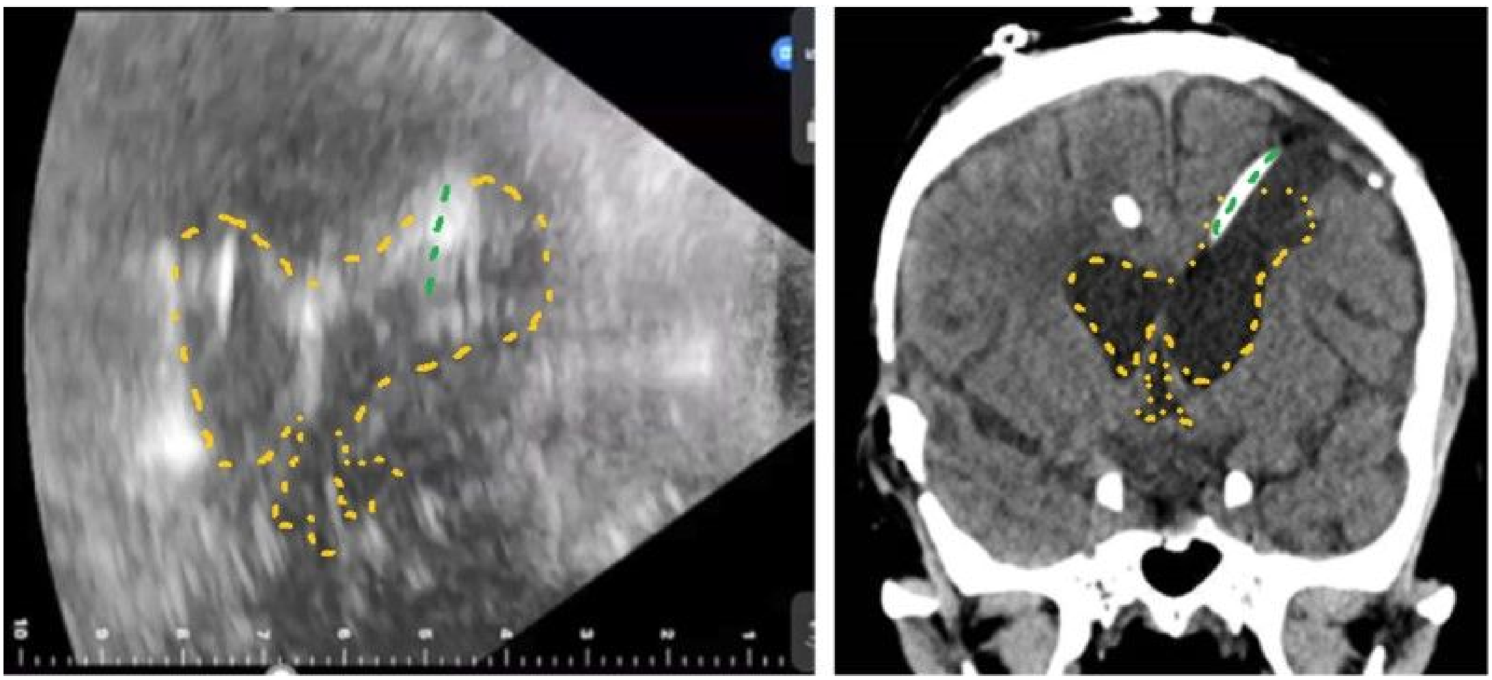

Figure 2

A Complex hydrocephalus case. Left, US, right CT. ventricles contour in yellow dashed line, catheter tip in green.

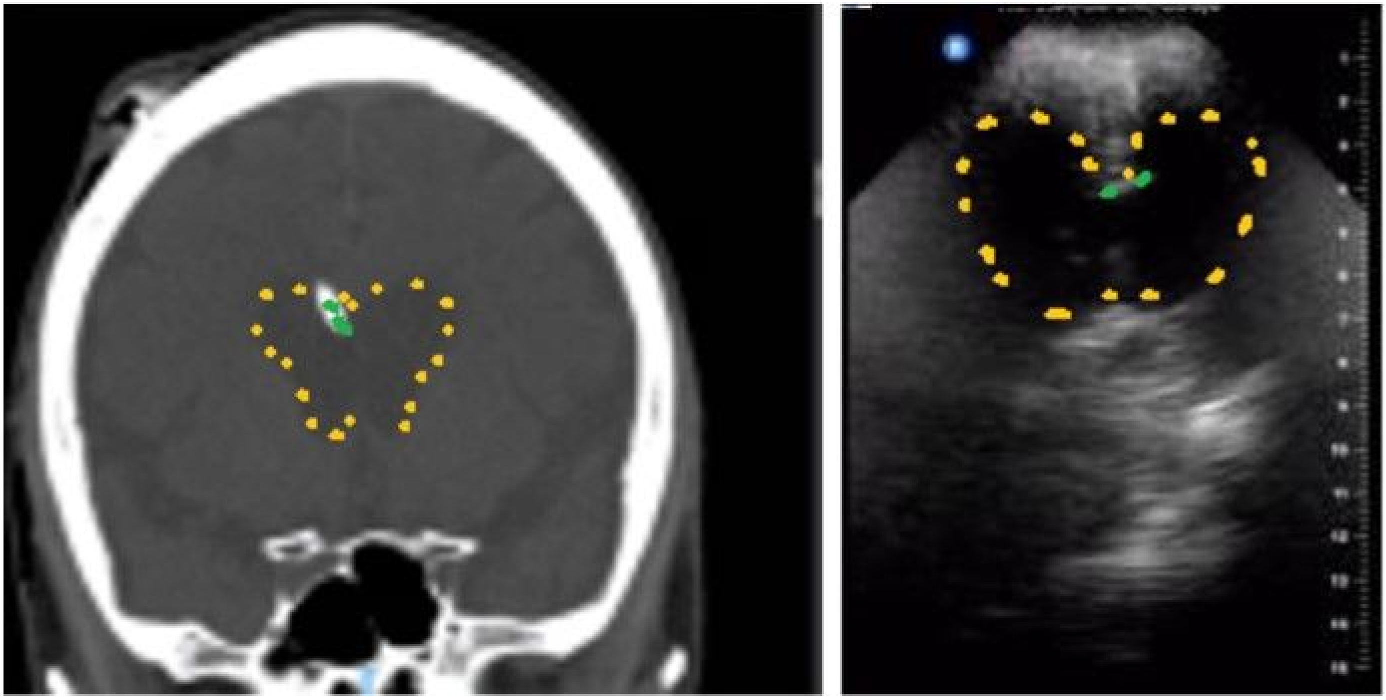

Figure 3

A Normal pressure hydrocephalus case. Left, CT, right US. ventricles contour in yellow dashed line, catheter tip in green.

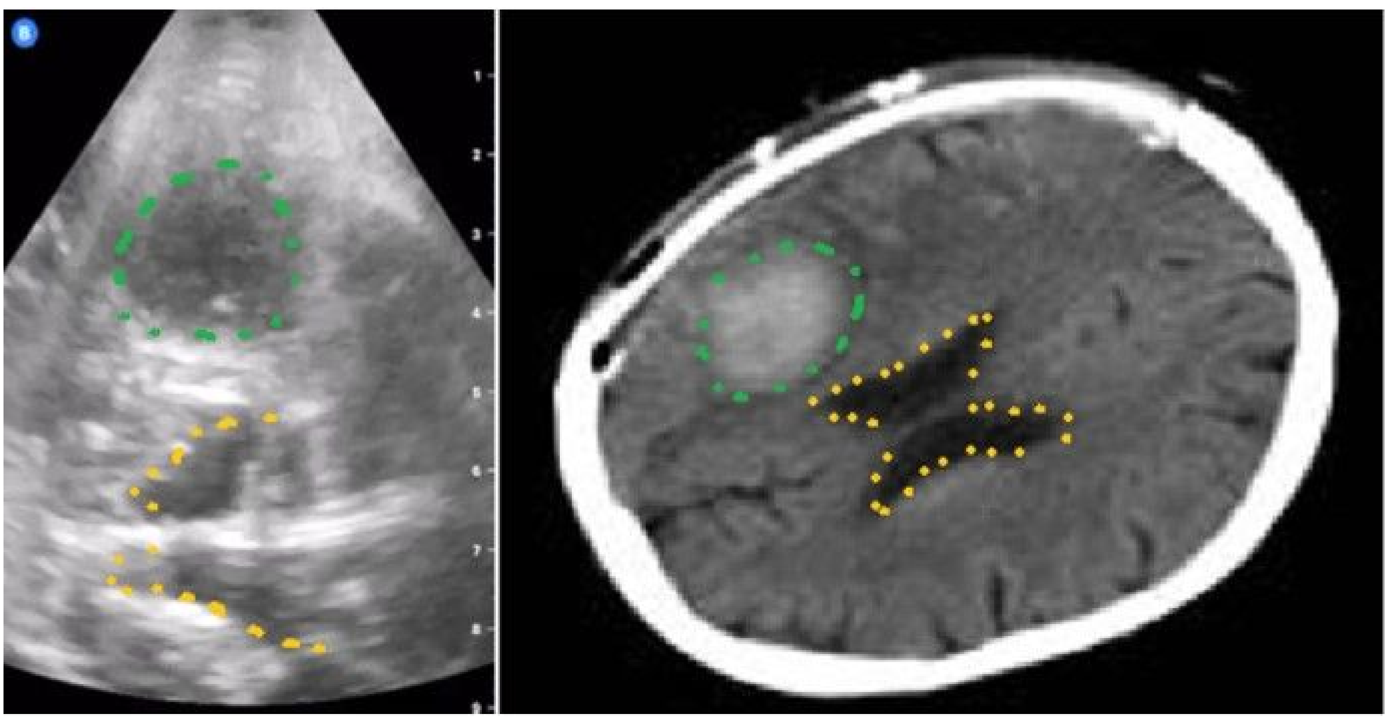

Figure 4

A case of cranioplasty post decompressive hemicraniectomy due to brain swelling and intraparenchymal hematoma. Left, US, right CT. ventricles contour in yellow dashed line, hematoma in green.

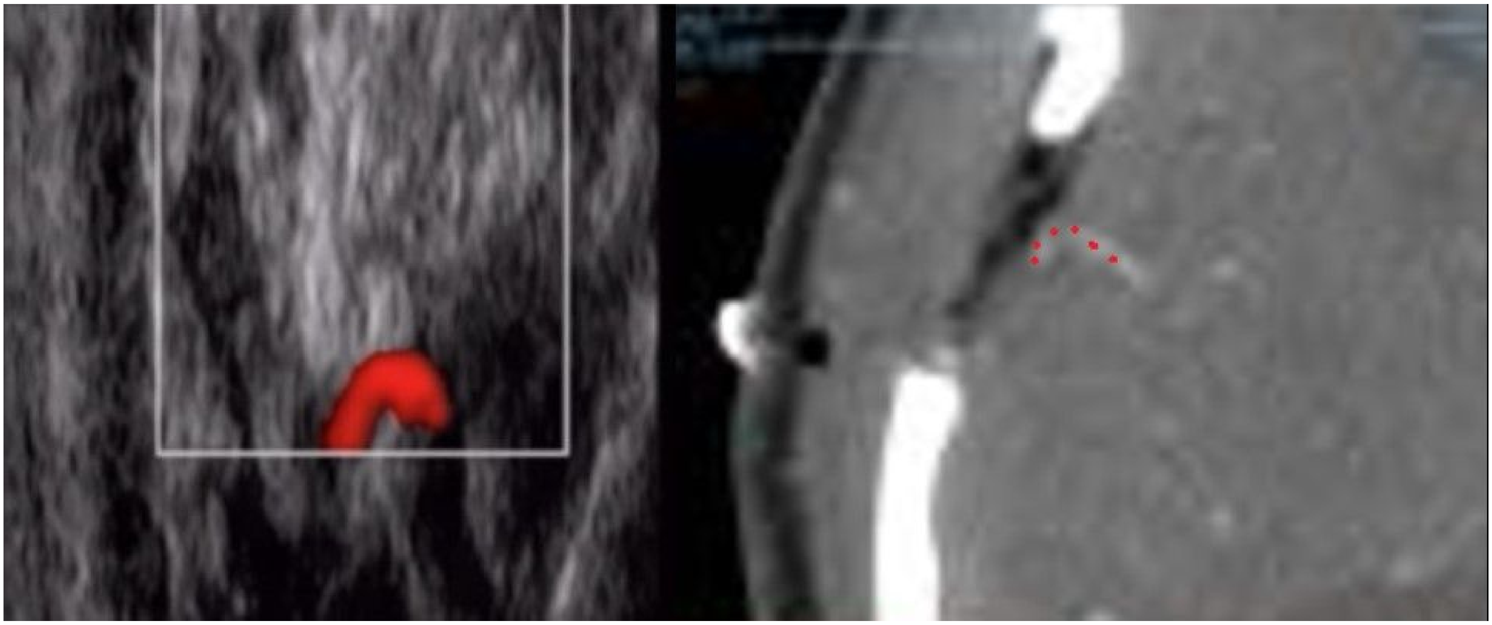

Figure 5

A case of STA to MCA bypass. Doppler mode (vessel marked in red) showing the flow through the graft as it dives into parenchyma after crossing the skull, on US (left) vs CT angiography (right).

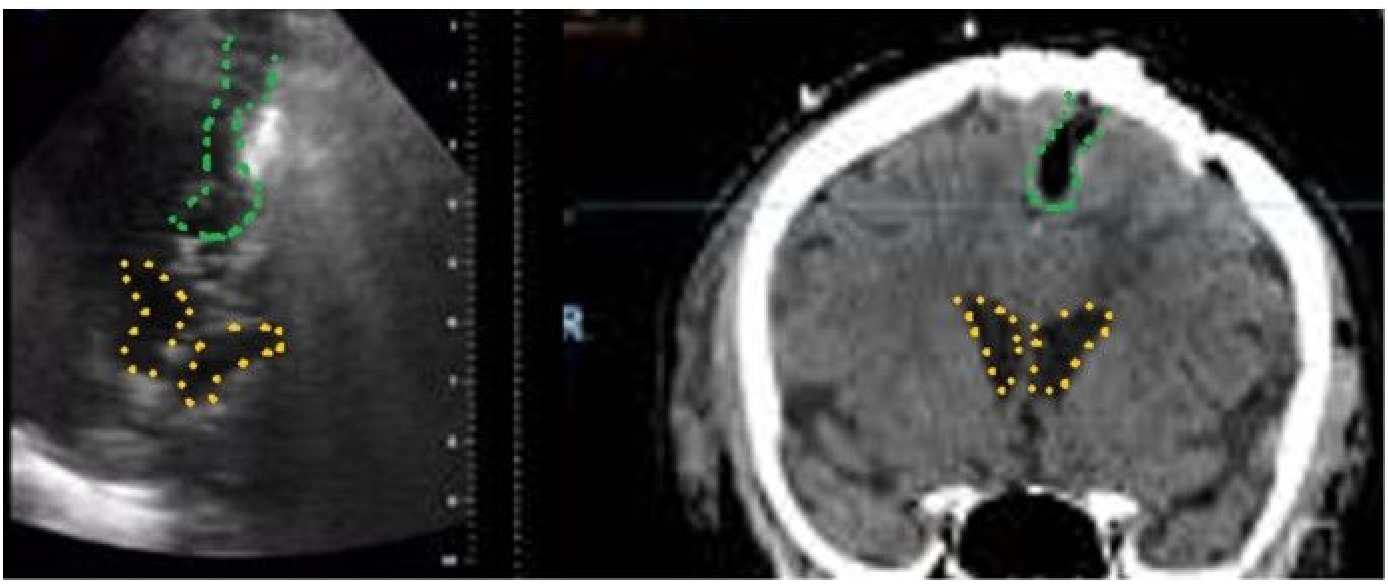

Figure 6

A case of Falx meningioma post resection. Left, US, right CT. ventricles contour in yellow dashed line, tumor cavity in green.