# Ultrasonography for Serial Monitoring and Management of Cerebrospinal Fluid Dynamic Disorders After Decompressive Craniectomy

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**Objective:** Decompressive craniectomy (DC) is widely used to treat intracranial hypertension following severe head injury. However, impairments of cerebrospinal fluid (CSF) hydrodynamics such as hydrocephalus and subdural effusion are common complications that occur after DC. Therefore, monitoring of intracranial pressure is a staple of neurocritical care post-DC. The aim of this study was to assess the usefulness of transcranial duplex sonography (TDS) for serial monitoring and management of CSF disorders after DC.

**Methods:** A total of 100 patients who underwent DC between June 2016 and May 2019 were recruited for the study. Transcranial duplex sonography examinations were performed between 1-day and 1-year post-DC. Transcranial duplex sonography was mainly used for monitoring changes in ventricle size and morphology, and also to monitor intraventricular hemorrhage, hydrocephalus, intracranial hygromas, and ventricle changes during CSF release procedures.

**Results:** A total of 456 TDS examinations were performed on patients after DC. Of these, 402 were performed in the neuro–intensive care unit. Two patients had intraventricular hemorrhage and underwent TDS-guided external ventricular drainage. Twenty-nine patients were diagnosed with hydrocephalus. The results of TDS were consistent with those of cranial computed tomography. Three cases of ventriculoperitoneal shunt and 1 case of lumbar peritoneal shunt underwent valve pressure reset according to TDS, to obtain satisfactory ventricle size. Transcranial duplex sonography was used to monitor ventricle changes and control drainage volume during CSF release procedures, including 2 external ventricular drainage, 6 external lumbar drainage, and 10 lumbar punctures. Eighteen patients were detected with single or multiple intracranial effusions, including 16 subdural hygromas, 5 longitudinal fissure hygromas, and 6 brain cysts.

**Conclusions:** Transcranial duplex sonography can efficiently help monitor changes in ventricle size and morphology and intracranial effusions. Due to its noninvasive nature, suitability for bedside application, real-time, and inexpensiveness, TDS can significantly replace cranial computed tomography and become part of the patient's daily inspection work after DC.

Decompressive craniectomy (DC) is widely used to treat intracranial hypertension following a severe head injury or cerebral vascular disease.[1,2] Although it is a lifesaving procedure, it may be associated with several postoperative complications such as including hematoma expansion, epilepsy, infection, herniation of the cortex through the bone defect, and cerebrospinal fluid (CSF) leakage through the scalp incision, CSF disorders, etc.[3] Among them, disorders of CSF dynamics including hydrocephalus, subdural effusion, and "syndrome of the trephined" are peculiar complications that develop after DC.[4,5] Therefore, monitoring of intracranial pressure (ICP) is a staple of neurocritical care post-DC.

Since its introduction in the 1970s, cranial computed tomography (CCT) remains the gold-standard imaging tool for primary intracranial injuries. Cranial computed tomography allows for the rapid assessment of intracranial hematoma, brain edema, ischemic infarcts, ventricle, and midline shift. However, the hazards of transferring an intubated or unstable patient to the computed tomography scanner may be a time-consuming and resource-consuming task.[6] A portable computed tomography scanner is not universally available and is expensive, especially in

developing countries. Recently, there has been an increasing interest in the use of ultrasonography to manage critically ill patients. Ultrasonography has become the frontline diagnostic tool in emergency care because of its noninvasiveness, suitability for bedside imaging, and the feasibility to perform repeated assessments in sick patients.

Ultrasonography is widely used in neurosurgery, especially for preoperative planning and intraoperative guidance. Transcranial duplex sonography (TDS) was first introduced in 1989, as an addition to CCT, for the visualization of the basal cerebral arteries through the intact skull by color-coding of blood flow velocity.[7] Transcranial duplex sonography allows monitoring of brain parenchyma, hematoma, ventricular size, midline shift, and cerebral hemodynamic changes.[8,9] Transcranial duplex sonography has potential advantages including concomitant assessment of brain hemodynamics and the feasibility of bedside application. Usually, skull thickness and bone density often limit the image quality achieved by TDS. However, DC may present an ideal window to visualize intracranial anatomy with a high resolution. The aim of this study was to increase the usefulness of TDS for serial monitoring and management of disorders of CSF hydrodynamics after DC.

## METHODS

### Patients

A total of 100 patients (58 males and 42 females; mean age: $54.7 \pm 15.5$ y) who underwent DC between June 2016 and May 2019 were included for the study. Among them, 14 patients suffered an ischemic stroke, 48 patients had a cerebral hematoma, 25 patients had a traumatic brain injury, 3 patients underwent tumor resection, and 10 patients underwent aneurysm clipping. Decompressive craniectomy was performed according to regular surgical procedures. Exclusion criteria included patients who underwent posterior fossa DC and died shortly afterward. Forty-three patients underwent left-sided DC, 52 had right-sided DC, and 5 had bilateral DC.

### Instrument and Procedures

Transcranial duplex sonography was performed using a hand-held pocket ultrasound device with a convex probe LOGIQ V2 (GE Healthcare, IL). The examinations were performed by a neurosurgeon under the guidance of a registered sonographer. The examination required little to no special patient preparation except for a good head position. The skin and probe were cleaned with saline solution. The probe assembly was directly inserted through the skin to rest on the bone. The transverse or axial plane was obtained by placing the probe on the anterior surface of the skin, and the coronal plane was obtained by placing the probe at a 45-degree angle to the orbito-meatal line with a varying angle between probe surface and skin.[6] Image brightness, contrast, and time-gain compensation were adjusted to get the best image.

The ventricular system in the brain was systematically observed. Hydrocephalus was diagnosed using the criteria described by Gudeman et al[10] (lateral and third ventricular enlargement) or the modified Frontal Horn Index $\geq 33\%$[11] combined with clinical symptoms. The width of the third ventricle, the largest width of the bilateral frontal horns, and the modified Frontal Horn Index was measured in all patients. Cranial computed tomography was performed before the final diagnosis of hydrocephalus and intracranial effusion. The data from CCT was measured by another neurosurgeon blinded to TDS results. The diagnosis of hydrocephalus was confirmed by at least 3 neurosurgeons.

For patients who underwent external ventricular drainage (EVD), external lumbar drainage (ELD), and ventriculoperitoneal shunt (VPS), TDS was performed before drainage and at 8 am every day after drainage. The speed of drainage was controlled at a constant rate. For patients who underwent lumbar puncture, TDS was performed before lumbar puncture and when the release volume was 10, 20, and 30 mL, respectively.

The study was approved by the hospital ethics committee. All study-related examinations were conducted in accordance with the World Medical Association Declaration of Helsinki.

### Statistical Analysis

Statistical analysis was performed with SPSS software 22.0 (IBM, Armonk, NY). Continuous variables with normal distribution are presented as mean $\pm$ SD. A linear regression analysis was used to compare the ventricle width values and Frontal Horn Index acquired using TDS and CCT. A value of $P < 0.05$ was considered statistically significant.

## RESULTS

A total of 456 TDS examinations were performed in all patients following DC. Of which, 402 (88.2%) were performed at the neuro–intensive care unit, the remaining at other locations including common ward (n = 30), outpatient department (n = 16), emergency department (n = 5), and the operation theater (n = 3). The basic demographics and characteristics of the patients are listed in Supplemental Table 1 (Supplemental Digital Content 1, http://links.lww.com/SCS/E169). The TDS examination was performed between 1-day and 1-year after DC. Transcranial duplex sonography was used for monitoring intracranial status, especially ventricle size and morphology.

### Intraventricular Hemorrhage and Transcranial Duplex Sonography–Guided External Ventricular Drainage

Transcranial Duplex sonography was very helpful for the detection and serial monitoring of IVH. Seven patients were observed for IVH. Of which, 5 cases had IVH before TDS examination. Two cases were found to have IVH and underwent TDS-guided EVD. The typical case is as follows.

### Case 1

A 32-year-old man underwent left-sided DC following a traumatic brain injury. Ventriculoperitoneal shunt was performed due to the presence of hydrocephalus 1-month post-DC. The patient fell into a persistently unconscious state. On postoperative day 12 after VPS, the patient was found to have dilated right-sided pupil and high ICP through the bone window. The patient could not be transported to the radiology department for CCT due to long-distance travel. Then bedside TDS was used to evaluate the intracranial status. The results revealed IVH and hydrocephalus. We speculated that the ventricular catheter was obstructed by blood. Urgently, the patient underwent bilateral EVD under the guidance of TDS. Transcranial duplex sonography was performed every day and CCT when necessary. About 1 week later, the hematoma was mostly absorbed, and hydrocephalus was relieved. The results of TDS were consistent with those of CCT (Fig. 1).

### Hydrocephalus

The lateral and the third ventricles could be clearly observed in all patients, but the fourth ventricle was restricted to only
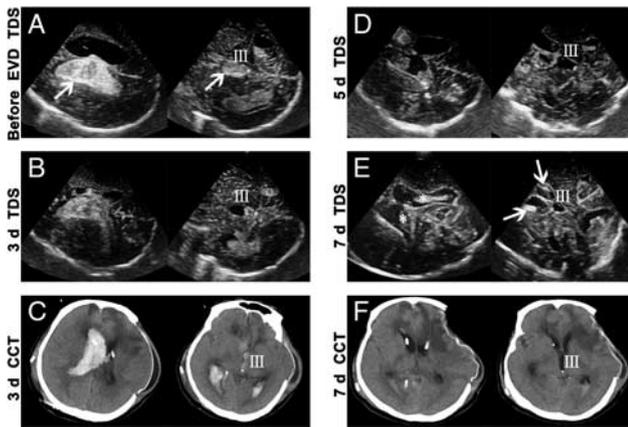
FIGURE 1. TDS was used for serial monitoring of intraventricular hemorrhage. (A) TDS revealed the right lateral and the third ventricular hematoma cast (arrow: the right ventricle hematoma, III: the third ventricle). (B and C) Three days after external ventricular drainage, only a small part of hematoma absorption, but hydrocephalus decreased, there was no significant difference between TDS and CCT. (D) Five days after external ventricular drainage, the hematoma further reduced. (E and F) One week after external ventricular drainage, both TDS and CCT revealed the hematoma mostly absorbed, and hydrocephalus relieved (III: the third ventricle, asterisk: choroid plexus, arrow: bilateral ventricular catheters). CCT indicates cranial computed tomography; TDS, transcranial duplex sonography.

72 patients. It might be related to the low position and irregular shape of the fourth ventricle. Twenty-nine patients were finally diagnosed with hydrocephalus. The mean width of the third ventricle of the 29 patients was 12.4 mm ($\pm$2.1) in TDS and 12.1 mm ($\pm$2.9) in CCT, respectively. There was a significant correlation between the 2 methods (correlation coefficient $r = 0.818$, $P < 0.001$) (Fig. 2A). The mean width of the bilateral frontal horns was 47.5 mm ($\pm$2.8) in TDS and 47.7 mm ($\pm$3.4) in CCT, respectively. There was a significant correlation between the 2 methods (correlation coefficient $r = 0.985$, $P < 0.001$) (Fig. 2B). The mean Frontal Horn Index was 0.39 ($\pm$0.04) in TDS and 0.40 ($\pm$0.04) in CCT, respectively. There was a significant correlation between the 2 methods (correlation coefficient $r = 0.829$, $P < 0.001$) (Fig. 2C).

Moreover, TDS was also used for monitoring ventricle changes after the CSF shunt. Three cases of VPS and 1 case of lumbar peritoneal shunt underwent valve pressure reset according to TDS, to obtain satisfactory ventricle size. The typical case is as follows.

## Case 2

A 53-year-old man underwent clipping of intracranial aneurysm and right-sided DC (Fig. 2D). One month later, TDS and CCT images revealed hydrocephalus (Fig. 2E). Then VPS was performed. Two days after VPS, the patient presented obvious depression in the bone window. Transcranial duplex sonography revealed extremely small ventricles and excessive diversion (Fig. 2F). Immediately, the value pressure was adjusted from 1.0 to 1.5 atm (Medtronic, Dublin, Ireland). Two days later, the ventricle reverted to a satisfactory size (Fig. 2F).

## Changes in Ventricle Size During Cerebrospinal Fluid Release

Transcranial duplex sonography was used for monitoring ventricle size changes during CSF release procedures including 2 EVD, 6 ELD, and 10 lumbar punctures. In the case of EVD and ELD, the drainage volume was controlled using TDS. The width of the third ventricle and drainage volumes is shown in Supplemental Table 2

(Supplemental Digital Content 1, http://links.lww.com/SCS/E169). The typical image of 1 case of ELD is shown in Figure 3. In the cases of lumbar puncture, the average CSF release volume was 30 mL; the mean diameter of the third ventricle was 10.8 mm ($\pm$3.6) before lumbar puncture and the diameter was 4.4 mm ($\pm$2.5) when the drainage volume was 30 mL.

## Ventricle Morphology, Interventricular Foramen, and Aqueducts of Sylvius

Lateral ventricle malformation and asymmetry were observed in 12 cases (Fig. 4A). About 94 cases showed fluent bilateral interventricular foramen (Fig. 4B). Three cases showed obstruction of the unilateral interventricular foramen, and these cases were often associated with lateral ventricle malformation and asymmetry (Fig. 4C). Three cases could not be inferred. Twenty-two cases clearly showed patency of the aqueducts of Sylvius (Fig. 4D).

## Intracranial Hygromas

Eighteen cases (18%) were detected with single or multiple intracranial hygromas, including 16 subdural hygromas, 5 longitudinal fissure hygromas, and 6 brain cysts. All patient cases were confirmed using CCT. One patient had abscess before CCT and underwent TDS-guided puncture and drainage, and the result was excellent (Fig. 5).

# DISCUSSION

## Applications of Transcranial Duplex Sonography

Cerebrospinal fluid helps protect and cushion the brain and acts as a shock absorber for the central nervous system. Continuous circulation of CSF is impaired after DC, inducing disturbances in CSF absorption and distribution, consequently, neurological symptoms, which are called CSF dynamic disorders.[5,12] Early warning and treatment of CSF dynamic disorders are very important for accelerating patient recovery. The postoperative monitoring after DC usually relies on repeated CCT. However, transporting the patient for CCT is sometimes inconvenient and has been associated with a high incidence of adverse events.[12] All critically ill patients need ECG monitors and respirators during transportation. The risk factors include heavy traffic and bad weather. Some patients appeared to suffer from epilepsy and respiratory arrest during transport. In such situations, TDS may be very helpful.

Previous studies have shown that TDS was helpful for observing cerebral hemorrhage, ventricular size, and midline shift. Especially for patients after DC, skull windows allow high resolution. Bendella et al[6] assessed and quantified the dimensions of all 4 ventricles using TDS. Kiphuth et al[13] proposed that TDS could be used for clamping and removal of the lumbar or extraventricular drainage. Even for patients who have undergone cranioplasty, some sonolucent cranial implants can also represent a postoperative window into the brain for TDS. Belzberg and colleagues[14,15] reported that TDS via the clear poly-methyl-methacrylate implant could reveal recognizable ventricle and epidural fluid collection corresponding to CCT in a single patient. In this study, we performed long-term serial monitoring in a large number of patients after DC using TDS. The main monitoring events were CSF circulation dynamic disorders.

## Intraventricular Hemorrhage

Intraventricular hemorrhage is an uncommon complication after DC.[16] Intraventricular hemorrhage often induces acute
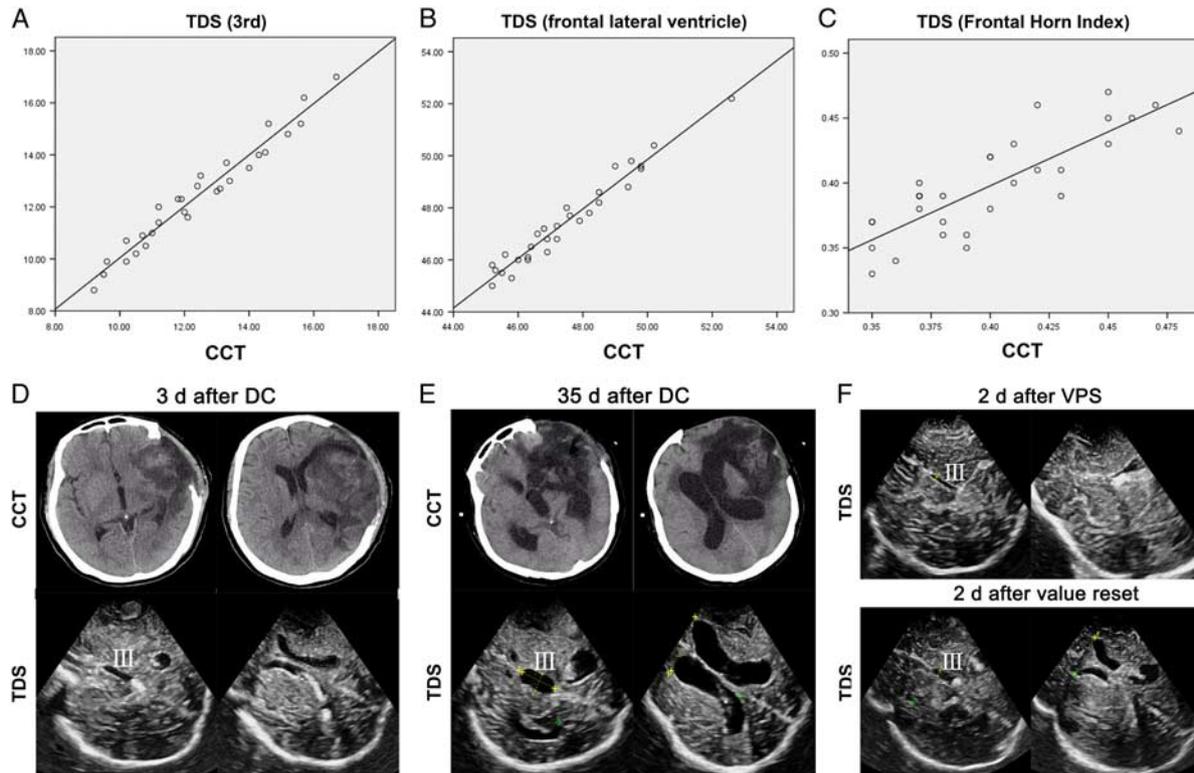
**FIGURE 2.** TDS was used for diagnosis and management of hydrocephalus after DC. (A) Linear correlation of the width of the third ventricle between TDS and CCT. (B) Linear correlation of the largest width of the bilateral frontal horns between TDS and CCT. (C) Linear correlation of Frontal Horn Index between TDS and CCT. (D) TDS and CCT 3 days after DC, the width of the third ventricle was 5.8 mm in TDS. (E) TDS and CCT 35 days after DC, the width of the third ventricle was 13.2 mm in TDS. (F) TDS 2 days after VPS, the width of the third ventricle was 2.6 mm. TDS 2 days after value reset, the width of the third ventricle was 6.4 mm (III: the third ventricle). CCT indicates cranial computed tomography; DC, decompressive craniectomy; TDS, transcranial duplex sonography; VPS, ventriculoperitoneal shunt.

hydrocephalus.[17] We found 2 cases of delayed IVH after operation by TDS, which provided great convenience for timely diagnosis and rescue. The hematoma appears as hyperechoic in the ventricle. Transcranial duplex sonography is also capable of guiding precise ventricular puncture because the ventricular catheter is visible under TDS. This represents the notable utility of TDS for directing management decisions.

## Hydrocephalus and Intracranial Hygromas

According to the previous reports, the incidence of hydrocephalus was reported to be 0.7% to 86%.[5] The diagnosis of hydrocephalus is based on the enlargement of the lateral ventricle and third ventricle, or the Frontal Horn Index and the Evans Index, combined with the clinical symptoms of the patient.[10,11] Kerscher et al[18] reported that changes in the width of the third ventricle directly reflect changes in the lateral ventricle in hydrocephalus. The third ventricle could be a reliable surrogate of the entire ventricular system to be measured alone. In this group of patients, the incidence of hydrocephalus after DC was 29%. Transcranial duplex sonography could clearly show the shape and precise size of the lateral ventricle and the third ventricle. Transcranial duplex sonography results were completely consistent with CCT. Through dynamic monitoring of ventricle changes after the CSF shunt, the surgeons performed valve pressure reset to obtain satisfactory ventricle size.

Recently, intracranial hygromas, also known as external hydrocephalus, have become a well-known clinical entity, including subdural hygromas, longitudinal fissure hygromas, and brain cysts. Among them, the most common is subdural hygromas, which are reported in 16% to 50% of patients after DC.[19,20] In this group of patients, the incidence of intracranial hygromas was 18%, and the incidence of subdural hygromas was 16%. Cranioplasty may be the method of choice to solve subdural hygromas.[21]

## Interventricular Foramen and Aqueduct of Sylvius

Interventricular foramen and aqueduct of Sylvius are important gateway connecting lateral ventricles, third ventricle, and fourth ventricle. The obstruction of interventricular foramen and aqueducts of Sylvius can lead to hydrocephalus.[22] There are only a few methods to observe the morphology of the interventricular foramen and aqueduct of Sylvius, such as magnetic resonance imaging (MRI) scan and phase-contrast MRI.[23] However, MRI is neither convenient nor necessary for the patient after DC. In this study, we observed the interventricular foramen and aqueduct of Sylvius using TDS in a group of patients. The interventricular foramen was clearly visible. Only 22% of patients clearly showed patency of the aqueduct of Sylvius. Even so, TDS is very helpful for the evaluation of some patients.

## Immature Transcranial Duplex Sonography–Based "CSF Release Control Concept"

Lumbar puncture and ELD have been used for the diagnostic and treatment of hydrocephalus and served as predictors
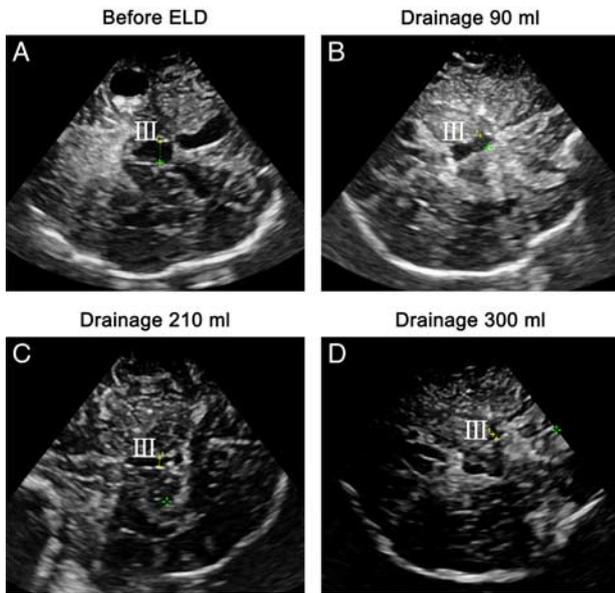
**FIGURE 3.** Transcranial duplex sonography was used for monitoring ventricle size changes after ELD. (A) The width of the third ventricle was 12.9 mm before ELD. (B) When the drainage volume was 90 mL, the width of the third ventricle was 9.0 mm. (C) When the drainage volume was 210 mL, the width of the third ventricle was 6.3 mm. (D) When the drainage volume was 300 mL, the width of the third ventricle was 3.1 mm (III: the third ventricle). ELS indicates external lumbar drainage.

of VPS.[24] However, it is problematic to control the appropriate CSF release volume as too much CSF volume may cause low cranial pressure, paradoxical hernia, and other complications. During drainage weaning and clamping attempts, monitoring the ventricular size is essential.[17] In our study, the dynamic monitoring of the third ventricle was performed in 8 patients
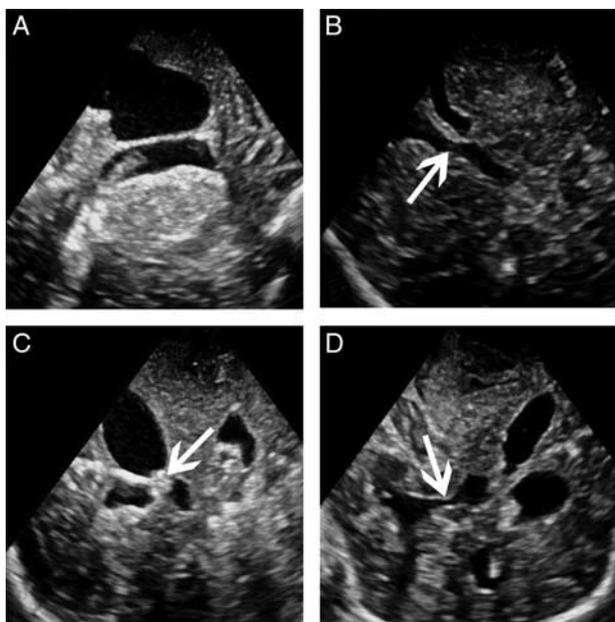


**FIGURE 4.** Typical images of lateral ventricle asymmetry, interventricular foramen, and aqueducts of Sylvius. (A) Lateral ventricle asymmetry. (B) Fluent bilateral interventricular foramen (arrow). (C) Obstruction of the unilateral interventricular foramen (arrow). (D) Patency of the aqueducts of Sylvius (arrow).
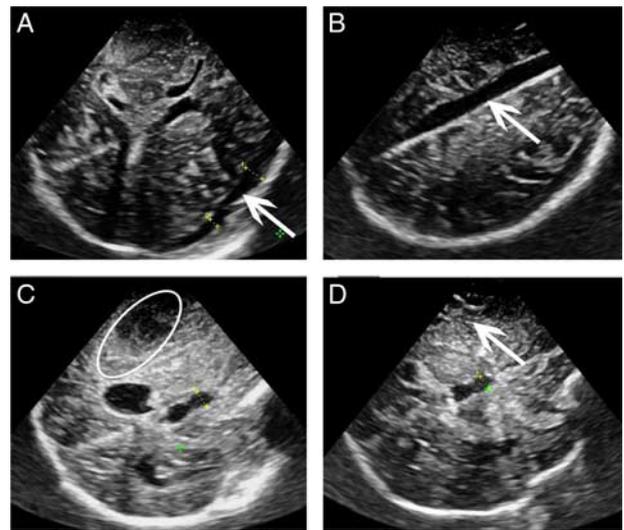


**FIGURE 5.** Typical images of intracranial hygromas. (A) Subdural hygroma (arrow). (B) Longitudinal fissure hygroma (arrow). (C) Brain abscess (ellipse). (D) Abscess reduction after puncture (arrow).

after EVD and ELD using TDS. Based on our results, we suggest a 120 to 300 mL of CSF release volume per day is appropriate for both drainage effects and patient safety. In cases of lumbar puncture, according to the width of the third ventricle, 30 mL of CSF release volume can be both effective and safe. In addition, there are individual differences in ventricular volume between patients. Therefore, we suggest that a TDS-based 'CSF release control concept' should be preliminarily established through subsequent studies.

## Advantages of Transcranial Duplex Sonography

TDS offers several advantages compared with traditional CCT and MRI such as real-time measurement, convenience, non-radioactive, quick, and safe. Transcranial duplex sonography has not been associated with any clinically relevant side effects during diagnostic procedures. To the best of our knowledge, there is no scientific evidence or a case reporting on the harmful effects of TDS.

## Limitations

There are some limitations to our study. Transcranial duplex sonography diagnosis depends on the examiner's experience, training and technique used. Neurosurgeons have to undergo a certain level of training before handling TDS. In this study, all TDS examinations were carried out by a single experienced neurosurgeon. To keep the examination simple, an external device to standardize the insonation angle was not used. Hence, inaccuracies are possible. Transcranial duplex sonography cannot clearly determine cerebral infarction and lesions below 1 cm. Therefore, TDS cannot completely replace CCT. When TDS suggests a significant change, CCT is still needed for confirmation.

## CONCLUSIONS

We have used TDS with a great deal of success in our hospital. Transcranial duplex sonography offers various advantages for monitoring and management of CSF dynamic disorders after DC. Transcranial duplex sonography can monitor changes in ventricle size and morphology, ventricle hematoma, intracranial effusions, etc. Transcranial duplex sonography can help ventricle puncture and ventricle size monitoring during CSF release procedures. Taking advantage of its continuity, real-time, cost-

saving, suitability for bedside application, and noninvasive character, TDS can greatly replace CCT and become part of the patient's daily inspection work after DC.

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