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Comparison of Transcranial Sonography with Computed Tomography of the Brain in Post-craniectomy Patients for Acquired Brain Injury

Bernice Thamarai Selvi[1], Goldwin Helancecil[1], Priyadharshini Muthiah[1], Judy Ann John[2], Naveen Cherian Thomas[2]

[1]Department of Clinical Radiology, [2]Department of Physical Medical and Rehabilitation, Christian medical College, Vellore, India.

Corresponding Author: Dr. Bernice Thamarai Selvi

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ABSTRACT

Background: Decompressive craniectomy is the treatment of choice to relieve raised intracranial pressure in patients with moderate to severe brain injury secondary to stroke and trauma. Computed Tomography (CT) scan is the standard test for monitoring complications in these patients; however, it poses concerns for cumulative radiation and transport risks of the critically ill. Transcranial sonography (TCS) can be an adjunct modality for a quick interim bedside assessment. It is rapid, cost-effective and radiation-free. Several studies have demonstrated that TCS provides a good description of these complications and is comparable to CT scan.

Objectives:

(1) To assess the degree of concordance between TCS and CT scan of the brain in post-craniectomy patients for acquired brain injury.

(2) To assess the diagnostic accuracy of TCS in this cohort.

(3) To describe the technical feasibility and challenges in performing TCS in this cohort.

Materials and methods: In this prospective diagnostic study, 35 patients who underwent decompression craniectomy for acquired brain injury and had a CT scan of the brain as part of routine clinical work-up were included. TCS were performed via craniectomy flap on the same day as the reference CT scan. Investigators were blinded to the CT findings. Various parameters were assessed and compared with CT for concordance and for diagnostic accuracy.

Results: Midline shift was seen in 8.6% and perfect diagnostic agreement was achieved between the two modalities (k=1.00, p<0.001). Almost perfect agreement was observed for ventriculomegaly (κ=0.819). Both modalities demonstrated 100% consensus for parenchymal gliosis, basal cistern patency, and interhemispheric collections. Subdural collections were seen in 20%, and hemorrhagic lesions in 5.7% on both modalities.

Third & fourth ventricular measurements also showed high degree of absolute agreement with no significant inter-modality bias. For ventricular and index metrics, ICC was > 0.97, Bland-Altman analysis showed no significant systematic bias. For ventriculomegaly, TCS demonstrated 92.3% sensitivity, 90.9% specificity, and a Youden Index of 0.832 and for midline shift, TCS achieved 100% sensitivity, 100% specificity, and a Youden Index of 1.0.

Conclusion: Although TCS cannot replace CT, with the given concordance, we conclude that TCS is a reliable, cost-effective adjunct tool for interim and quick evaluation of critically-ill craniectomised patients and in a resource-limited setting.

Keywords: transcranial sonography, post-craniectomy, acquired brain injury, midline shift, ventriculomegaly.

INTRODUCTION

Transcranial Sonography (TCS) is a well-recognised imaging modality to assess the brain in select population. In neonates and infants, the fontanelles are used as the acoustic window. Even in adults, the thin squamous temporal bone provides a good acoustic window to assess the intracranial landmarks and pathologies**(1,2)**. TCS is quick to perform, non-invasive, cost-effective, can be used at the bedside for evaluating critically ill patients, who are unstable to undergo other conventional imaging. It can detect intracerebral hematomas, hydrocephalus, midline shift, and intracranial mass lesions. Transporting such critically ill patients to the CT suite increases the risks of serious complications and increased mortality, alongside the concern for radiation exposure. In this study, we performed TCS on 35 patients with acquired brain injury and assessed its concordance with the standard diagnostic tool, CT scan of the brain.

Acquired Brain Injury:

Acquired brain injury can be either traumatic brain injury (TBI) or non-traumatic (non-TBI). Non-TBI includes stroke, neoplasm, infection, etc.**(3)**.

Traumatic brain injury (TBI) is a major global health problem with high rates of mortality & morbidity**(4)**. It is commonly due to road traffic accidents, assault, and falls. Imaging, mainly Computed Tomography (CT), plays an important role in its management & prognostication. TBI is graded according to the Glasgow Coma Scale (GCS) as mild [13-15], moderate [9-12] and severe [3-8], based on eye, verbal and motor response. Non-contrast CT of the head is the initial imaging modality. It has very high sensitivity to detect fractures, intracranial hemorrhages and raised intracranial pressure (ICP). MRI can be helpful in detecting small foci of TBI, like Diffuse Axonal Injury (DAI). Traumatic intracranial hemorrhages can be intraparenchymal or extra-axial, like subdural hemorrhage (SDH), extradural hematomas (EDH) and subarachnoid hemorrhages (SAH). Parenchymal contusions occur at the coup or contrecoup sites. Secondary brain injuries are caused by mass effect and can result in herniations, infarcts and hydrocephalus.**(3)**

The recommended CT protocol is on a Multidetector CT, with axial sections, on an angled gantry and 5 mm sections are acquired in standard algorithm & 2.5 mm in bone algorithm, along with coronal reconstruction**(4)**. CT findings of raised ICP include effaced sulcal spaces and ventricles, tight posterior fossa and foramen magnum, and/or herniations. These findings require close monitoring and timely surgical interventions like hematoma evacuation and decompressive craniectomy**(5)**. In DAI, a higher GCS score at discharge is strongly associated with a better survival rate & functional recovery**(6)**.

Among the non-TBI, stroke constitutes a major proportion. It can be ischemic or hemorrhagic**(3)**. Ischemic stroke commonly involves occlusion by thrombus of the middle cerebral artery (MCA). Swelling and other neurological symptoms related to raised ICT peak at 48 hours**(3)**. Hemorrhagic stroke is less common. It involves bleeding into the brain parenchyma or into the subarachnoid space. Causes include hypertension: the most frequent cause, anticoagulation, cerebral amyloid angiopathy and vascular malformations. Progressive hemorrhage in a hemorrhagic stroke has poor outcomes**(7)**. As an

immediate measure to reduce the raised ICT, hemicraniectomy is often performed **(3)**.

MATERIALS & METHODS

Study Design and Setting:

This was a prospective, single-centre, diagnostic study conducted in the Department of Clinical Radiology at a tertiary care centre in Tamil Nadu, South India.

Ethical Considerations:

The study was approved by the Institutional Review Board and Ethics Committee [IRB Min. No. 15939 [DIAGNO] dated 06.12.2023]. Written informed consent was obtained from all patients or from their legally authorized representatives. Consent forms were drafted in various languages like English, Tamil, Telugu, Malayalam and Bengali. The same was also explained verbally in detail by the investigators prior to obtaining the consent.

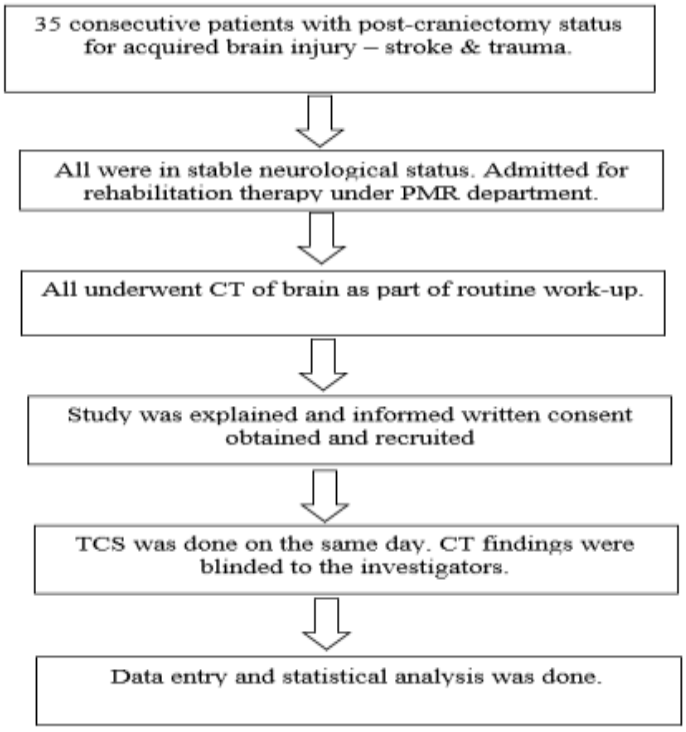
Participant Selection:

We consecutively screened 35 adult patients who had undergone decompressive craniectomy for acquired brain injury and were planned for inpatient rehabilitation in the Physical Medicine and Rehabilitation (PMR) department (figure 1). These patients had a non-contrast CT of the brain as part of their routine clinical work-up. We recruited the participants, after obtaining consent. The interval between the decompressive craniectomy and transcranial sonography (TCS) evaluation ranged from 1 to 11 months. All the patients were in a stable neurological status. The craniectomy flap site was healthy

Eligibility Criteria:

- Inclusion Criteria: Age 18 years and above. Patients who were neurologically stable and were admitted for inpatient rehabilitation, and for whom CT scan of the brain was scheduled as part of their clinical work-up.
- Exclusion Criteria: Patients with poor or unstable sensorium, post-op site ulcers or infection. (However, none of the screened patients were excluded from this study).

Figure 1: Diagrammatic algorithm of the study.



Sample size:

The target sample size was established based on the primary objective: assessing the diagnostic concordance between TCS and brain CT. Relying on data from Caricato et al. **(8)** which reported a 90% baseline concordance rate, the minimum sample size required was determined to be 35 cases. This calculation assumed a 10% margin of error (precision) and a 95% confidence interval.

Imaging Technique and Protocol:

The reference standard was a non-contrast CT scan of the brain. As per our department protocol, it was acquired as 5 mm slice thickness, in brain window, from the occipital condyles to the vertex. Subsequently TCS were performed using a high-resolution B-mode ultrasound device Toshiba Xario 100 W5A16Y224 equipped with 2.5–5 MHz convex probe and 4–11 MHz linear phased-array probes.

TCS was done on the same day as the CT scan. TCS was done using the craniectomy flap as the acoustic window, after applying a coupling gel. To ensure anatomical comparability, TCS images were acquired in the axial plane along the orbitomeatal line, replicating standard CT axial sections. The probe was placed parallel to the orbitomeatal line and by angulating and in sweeping motion, axial sections were obtained from vertex to the skull base. This was followed by a coronal scan perpendicular to the starting plane**(9)**.

On TCS, we assessed & documented the midline, frontal and occipital horns of the lateral ventricles, third ventricle width & fourth ventricular size. We also assessed the gliotic parenchyma for any hemorrhagic focus, any intra & extra-axial collections or interhemispheric hygromas.

Images were archived into PACS and analyzed subsequently.

TCS was done by the third author under the direct supervision of the first author, who is a senior radiologist. To prevent observer bias, the investigator performing the TCS was completely blinded to the patient's CT scan findings. Subsequently, the reference CT was assessed by the first author for the above said parameters and tabulated. The results were then analysed and compared. The average time taken for performing TCS was approximately 15-20 minutes.

Other parameters that were assessed on TCS & CT were basal cistern patency, intra and extra-axial collections and hematomas, interhemispheric collections such as hygromas, parenchymal gliosis.

Statistical Analysis:

Diagnostic statistics and all analyses were performed using SPSS version 21.0. Continuous variables like patient's age, frontal horn size, linear ventricular measurements (3rd ventricle, 4th ventricle) and calculated indices (Cella Media Index, Modified Frontal Horn Index) were presented as means ± standard deviations (SD). The strength of the linear association between TCS and CT was assessed using Pearson correlation coefficients and intraclass correlation co-efficient and corresponding 95% confidence intervals (CI) was calculated via Fisher's z - transformation.

Categorical variables and diagnostic screening outcomes (presence of midline shift, ventriculomegaly, hydrocephalus) are expressed as absolute frequencies and percentages. For this data, inter-modality diagnostic consensus and reliability were quantified using Cohen's kappa statistics with asymptotic 95% CIs. The strength of agreement for Kappa values was interpreted according to the Landis and Koch benchmark.

To evaluate diagnostic performance and screening risk profiles, 2x2 contingency cross-tabulations were constructed, with CT as the reference test. To assess the statistical significance of the association between binary diagnostic classifications, Fisher's exact tests (two-tailed) were utilized. Clinical utility and predictive values were further quantified by calculating Odds Ratios (OR), Positive Likelihood Ratios (PLR), and Negative Likelihood Ratios

(NLR) and Youden Index (J) with their respective 95% CIs. For parameters demonstrating absolute diagnostic consensus with values tending towards infinity or zero, were interpreted as reflecting complete mathematical saturation.

A two-tailed p-value of less than 0.05 was considered statistically significant for all analyses. Bland-Altman plots were constructed to quantify potential systematic bias between TCS and CT measurements.

Figure 2: Methods of assessment of the above-mentioned parameters.

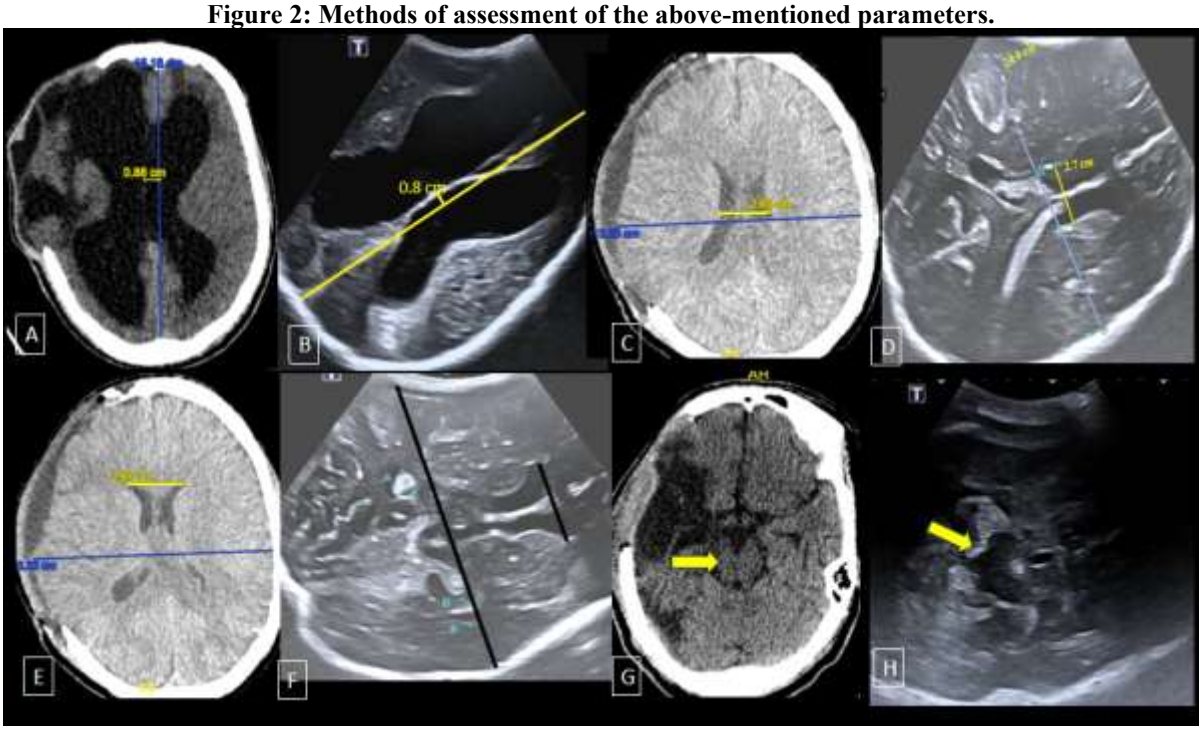


Figure 2: Images A-H are axial non-contrast CT sections of the head in brain window and corresponding axial TCS images.
A & B demonstrate the method of measuring MLS, by drawing a straight line along the midline (blue line on CT image & yellow line on the TCS image) and measuring the displacement of the septum pellucidum ~ 8 mm in this patient.
C & D demonstrate cella media index measurement, which is the ratio of the maximum biparietal diameter (blue line) and maximum external width of the central portions of the lateral ventricles, the cella media (yellow line).
E & F demonstrate modified frontal horn index measurement which is the ratio of maximum width of the frontal horns (yellow line & short black line) of the lateral ventricle to the bicortical distance in the same plane (blue line and long black line).
G & H demonstrate the 'butterfly' shape of the hypoechoic midbrain (yellow arrows), with surrounding anechoic CSF containing basal cistern.

RESULTS

There was 100% data completion on both CT & TCS across all 35 cases, with no missing data. The mean age of the patients in our cohort was 40.2 ± 14.6 years. The most frequent age group was 31–40 years (n=11). 83% were males (n=29) and 17% were females (n=6). 60% had left frontotemporoparietal (FTP) craniectomy, right in 34.3% and bilateral in 5.7% of the patients.

On TCS, the mean ± SD for the ventricles were, Frontal horn: 13.19 ± 6.7 mm, Occipital horn: 18.57 ± 8.3 mm, Temporal horn: 13.81 ± 8.6 mm. The modified frontal horn index and cella media index measured 0.31 ± 0.1 and 4.5 ± 1.1, respectively. Ventricular measurements obtained via TCS demonstrated high linear correlation and

absolute agreement with CT measurements. TCS and CT measurements for the 3rd ventricle were 8.17 ± 4.53 mm and 8.37 ± 4.29 mm, respectively, while the 4th ventricle measured 10.12 ± 4.65 mm on TCS and 10.31 ± 4.31 mm on CT, demonstrating excellent alignment. The mean absolute error (MAE) across all ventricular horns and diameters remained low, ranging from 0.95 mm to 1.94 mm. Paired *t*-test analysis confirmed no statistically significant mean difference between the two modalities for the Cella Media Index ($p = 0.751$), 3rd ventricle ($p = 0.208$), or 4th ventricle ($p = 0.239$). However, a small but statistically significant underestimation was noted on TCS for the Modified Frontal Horn Index (0.306 ± 0.102 vs. 0.324 ± 0.098; ($p = 0.016$). Pearson correlation coefficients demonstrated strong linear tracking in all of the above variables ($p < 0.001$).

To evaluate absolute measurement agreement and device interchangeability, a two-way mixed absolute agreement model was utilized. The intraclass correlation coefficients confirmed excellent absolute agreement for the 4th ventricle (ICC: 0.979, 95% CI: [0.957, 0.990], $p < 0.0001$) and the 3rd ventricle (ICC = 0.978, 95% CI: [0.955, 0.989], $p < 0.0001$). The Modified Frontal Horn Index demonstrated very strong correlation ($r = 0.910$, 95% CI: [0.827, 0.954], $p < 0.0001$) and good-to-excellent absolute reliability (ICC = 0.899, 95% CI: [0.801, 0.949], $p < 0.0001$). Similarly, the Cella Media Index also showed a strong data scalability ($r = 0.906$, 95% CI: [0.821, 0.952], $p < 0.0001$), (ICC = 0.897, 95% CI: [0.798, 0.948], $p < 0.0001$).(Table:1) The slight marginal reduction in ICC compared to Pearson coefficients reflects the effect of a minimal, consistent underestimation bias by TCS

Table 1: Statistical and diagnostic concordance evaluation of TCS versus CT for continuous variables

Index	Pearson Correlation	Intraclass correlation (ICC)	95%CI (Pearson)	95% CI (ICC)	P value	Overall interpretation of correlation and agreement
mFHI	0.899	0.910	0.827, 0.954	0.801, 0.949	<0.0001	Good to excellent
CM index	0.897	0.906	0.821, 0.952	0.798, 0.948	<0.0001	Good to excellent
3rd V (mm)	0.980	0.978	0.960, 0.990	0.955, 0.989	<0.0001	Excellent
4th V (mm)	0.981	0.979	0.961, 0.990	0.957, 0.990	<0.0001	Excellent

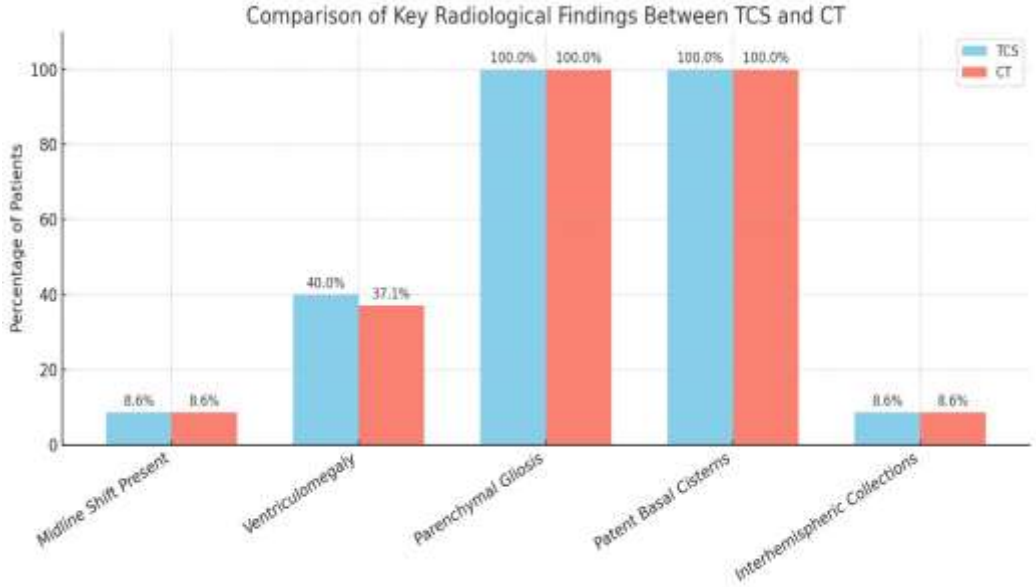
mFHI – Modified Frontal Horn Index; CM – Cella Media; V – Ventricle.

Midline shift was present in 8.57 % of patients (n=3) on both modalities, predominantly toward the right side, and ranging from 6.6 to 10.6 mm.

There was a strong baseline diagnostic concordance between TCS and CT to demonstrate other parameters namely parenchymal gliosis (n=35) and haemorrhage (n=2), which were consistently identified on both modalities in all positive cases. Assessment of basal cisterns patency yielded absolute agreement between modalities (100%), on both TCS and CT. Similarly, interhemispheric collections were infrequent (n=2), with 100% consensus among the modalities.

Extra-axial collections predominantly manifested as subdural hematomas (n=8), localized to frontal or frontoparietal areas with left-hemispheric predominance. Subgaleal collections (n=1) was rarely observed. The thickness of the extra-axial collections correlated closely between modalities (for instance, subdural measurement of 10.7 mm on TCS versus 10.9 mm on CT). None of the patients had intraventricular hemorrhage or intra-axial collections, whereas hemorrhagic lesions were identified in 5.7% in both TCS and CT.

Figure 3: Bar chart comparing TCS and CT findings for the key parameters.



TCS demonstrated diagnostic reliability and agreement when compared against the CT benchmark (Table 2). Absolute consensus and diagnostic divergence of zero were observed for the detection of midline shift, hydrocephalus and a cella media Index of less than 4. For each of these criteria, Cohen's Kappa reached "perfect agreement" (kappa = 1.000, 95% CI: [1.000, 1.000], $p < 0.0001$), while two-tailed Fisher's Exact Tests confirmed the statistically significant association ($p < 0.0001$). The reliability of these parameters was further validated by the Youden index reaching absolute maximum (J=1.000). Due to this complete diagnostic alignment, the corresponding Odds Ratios (OR) and Positive Likelihood Ratios approached infinity or non-estimable, while the Negative Likelihood Ratios dropped to 0.00, demonstrating absolute sensitivity and specificity.

Ventriculomegaly was observed in 40% on TCS and 37.1% on CT and it demonstrated an "almost perfect" agreement (kappa = 0.819, 95% CI: [0.624, 1.000], ($p < 0.0001$). Cross-tabulation showed 3 minor disagreements out of the 35 patients. Despite these minor discrepancies, a positive ventriculomegaly classification on TCS was strongly associated with CT diagnosis (Fisher's exact $p < 0.0001$), with a high diagnostic Odds Ratio of 120 and a Youden Index score of 0.832. The Positive Likelihood Ratio was 10.15 (95% CI: [2.65, 38.92]), and Negative Likelihood Ratio was 0.08 (95% CI: [0.01, 0.58]).

While utilizing the binary cut-off for the Modified Frontal Horn Index (> 0.33), the two modalities demonstrated a "substantial" diagnostic agreement (kappa = 0.763, 95% CI: [0.545, 0.981], $p < 0.0001$). Fisher's Exact Test confirmed that an abnormality on TCS remained highly indicative of a similar finding on CT ($p < 0.0001$). The Odds Ratio was 76 (95% CI: [8.35, 1827.20]) and the Youden Index score was 0.76. The Positive Likelihood Ratio was 6.76 (95% CI: [2.33, 19.60]) and the Negative Likelihood Ratio was 0.089 (95% CI: [0.013, 0.590]). (Table 2)

Table 2: Statistical and diagnostic concordance of Transcranial Sonography (TCS) with Computed Tomography (CT) for categorical variables.

Clinical Evaluation Parameter	Statistical Validator Model	Quantified Parameter Value	95% CI	p-value	(J)	Interpretation
Midline Shift	Cohen's Kappa Fisher's Exact Test OR PLR NLR	1.000 Significant NE NE 0	1.000, 1.000 N/A N/A N/A N/A	< 0.001 < 0.001 < 0.001 < 0.001 < 0.001	1	Perfect Agreement
Cella Media Index (< 4)	Cohen's Kappa Fisher's Exact Test OR PLR NLR	1.000 Significant NE NE 0	1.000, 1.000 N/A N/A N/A N/A	< 0.001 < 0.001 < 0.001 < 0.001 < 0.001	1	Perfect Agreement
Ventriculomegaly	Cohen's Kappa Fisher's Exact Test OR PLR NLR	1.000 Significant NE NE 0	0.624, 1.000 N/A 8.18, 1759.5 2.65, 38.92 0.01, 0.58	< 0.001 < 0.001 < 0.001 < 0.001 < 0.001	0.83	Almost Perfect Agreement
Modified Frontal Horn Index (> 0.33)	Cohen's Kappa Fisher's Exact Test OR PLR NLR	1.000 Significant NE NE 0	0.545, 0.981 N/A 7.06, 817.7 2.33, 19.60 0.013, 0.590	< 0.001 < 0.001 < 0.001 < 0.001 < 0.001	0.76	Substantial Agreement.

CI – Confidence Interval; p-Statistical Significance; OR-Odds Ratio; PLR-Positive Likelihood Ratio; NLR-Negative Likelihood Ratio; NE – Not estimable; N/A-Not applicable; J – Youden Index.

On Bland-Altman analysis for the 3rd ventricle width, the mean systematic bias between modalities was remarkably narrow at -0.200 mm, with 95% Limits of Agreement (LoA) stretching from -1.938 mm to +1.538 mm. Evaluation of the 4th ventricle width yielded an identical pattern, revealing a mean bias of -0.191 mm and corresponding 95% LoA thresholds of -1.945 mm and +1.563 mm. The tightly clustered spatial tracking across the spectrum of ventricular diameters reaffirms the agreement, showing that bedside TCS provides structurally reproducible results, free from confounding artifacts.

Figure 4: Bland-Altman Plot for various ventricular indices.

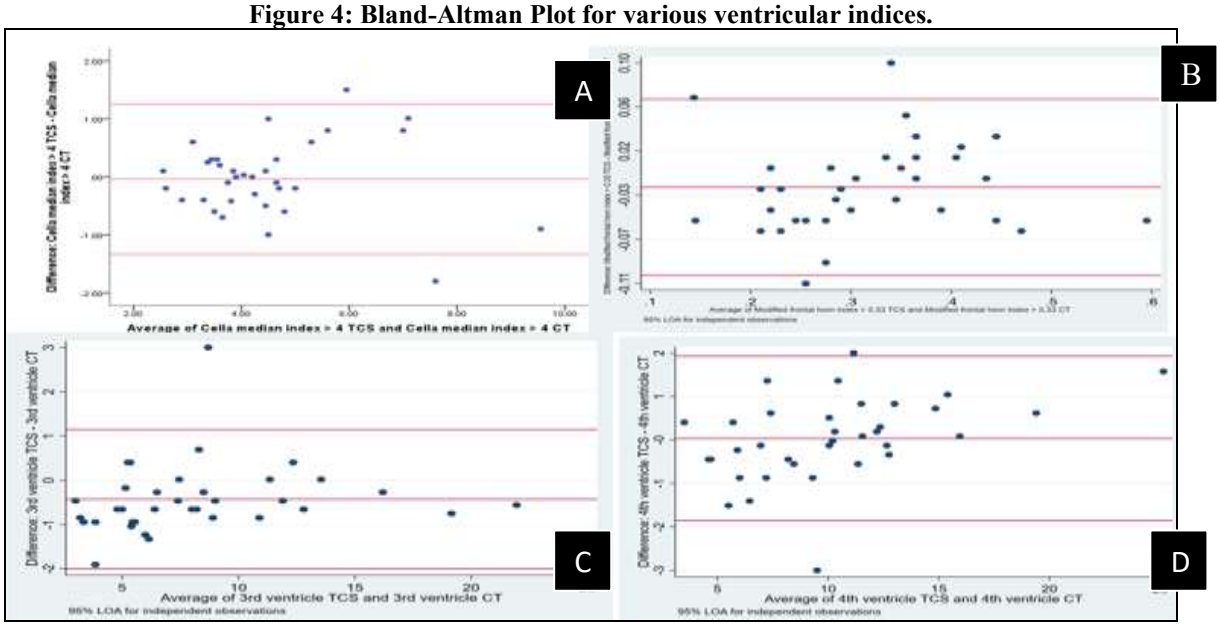


Figure 4: Bland-Altman plots for various ventricular indices on TCS and CT; A-Cella Media Index; B-Modified Frontal Horn Index; C-Third Ventricle and D-Fourth Ventricle.

DISCUSSION

In this prospective study, we analysed the diagnostic performance of TCS compared to CT in 35 consecutive patients, who underwent decompressive craniectomy (DC) following an acquired brain injury. The interval between the DC and transcranial sonography (TCS) evaluation ranged from 1 to 11 months. All the patients were in a stable neurological status at the time of evaluation. Time taken to perform a TCS was about 15-20 minutes.

Mean age of this study population was 40.2 years and males constituted 82.1% of the sample, reflective of the typical demography affected by traumatic or ischemic brain injuries requiring decompressive surgery**(10)**. Patients with left-sided frontotemporoparietal (FTP) craniectomy was more frequently noted in our cohort, and it is consistent with predominant left hemispheric dominance and therefore, due to clinical necessity.

Moderate to severe brain injury due to traumatic or non-traumatic etiologies usually results in decreasing sensorium and increasing intracranial pressure. DC is the preferred surgical intervention in medically refractory intracranial hypertension**(11)**. It stabilizes the degree of morbidity, however, the neurological outcomes range from moderate to severe disability to vegetative state**(12)**.

DC, if performed early in the course of the disease, can be life-saving and improves clinical outcomes**(13)**. Anatomically, DC can be supratentorial or suboccipital, unilateral or bilateral, small (overlying one lobe) or large (FTP) / hemicraniectomy.

Non-contrast CT of the brain is the 'gold standard' for assessment and prognostication of these patients. Various complications have been described following DC, either due to the surgery itself or due to the underlying brain injury, causing disturbances in CSF flow circulation. Clinically significant hydrocephalus results in worsening neurological status or unexplained lack of improvement of sensorium**(14)**. Delayed complications of DC include subdural hygromas – commonly along the falx, paradoxical herniations, syndrome of the Trephined, expansion of previously seen hematomas due to lack of tamponade effect, etc.**(15)**

Hydrocephalus and midline shift are the major complications, which can worsen the morbidity or can be life-threatening. Various studies have shown the usefulness and advantages of TCS in monitoring these complications. Bendella et al in his study quantified the ventricular size **(12)**, while Kiphuth et al established the efficacy of TCS in assisting with programmed drainage of CSF based on the size of the ventricles **(16)**. TCS can effectively detect ventriculomegaly and midline shift, both of which are indicative of evolving hydrocephalus **(17)**.

Ventricular indices like modified frontal horn index (mFHI) of >0.33 and cella media index of <4 and the width of the third ventricle are used to describe ventriculomegaly. Third ventricular width is considered as a reliable surrogate for hydrocephalus**(18)**.

The mFHI is measured by taking the ratio of maximum width of the frontal horns of the lateral ventricle to the bicortical distance in the same plane, value of >0.33 indicates ventriculomegaly. Whereas Evan's index is the ratio of the frontal horn distance to the maximum internal diameter of the skull. Normal value is 0.20 to 0.25. Cella media index is the ratio of biparietal diameter of the skull to the maximum external width of the central portions of the lateral ventricles, the cella media**(19)**. Value less than 4 is considered as ventriculomegaly.

Midline shift (MLS) is measured as the distance from the anatomical midline to the septum pellucidum, at the point of maximum deviation. MLS of >5 mm on the initial CT results in poor neurological outcome with a PPV of 78% and >10 mm results in two-fold increase in mortality**(20)**.

Basal cistern patency is an important indicator of normal intracranial pressure and

preserved midline. Midbrain is a standard and consistent landmark on both CT & TCS. It is identified as a well-demarcated hypoechoic 'butterfly' shaped structure in the centre of the cranium. It is a reliable landmark for localising other structures on TCS. It is surrounded by anechoic CSF, which is the basal cistern(2). Obliteration of this CSF space indicates raised pressure and if the space appears hyperechoic, it suggests haemorrhage into the subarachnoid space. Methods of measuring these parameters are shown in Figure 1.

Figure 5: CT and TCS images of patients demonstrating the relevant observations.

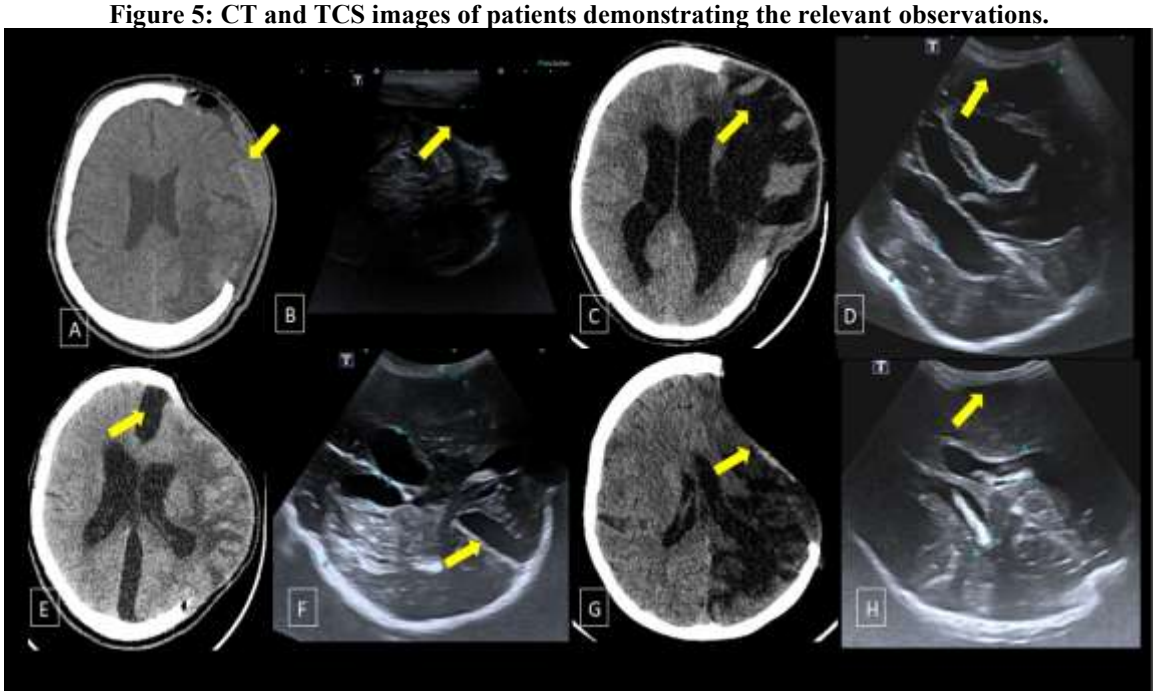


Figure 5: Images A & B demonstrate a crescent shaped subgaleal collection (yellow arrow) along the left frontal convexity on the CT. Corresponding TCS image with a high frequency probe shows an anechoic collection (yellow arrow). Although it appeared isodense on CT, we could not demonstrate any debris within this collection on TCS.
Images C & D demonstrate a large area of gliotic parenchyma in the left frontal lobe, bulging through the craniectomy defect (yellow arrow). Although there was technical difficulty in achieving good contact with the convex probe, there was adequate visualization of the intracranial structures on TCS, as demonstrated in image D.
Images E & F demonstrate subdural hygroma, along the left side of the anterior & posterior falx (yellow arrow), which is of CSF density on the CT and anechoic (yellow arrow) on TCS.
Images G & H demonstrate mild inward sinking of the craniectomy flap (yellow arrow) along the left frontal convexity on the CT. However, there was adequate visualization of the intracranial structures on TCS.

Figure 6: CT and TCS images demonstrating few other relevant observations.

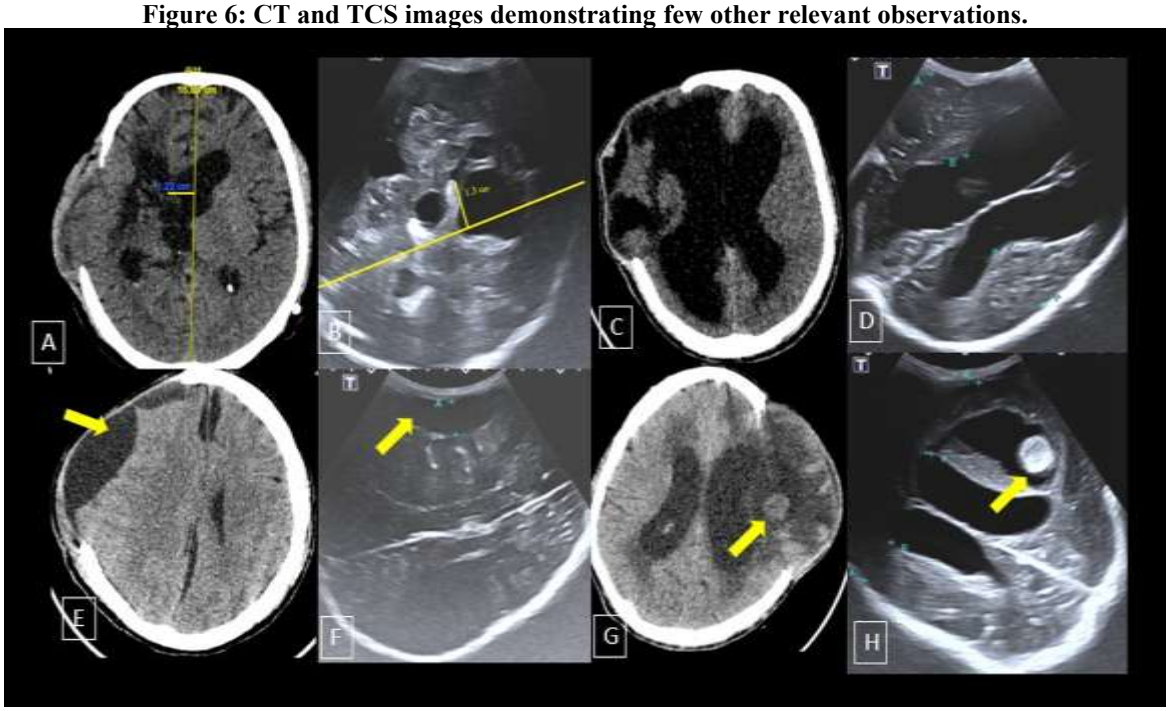


Figure 6: Images A & B demonstrate MLS. Anatomical midline is first drawn (long yellow line on CT and TCS). The distance of the displaced septum pellucidum from the midline is drawn (small yellow line on both). There is a MLS midline shift of 1.3 cm to the right.
Images C & D demonstrate ventriculomegaly, more prominent on the right. TCS image also shows Cella Media index, marked by blue calipers, 'a' width of bilateral cella media and 'b' the biparietal distance.
Images E & F demonstrate chronic subdural CSF density collection along the right frontal convexity on the CT. Corresponding anechoic area is seen on the TCS, indicated by yellow arrows in both images. There is mild indentation of the brain parenchyma. CT also shows that the collection is loculated.
Images G & H demonstrate a small rounded organized hemorrhage within the gliotic parenchyma in the left frontal lobe, suggestive of resolving hemorrhage. It appears well-defined, hyperdense on CT and hyperechoic on TCS, indicated by yellow arrows.

Our study population included two different etiologies i.e., trauma and stroke, however, the resultant brain injury is similar across the cohort, which is moderate to severe, thereby requiring decompression craniectomy. There was no change or drop in the neurological status between the CT & TCS. None of the patients had poor acoustic window. Belzberg et al have documented that polymethyl methacrylate (PMMA) implants used for cranioplasty can also be used as good acoustic window to perform TCS**(21)**.

Investigators were blinded to the CT findings before performing TCS, which minimized the confirmation bias. In our study, quantitative measurements of the frontal, occipital, and temporal horns, as well as the third and fourth ventricles, demonstrated excellent agreement between the two modalities, with intraclass correlation coefficients (ICC) exceeding 0.9 for all structures. Cronbach's alpha values were above 0.9 further indicated high internal consistency, confirming the reliability of TCS in ventricular assessment. This was consistent with Aggarwal et al, who demonstrated a strong correlation between TCS and CT findings**(9)**.

The modified frontal horn Index measurement in TCS demonstrated high diagnostic accuracy in detecting ventriculomegaly, with a sensitivity and specificity of 92.3% and 90.9%.

5.7% of our patients had hemorrhagic lesions which were identified in both TCS and CT. This was similar to the study

conducted by Ha et al., who observed a strong correlation between TCS and CT(22). Overall, the analysis highlights the emerging role of TCS as a reliable, non-invasive, bedside imaging modality in neurocritical care and neuro-rehabilitation.

Brief comparison of our study with other published articles, emphasizing differences in sample size and diagnostic parameters:

Previous studies evaluating the diagnostic utility of transcranial sonography (TCS) have generally been limited by relatively small sample sizes, retrospective study designs, or assessment of a restricted number of imaging parameters. Aggarwal et al. evaluated 40 patients and assessed only two parameters, namely midline shift and mass lesion (9). Kapoor et al. included a smaller cohort of 17 patients and focused exclusively on the assessment of midline shift through third ventricular evaluation (23). Likewise, Oliveira et al. studied 15 patients and assessed third ventricular width, perimesencephalic cistern patency, and the sylvian fissure (24). De Bonis et al. conducted a study involving 10 patients and reported only selected ventricular indices (25). Bendella et al. retrospectively evaluated 20 patients with different intracranial pathologies, limiting their assessment to ventricular dimensions and Doppler evaluation of the intracranial arteries (12). Although Lasselin et al. reported a considerably larger single-centre retrospective study comprising 177 patients, their analysis was confined to midline shift and third ventricular diameter (26).

Technical Challenges and Limitations of our study:

Although TCS have been assessed by various researchers in many studies, it is a less commonly performed test. Being a novel technique, there was a learning curve to perform TCS, which could have impacted the results. Sonography, being an operator-dependent modality, could exaggerate the variability of the results. To minimize this bias, all the scans were done by the third author under direct supervision of the first author who is a senior radiologist, ensuring consistency in technique and interpretation.

We did not assess inter-observer variability, which is an important limitation. Future studies should incorporate assessment of inter-observer agreement and establish reproducibility among different operators and different clinical settings.

Being a single centre study and the given modest sample size, generalization of the results might be challenging. Larger multicentre trials are required to validate TCS in terms of standardizing protocol, establish training modules and to achieve reproducibility. TCS can be integrated into the neuro-ICU imaging work-flow, to aid in early detection of ventriculomegaly and midline shift. Although TCS cannot replace CT, it is an excellent triage tool.

Limitation regarding patient selection is that our cohort included patients with stable neurological status, which might have facilitated clearer visualisation of the intracranial structures. However, in an ICU setting, the neurological conditions are expected to be heterogenous, and of variable morbidity. In critically ill patients, the results may be influenced by the need for quick decision making, technical difficulties and the expertise of the radiologist. Future studies should include patients with a wide spectrum and severity of neuro-morbidity.

Bulging of the gliotic parenchyma at the craniectomy site was seen in few patients. There was also mild inward sinking of flap in few other patients. These resulted in some technical difficulty. We could partially overcome this by rocking motion of the probe or by using an acoustic phantom like gel pad.

Another minor limitation is that we did not perform serial TCS to assess the natural course of the pathologies or follow-up scans after treatment – like shunt placement.

Pending validation in larger prospective studies, we conclude that TCS is a reliable bedside neuro-monitoring tool and can aid in clinical decision making in resource-

limited settings or in critically ill patients. However, generalizability of results beyond this subset of patients is restrictive.

CONCLUSION

With technological advances, TCS has gained increasing utility in the past two decades, even through an intact skull, in applications like DBS lead localisation, detection of early Parkinsonism & space occupying hematomas. However, TCS through craniectomy flap offered better acoustic window and thereby better visualisation of the intracranial structures and abnormalities. Our article highlights the utility of TCS in clinically vulnerable patient subset.

Our study demonstrated excellent diagnostic accuracy and strong concordance between TCS and CT in evaluating post-craniectomy complications like ventricular enlargement, midline shift, intracranial hematomas, interhemispheric collections, basal cistern patency, and parenchymal gliosis. TCS provides a good point-of-care investigation, affordable in a resource-limited setting and when there is a drop in sensorium of a craniectomized patient, utilizing TCS enhances patient safety by avoiding transportation of these patients to the CT suite. As an interim exam, between CT scans, risk of cumulative effects of radiation exposure can be minimized in younger patients.

Declaration by Authors:

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