Ultrasonography for Serial Monitoring and Management of CSF Dynamic Disorders After Decompressive Craniectomy

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Research

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ABSTRACT

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. TDS examinations were performed between 1 day and 1-year post-DC. TDS was mainly used for monitoring changes in ventricle size and morphology, and also to monitor intraventricular hemorrhage (IVH), 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-ICU. Two patients had IVH and underwent TDS-guided external ventricular drainage (EVD). Twenty-nine patients were diagnosed with hydrocephalus. The results of TDS were consistent with those of cranial computed

tomography (CCT). Three cases of ventriculoperitoneal shunt and 1 case of lumbar peritoneal shunt underwent valve pressure reset according to TDS, in order to obtain satisfactory ventricle size. TDS was used to monitor ventricle changes and control drainage volume during CSF release procedures, including 2 EVD, 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

TDS 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 CCT and become part of the patient's daily inspection work after DC.

KEYWORDS: Cerebrospinal fluid disorders, decompressive craniectomy, monitoring, management, transcranial duplex sonography

Introduction

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, 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 is a staple of neurocritical carepost-DC.

Since its introduction in the 1970s, cranial computed tomography (CCT) remains the gold standard imaging tool for primary intracranial injuries. CCT 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 CT scanner may be a time- and resource-consuming task [6]. A portable CT 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 non-invasiveness, 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 duplexsonography (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]. TDS allows monitoring of brain parenchyma, hematoma, ventricular size, midline shift, and cerebral hemodynamic changes [8 9]. TDS has potential advantages including concomitant assessment of brain hemodynamics and the feasibility of bedside application. 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 ± 15.5 years) 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. DC 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, and5had bilateral DC.

Instrument and procedures

TDS was performed using a hand-held pocket ultrasound device with a convex probe LOGIQ V2 (GE Healthcare, Illinois, USA). 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° angle to the orbitomeatal 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. But only the width of the third ventricle was measured in all patients. CCT was performed before the final diagnosis of hydrocephalus and intracranial effusion. The width was measured at the widest position in front of the third ventricle using both TDS and CCT. The width of the third ventricle was measured using CCT by another neurosurgeon blinded to TDS results. Hydrocephalus occurs when the lateral ventricle and the third ventricle enlarge combined with clinical symptoms; the diagnosis is 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 ml, 20 ml, and 30 ml respectively.

Informed consent was obtained from all individual participants included in the study. 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, USA). Continuous variables with normal distribution are presented as means ±SD. A linear regression analysis was used to compare the third ventricle width values 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-ICU, the remaining at other locations including common ward (n=30), outpatient department (n=16), emergency department (n=5), and the operation theatre (n=3). The basic demographics and characteristics of the patients are listed in Table 1. The TDS examination was performed between 1-day and 1-year after DC. TDS was used for monitoring intracranial status, especially ventricle size and morphology.

Intraventricular hemorrhage (IVH) and TDS-guided EVD

TDS was very helpful for the detection and serial monitoring of IVH. Seven patients were observed for IVH. Of which, five cases had IVH prior to TDS examination and 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 traumatic brain injury. VPS was performed due to the presence of hydrocephalus 1-month post-DC. The patient fell into a persistently unconscious state. On a postoperative day 12 after VPS, the patient was found to have dilated right-sided pupil and high intracranial pressure through the bone window. The patient could not be transported to the radiology department for CCT due to a rainstorm and 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. Urgently, the patient underwent bilateral EVD under the guidance of TDS. TDS was performed every day and CCT weekly. About 1 week later, the hematoma was mostly absorbed, and hydrocephalus was relieved (Fig. 1)

Hydrocephalus

The lateral and the third ventricles could be clearly observed in all the patients,

but the fourth ventricle was restricted to only 72 patients. It might be related to the low position and irregular shape of the fourth ventricle. According to the width of the third ventricle, 29 patients were finally diagnosed with hydrocephalus. The mean width of the third ventricle of the 29 patients was 12.4 mm (±2.1) in TDS and 12.1 mm (±2.9) in CCT, respectively. There was a significant correlation between the two methods (correlation coefficient r = 0.818, $p<0.001$, Fig. 2A). 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, in order 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. 2B). One month later, TDS and CCT images revealed hydrocephalus (Fig. 2C). Then VPS was performed. Two days after VPS, the patient presented obvious depression in the bone window. TDS revealed extremely small ventricles and excessive diversion (Fig. 2D). Immediately, the value pressure was adjusted from 1.0 to 1.5atm (Medtronic, Dublin, Ireland). Two days later, the ventricle reverted to a satisfactory size (Fig. 2E)

Changes in ventricle size during CSF release

TDS was used for monitoring ventricle size changes during CSF release procedures including two EVD, six ELD, and ten 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 Table 2.The typical image of one case of ELD is shown in Fig. 3. In the cases of lumbar puncture, the average CSF release volume was 30ml; the mean diameter of the third ventricle was 10.8 mm (±3.6) before lumbar puncture and the diameter was 4.4 mm (±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 TDS

CSF 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, 10]. 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 inconvenient sometimes and has been associated with a high incidence of adverse events [10]. Many critically ill patients need to wear 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. Bendella *et al* assessed and quantified the dimensions of all four ventricles using TDS [6]. Kiphuth et al proposed that TDS could be used for clamping and removal of the lumbar or extraventricular drainage [11]. In this study, we performed long-term serial monitoring in a large number of patients after DC using TDS for the first time. The main monitoring events were CSF circulation dynamic disorders.

IVH

IVH is an uncommon complication after DC [12]. IVH often induces acute

hydrocephalus [13]. We found 2 cases of delayed IVH after operation by TDS, which provided a great convenience for timely diagnosis and rescue. TDS 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 0.7–86% [5]. The diagnosis of hydrocephalus is based on the enlargement of the lateral ventricle and third ventricle, or the Evans Index, combined with the clinical symptoms of the patient [14]. Susanne et al reported that changes in the width of the third ventricle directly reflect changes in the lateral ventricle in hydrocephalus [15]. 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%. TDS could clearly show the shape and precise size of the lateral ventricle and the third ventricle. TDS 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%–50% of patients after DC [16, 17]. In this group of patients, the incidence of intracranial hygromas was 18%, and the incidence of

subdural hygromaswas 16%. Cranioplasty may be the method of choice to solve subdural hygromas [18].

Interventricular foramen and aqueduct of Sylvius

Interventricular foramen and aqueduct of Sylvius is the important gateway connecting the lateral ventricle, the third ventricle, and the fourth ventricle. The obstruction of interventricular foramen and aqueducts of Sylvius can lead to hydrocephalus [19]. There are only a few methods to observe the morphology of the interventricular foramen and aqueduct of Sylvius, such as MRI scan and phase-contrast MRI [20]. However, MRI is neither convenient nor necessary for the patient after DC. In this study, we first 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 aqueducts of Sylvius. Even so, TDS is very helpful for the evaluation of some patients.

Immature TDS-based 'CSF release control concept'

Lumbar puncture and ELD have been used for the diagnostic and treatment of hydrocephalus and served as predictors of VPS [21]. 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 [11]. In our study, the dynamic monitoring of the third ventricle was performed in 8 patients

after EVD and ELD using TDS. Based on our results, we suggest a 120–300 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 canbe 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 TDS

TDS offers several advantages compared to traditional CCT and MRI such as real-time measurement, convenience, non-radioactive, quick, and safe. TDS 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. TDS 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. TDS 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

In conclusion, we have used TDS with a great deal of success in our hospital. TDS offers various advantages for monitoring and management of CSF dynamic disorders after DC. TDS can monitor changes in ventricle size and morphology, ventricle hematoma, intracranial effusions, etc. TDS 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.

Abbreviations

DC, decompressive craniectomy; CSF, cerebrospinal fluid; TDS, transcranial duplex sonography; IVH, intraventricular hemorrhage, EVD, external ventricular drainage; CCT, cranial computed tomography; ELD, external lumbar drainage; VPS, ventriculoperitoneal shunt

Acknowledgments

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Contributions

Meng Zhu wrote the first draft of the manuscript. Meng Zhu and Jiahui Zhang acquired the data. Shuang Mu, Wei Liu, Anjing Gong and Zhaozhong He analyzed and interpreted the data. Wenshuai Deng and Xin Liu edited the figure of the article. Huanting Li and Yugong Feng conceived and designed the research. All authors read and approved the final manuscript.

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Ethics approval and consent to participate

The ethics committee of The Affiliated Hospital of Qingdao University.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Legends

Fig. 1: TDS was used for serial monitoring of IVH. TDS revealed the right lateral and the third ventricular hematoma cast (arrow: the right ventricle hematoma, III: the third ventricle) (**A** and **B**). Three days after EVD, only a small part of hematoma absorption, but hydrocephalus decreased (**C** and **D**). Five days after EVD, the hematoma further reduced (**E** and **F**). One week after EVD, the hematoma was mostly absorbed, and hydrocephalus relieved (**G** and **H**) (asterisk: choroid plexus, arrow: bilateral ventricular catheters)

Fig. 2: TDS was used for diagnosis and management of hydrocephalus after DC. (**A**) Linear correlation of the width of the third ventricle between SDT and CCT. (**B**)TDS and CCT 3 days after DC, the width of the third ventricle was 5.8 mm in SDT. (**C**) TDS and CCT 35 days after DC, the width of the third ventricle was 13.2 mm in SDT. (**D**) TDS 2 days after VPS, the width of the third ventricle was 2.6 mm in SDT. (**E**) TDS 2 days after value reset, the width of the third ventricle was 6.4 mm in SDT. (III: the third ventricle)

Fig. 3: TDS 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)

Fig. 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 unilateral interventricular foramen (arrow). (**D**) Patency of the aqueducts of sylvius (arrow).

Fig. 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).

Figures

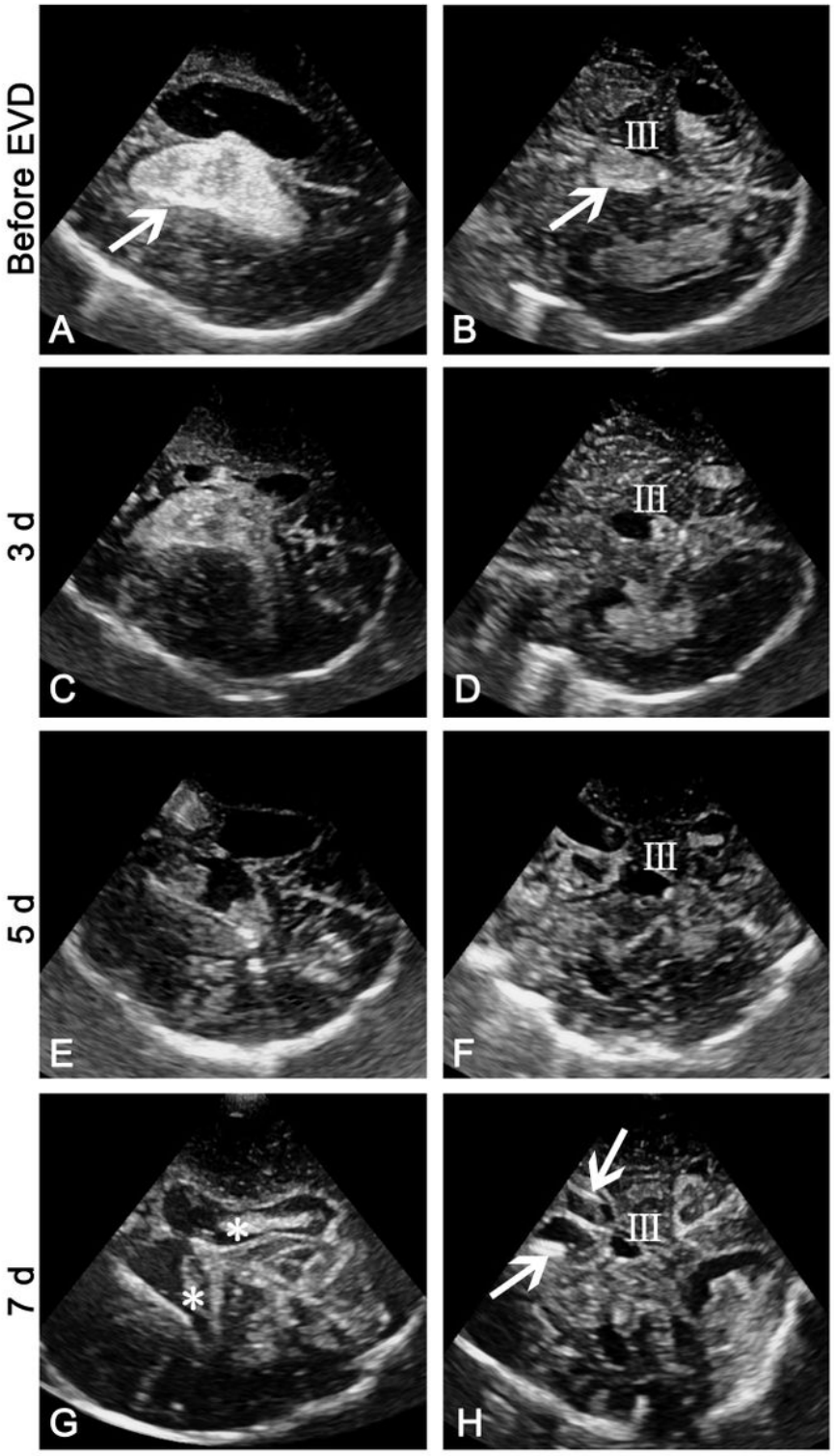

Figure 1

TDS was used for serial monitoring of IVH. TDS revealed the right lateral and the third ventricular hematoma cast (arrow: the right ventricle hematoma, III: the third ventricle) (A and B). Three days after EVD, only a small part of hematoma absorption, but hydrocephalus decreased (C and D). Five days after

EVD, the hematoma further reduced (E and F). One week after EVD, the hematoma was mostly absorbed, and hydrocephalus relieved (G and H) (asterisk: choroid plexus, arrow: bilateral ventricular catheters)

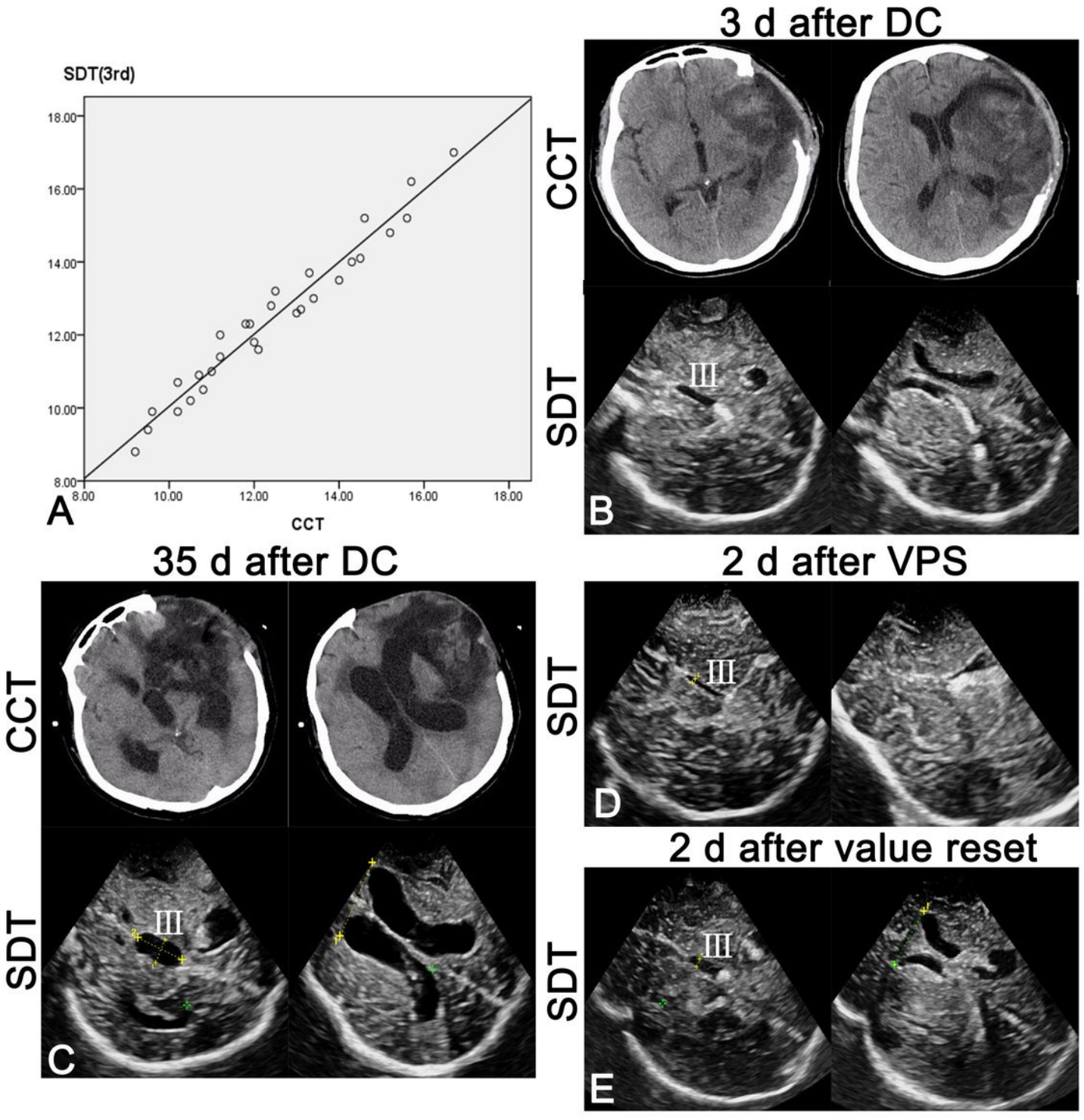

Figure 2

TDS was used for diagnosis and management of hydrocephalus after DC. (A) Linear correlation of the width of the third ventricle between SDT and CCT. (B)TDS and CCT 3 days after DC, the width of the third ventricle was 5.8 mm in SDT. (C) TDS and CCT 35 days after DC, the width of the third ventricle was 13.2

mm in SDT. (D) TDS 2 days after VPS, the width of the third ventricle was 2.6 mm in SDT. (E) TDS 2 days after value reset, the width of the third ventricle was 6.4 mm in SDT. (III: the third ventricle)

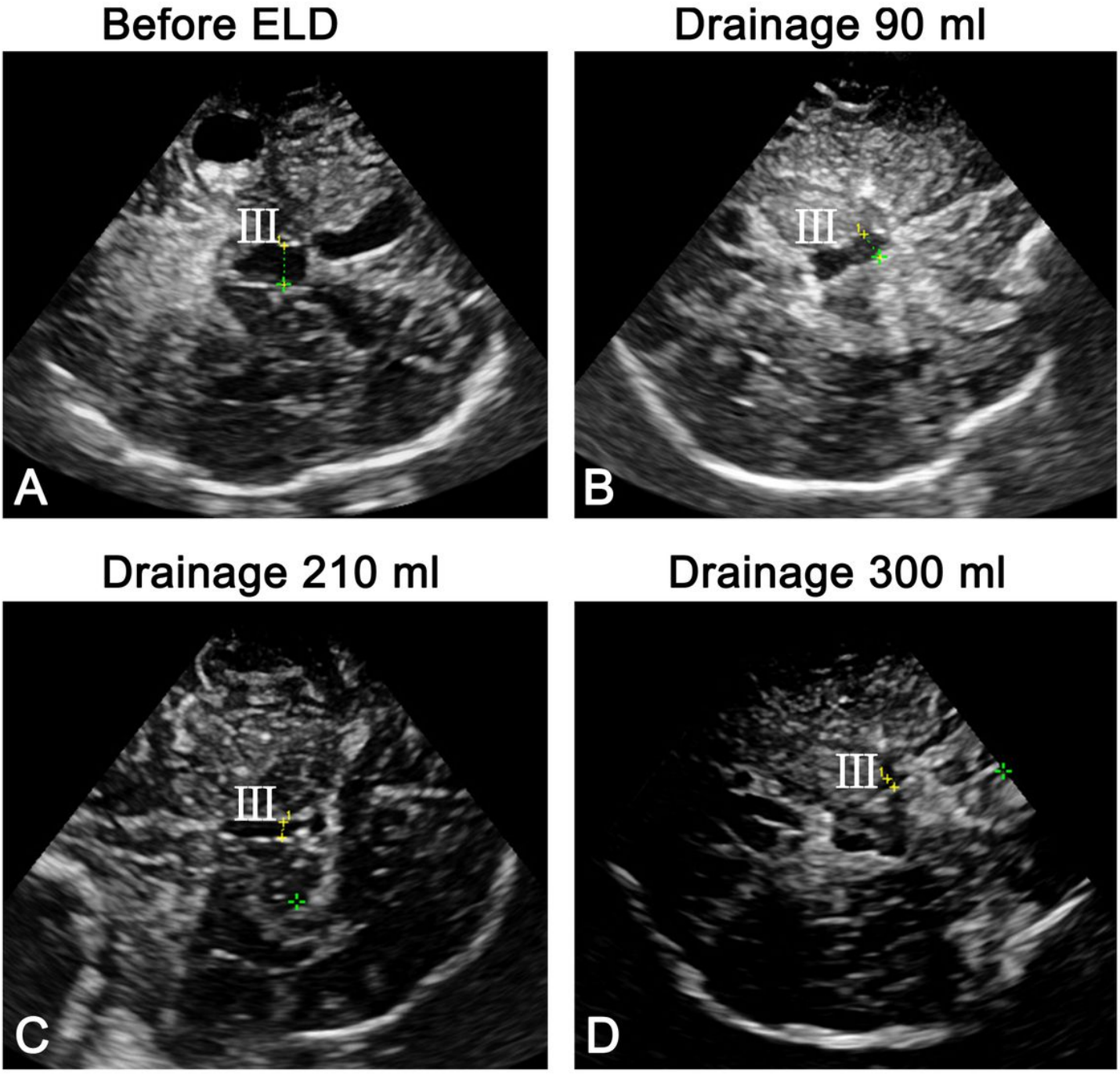

Figure 3

TDS 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)

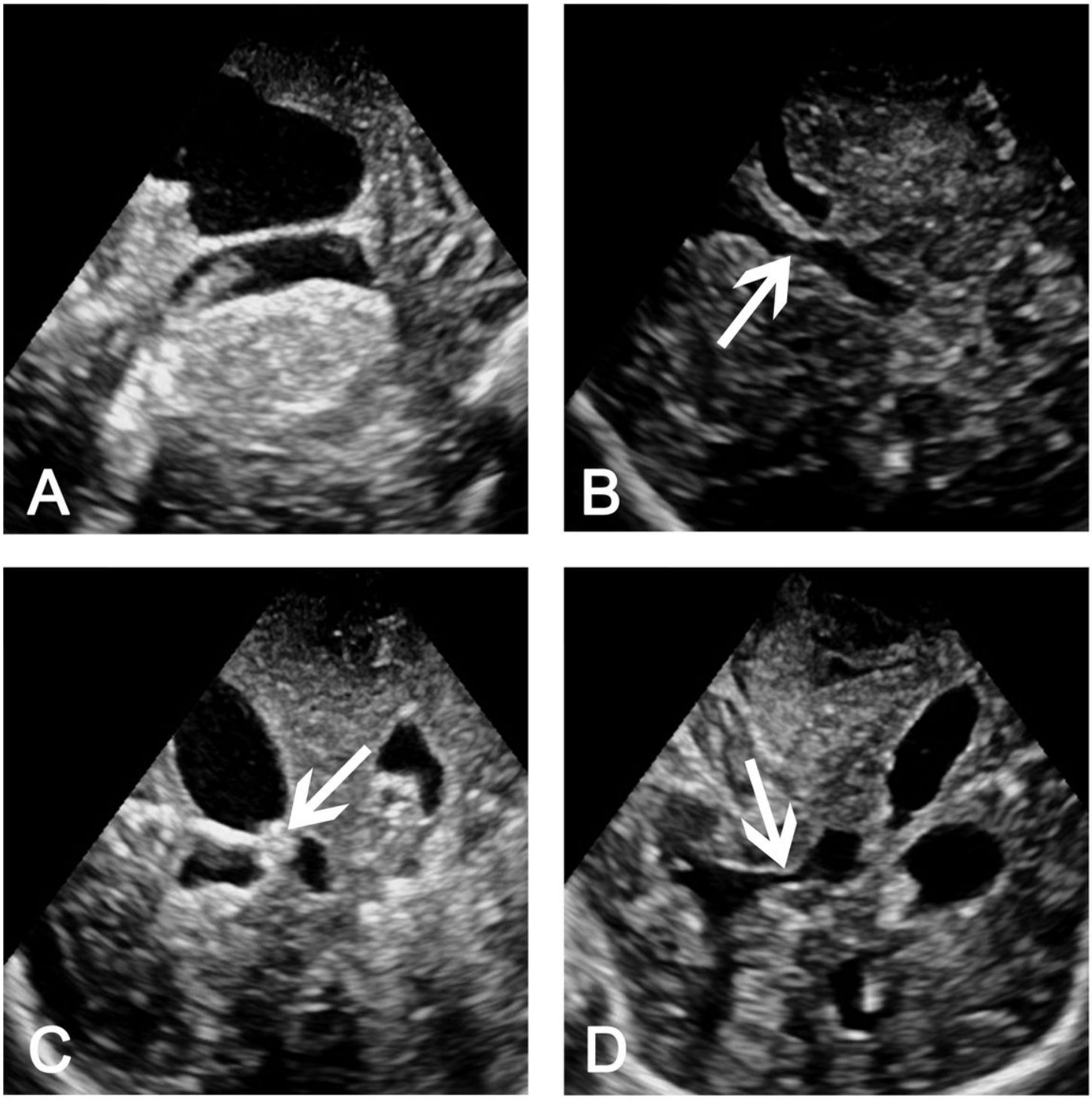

Figure 4

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 unilateral interventricular foramen (arrow). (D) Patency of the aqueducts of sylvius (arrow).

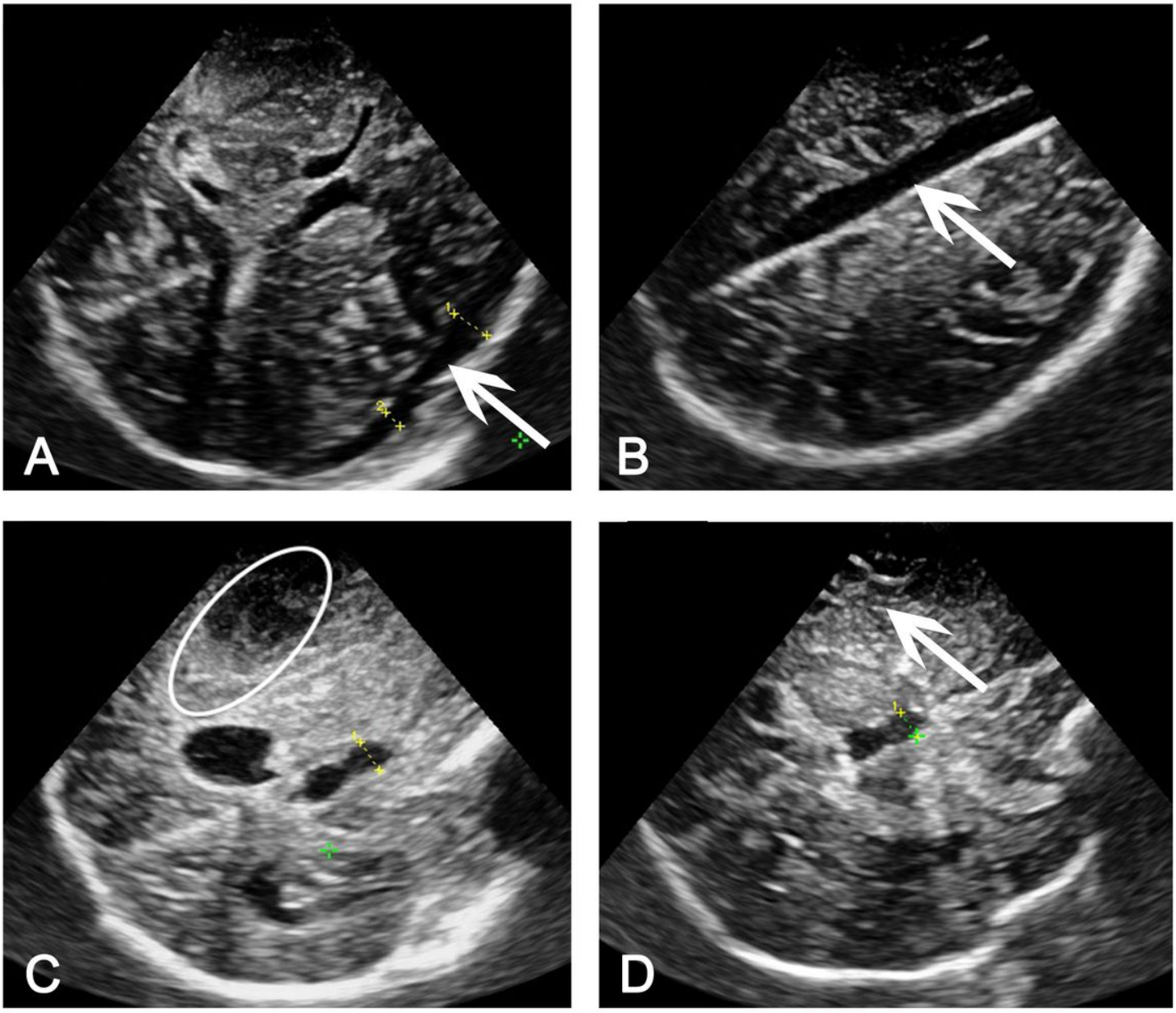

Figure 5

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

Supplementary Files

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