

REVIEW

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Transcranial Doppler ultrasonography (uses, limitations, and potentials): a review article



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Abstract

Background: The additional information that transcranial Doppler can provide as part of a multimodal imaging protocol in many clinical settings has not been evaluated.

Main body: Transcranial Doppler is a bedside procedure used to assess cerebral blood flow velocity via cerebral circulation and pulsatility index (PI). Many diseases can lead to cerebral vessels vasospasm as in subarachnoid hemorrhage and trauma. Cerebral vessels vasospasm represented by abnormal elevation of cerebral blood flow velocity. Intracranial pressure can be monitored by pulsatility index which reflects blood flow resistance in cerebral vessels. Transcranial Doppler ultrasonography is also the unique modality for detection of micro emboli in high-risk patients. Also, it can be used for evaluation of circulatory arrest with subsequent confirmation of brain death

Conclusion: Transcranial Doppler ultrasonography is the only diagnostic modality that provides a reliable assessment of cerebral blood flow patterns in real time. The physiological information obtained from TCD is complementary to the anatomical details obtained from other neuroimaging modalities. TCD is relatively cheap, can be performed bedside, and allows monitoring in acute emergency settings.

Keywords: Transcranial Doppler, Cerebral vasospasm, Subarachnoid hemorrhage, Ischemic stroke, Arteriovenous malformation, Traumatic brain injury

Background

Transcranial Doppler ultrasonography (TCD) was first introduced on clinical practice in 1986. Since TCD was extensively used in outpatient, intraoperative, and critical care units. TCD represents bedside, noninvasive, cheapest, easy repetitive modality which became widely used in patients with cerebrovascular diseases [1, 2]. It provides information about of brain hemodynamics in real time. Repetitive TCD monitoring may recognize recanalization during antifibrinolytic therapy for acute ischemic stroke [3].

This article describes the important clinical role of TCD in neuro surgical practice as in monitoring of patients with post-aneurysmal subarachnoid hemorrhage vasospasm, patient with ischemic stroke, and traumatic brain injury (TBI) [4]. Other clinical applications are arteriovenous malformation (AVM), diagnosis of brain

death, detection of emboli and in parenchymal brain disease. Also, it has crucial role in carotid endarterectomy for diagnosis of hyper perfusion syndrome and prevention of its sequelae [5, 6].

Main text

Transcranial Doppler basic concepts

Procedure of TCD involves the placement of electrical probe of range gated ultrasonography permitting assessment of blood flow velocity in the cerebral arteries. At low frequencies (2 MHz) soft tissues and bone attenuation is low compared with high frequencies, thus providing accurate recoding of cerebral blood flow velocity (CBFV) [7, 8].

The ultrasonic beam that emitted from TCD probe crosses the skull at the target location and reflected from the erythrocytes which flow at different speeds in the cerebral vessels and the resultant signals are recorded [9].

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Table 1 Mean cerebral blood flow velocities (cm/s) based on age groups [5]

Artery	Age 20–40 years	Age 40–60 years	Age > 60 years
Anterior cerebral artery	56–60	53–61	44–51
Middle cerebral artery	74–81	72–73	58–59
Posterior cerebral artery (PCA) (P1)	48–57	41–56	37–47
PCA (P2)	43–51	40–57	37–47
Vertebral artery	37–51	29–50	30–37
Basilar artery	39–58	27–56	29–47

The difference between the transmitted and received signals is known as the Doppler shift. The time interval between pulse emission to pulse reception determines the depth from which the Doppler shift obtained [9–11]. Mean CBFV is calculated using a spectral envelope (also known as fast Fourier transformation) Mean CBFV $5 [PSV + (EDV \times 2)]/3$, where PSV is peak systolic CBFV and EDV is end-diastolic CBFV [9, 12].

The basic principle of TCD ultrasonography is based that the CBFV in a cerebral artery is inversely proportional to the diameter of that artery. Thus, transcranial ultrasonography provides an indirect assessment of cerebral vessels diameter through calculating the Doppler shift. Also, TCD can assess PSV and EDV and by the use of these values, we can calculate CBFV (Table 1), pulsatility index (PI), and resistant index (RI) [6, 12–14]. Cerebral blood flow velocity is usually affected by some physiological factors as age, gender, hematocrit value, presence of fever, metabolic factor, and diameter of blood vessel [15].

The pulsatility index (PI) and resistant index (RI) are calculated from TCD parameters as follows: PI $(PSV-EDV)/\text{mean CBFV}$ and RI $(PSV-EDV)/PSV$ (Table 2). The pulsatility index is an indicator of amount of vascular resistance in distal intracranial pressure and it is used as indirect evaluation of intracranial pressure when ICP exceeding 20 mmHg. It is also found that there is a good correlation between ICP and RI but this correlation is less sensitive than IP [6, 16].

In isolation of intracranial arteries, the first concern is to determine the site (window) where the ultrasound wave can penetrate the skull to evaluate the cerebral arteries (Fig. 1). To assess intracranial arteries, there are three windows through which the ultrasound waves pass through. Transtemporal window (between the eye and

ear pinna) to assess the middle cerebral artery often presents at 30–60 mm depth from the skull surface while anterior cerebral artery at depth 65–80 mm with the probe placed in anterosuperior position and internal carotid artery at depth 55–70 mm with the probe placed in poster-inferior position. Second window is the trans-orbital window to assess the ophthalmic artery. Third window is the transforaminal window (across the foramen magnum) to evaluate vertebral arteries [15–17].

Role of transcranial Doppler in cerebral vasospasm

Vasospasm of intracranial blood vessels is defined as a transient narrowing of cerebral arteries that may lead to transient or permanent neurological dysfunctions. It can occur in many CNS (central nervous system) disorders; the most common one is following of spontaneous subarachnoid hemorrhage (SAH) due to rupture of cerebral aneurysm. Other disorders include trauma, pre-eclampsia, and meningitis, but the course of vasospasm in these conditions is usually milder [18–21].

Vasospasm due to aneurysmal SAH is usually initiated between 3rd and 5th day after hemorrhage and gradually declining after the 14th day, and it is the most common cause of morbidity and mortality in aneurysmal SAH. The pathogenesis of this phenomena is not well understood, and it is hypothesized that blood extravasated from SAH hemorrhage initiates complex cellular mechanisms that may lead to vascular smooth muscle contraction [18, 20, 22].

Cerebral digital subtraction angiography remains the most important diagnostic tool for vasospasm but it is invasive, associated with significant morbidity, and not as feasible as bedside tool. Thus, TCD is noninvasive bedside tool and can detect vasospasm at earlier stages before it become clinically manifested and can be used

Table 2 Normal pulsatility index (mean \pm SD) based on age groups [5]

Artery	Age 20–40 years	Age 40–60 years	Age > 60 years
Anterior cerebral artery	0.80 \pm 0.14	0.85 \pm 0.16	0.85 \pm 0.16
Middle cerebral artery	0.83 \pm 0.14	0.82 \pm 0.13	0.82 \pm 0.13
Posterior cerebral artery	0.76 \pm 0.12	0.79 \pm 0.12	0.79 \pm 0.12
Vertebral artery	0.82 \pm 0.03	0.78 \pm 0.04	0.78 \pm 0.04
Basilar artery	0.81 \pm 0.05	0.78 \pm 0.05	0.78 \pm 0.05

Table 3 Ranges of sensitivity and specificity of transcranial Doppler ultrasonography to detect vasospasm in different arteries [5]

Vessels	Sensitivity (%)	Specificity (%)
Internal carotid artery C1 segment	100	91
Anterior cerebral artery A1 segment	13–82	65–100
Middle cerebral artery M1 segment	38–91	94–100
Posterior cerebral artery P1 segment	48	69
Vertebral artery	43.8	88
Basilar artery	73–76.9	79

during and after aneurysmal surgery [23, 24]. Also, TCD can be daily repeated for monitoring of progression of vasospasm and efficacy of treatment [25].

Many studies recommended daily monitoring of patients with aneurysmal SAH with high risk for developing of vasospasm for early detection of vasospasm before it becomes clinically manifested and introducing of early management either by triple H therapy or endovascular procedures [15, 17, 26].

The sensitivity of transcranial Doppler in detecting of vasospasm is high in middle cerebral artery (75 to 90%), also in vertebral and basilar arteries (77%), but its sensitivity is low in detecting anterior cerebral artery vasospasm (15%) due to its collateral pattern of flow (Table 3) [2, 17].

TCD in predicting vasospasm

Generally, increasing in mean cerebral blood flow velocity (CBFV) is an indicator of vasospasm in major

cerebral vessels. Some studies found that low pulsatility index (PI) is another indicator of vasospasm [2, 6].

In middle cerebral artery vasospasm (MCA), several studies suggest a correlation between MCA FVm and severity degree of vasospasm. Mild vasospasm (FVm < 120 cm s⁻¹), moderate vasospasm (FVm ranges from ≥ 120 cm s⁻¹ to < 200 cm s⁻¹), and severe vasospasm (FVm > 200 cm s⁻¹ c). These spikes in FVm can be detected via TCD up to 2 days before the occurrence of symptoms onset with high sensitivity and specificity [25, 26].

In basilar artery (BA) vasospasm, some studies found that CBFV ratio between BA and extracranial vertebral artery correlates strongly with BA narrowing. A ratio MRE than 3.0 with BA flow velocity greater than 85 cm/s is usually associated with 92% sensitivity and 97% specificity for BA narrowing [26–28].

The role of TCD in the evaluation of acute stroke

Transcranial Doppler (TCD) is one of the most useful tools in diagnosis of acute ischemic stroke. It provides valuable information about micro emboli, degree of cerebral vessel stenosis, and collateral flow. TCD can detect acute occlusion of middle cerebral artery with sensitivity more than 90% (Fig. 2) [29–31].

TCD has a prognostic value in acute ischemic stroke. Complete cerebral occlusion detected by TCD is usually associated with poor functional outcome, disability, and even death while normal parameters are associated with good outcome with early recovery from stroke. Detection of occlusion of M1 segment of middle cerebral artery within 6 h from stroke onset by TCD may be

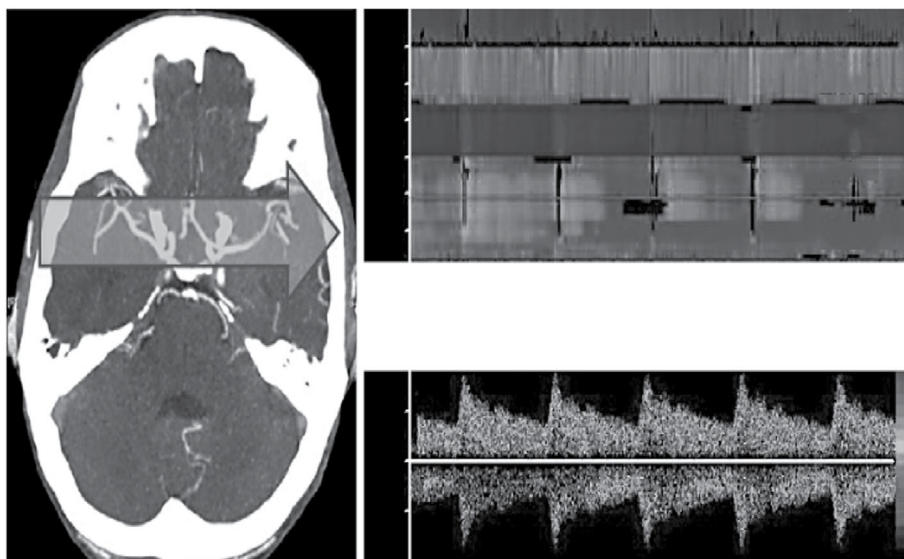


Fig. 1 Transcranial insolation of anterior circulation. Power-mode multigated transcranial Doppler (TCD) employs 2 MHz ultrasound that penetrates the entire diameter of the skull (a). In an average adult skull, midline is believed to be at 75 mm. Thus, the flow signals obtained from beyond 75 mm are from contralateral arteries [6].

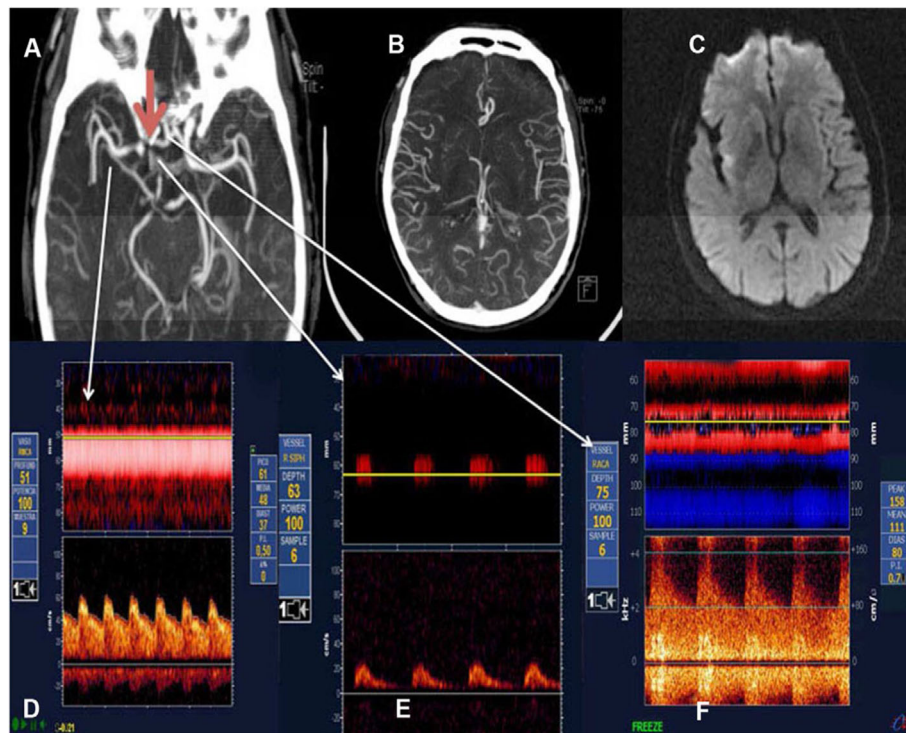


Fig. 2 Case 19: 78-year-old male, arrived within 30 min of symptom onset of a right-side MCA stroke. Initial NIHSS score of 2 points. **a** CTA interpreted as normal by the neuroradiologist on call; the red arrow demonstrates a short right terminal carotid occlusion. **b** CTA demonstrates symmetrical filling of both MCA territories, which may be due to collateral flow. **c** DWI showing small insular ischemic changes. **d** TCD at the beginning of thrombolysis demonstrates a middle cerebral artery with good flow velocity but with low pulsatility index suggesting post-stenotic flow and a proximal vascular lesion. **e** Occlusion of right terminal carotid as revealed by the TCD. **f** Inverted, high velocity flow in the right anterior cerebral artery compatible with anterior cross filling (collateral flow) [33]

associated with hemorrhagic transformation in the infarcted area [29, 32, 33].

Patients with sickle cell anemia have high risk of developing ischemic stroke which can be prevented by chronic blood transfusion. TCD is used for screening of these children and identify of those who have risk for developing stroke [29, 34].

After initiation of the treatment protocol of ischemic stroke, recanalization starts to occur. TCD is used to monitor the effectiveness of treatment, adjustment of doses, and duration particularly with antifibrinolytic agents as recanalization occurs rapidly [30, 35]

Role of TCD in emboli monitoring

TCD ultrasound is considered as the only available model for detection of micro emboli in real time within cerebral arteries. Micro emboli have high-intensity signal in TCD ultrasound and has characteristic acoustic impedance, and it can be distinguished easily from erythrocytes that flow simultaneously [1, 36].

Detection of asymptomatic emboli by TCD is crucial in patients whom at high risk for development of cerebral stroke, e.g., carotid artery stenosis, atrial fibrillation,

prosthetic cardiac valve, cardiomyopathy, endocarditis, and carotid endarterectomy [11, 37].

Screening of patients of ischemic stroke and patients with significant carotid occlusion by TCD is helpful in evaluation of degree of cerebral embolization, thus will be reflected in their management strategy [36, 37].

Role of transcranial Doppler in assessment and management of cerebral arteriovenous malformations

Arteriovenous malformations (AVMs) are congenital anomalies of the cerebral blood vessels characterized by presence of direct connection between arteries and veins, with an absence of arterioles and capillaries. They are usually presented with intracranial hemorrhage, convulsions, or both [38–40].

After treatment of AVM, the former feeder arteries usually exhibit reduction in the mean velocity and elevation of arterial pressure that may led to intracerebral hemorrhage and venous infarction. These changes vary between patients according to the degree of arteriovenous shunting within the AVM. Because of the importance of the changes and their impact on the neurological condition of the patients,

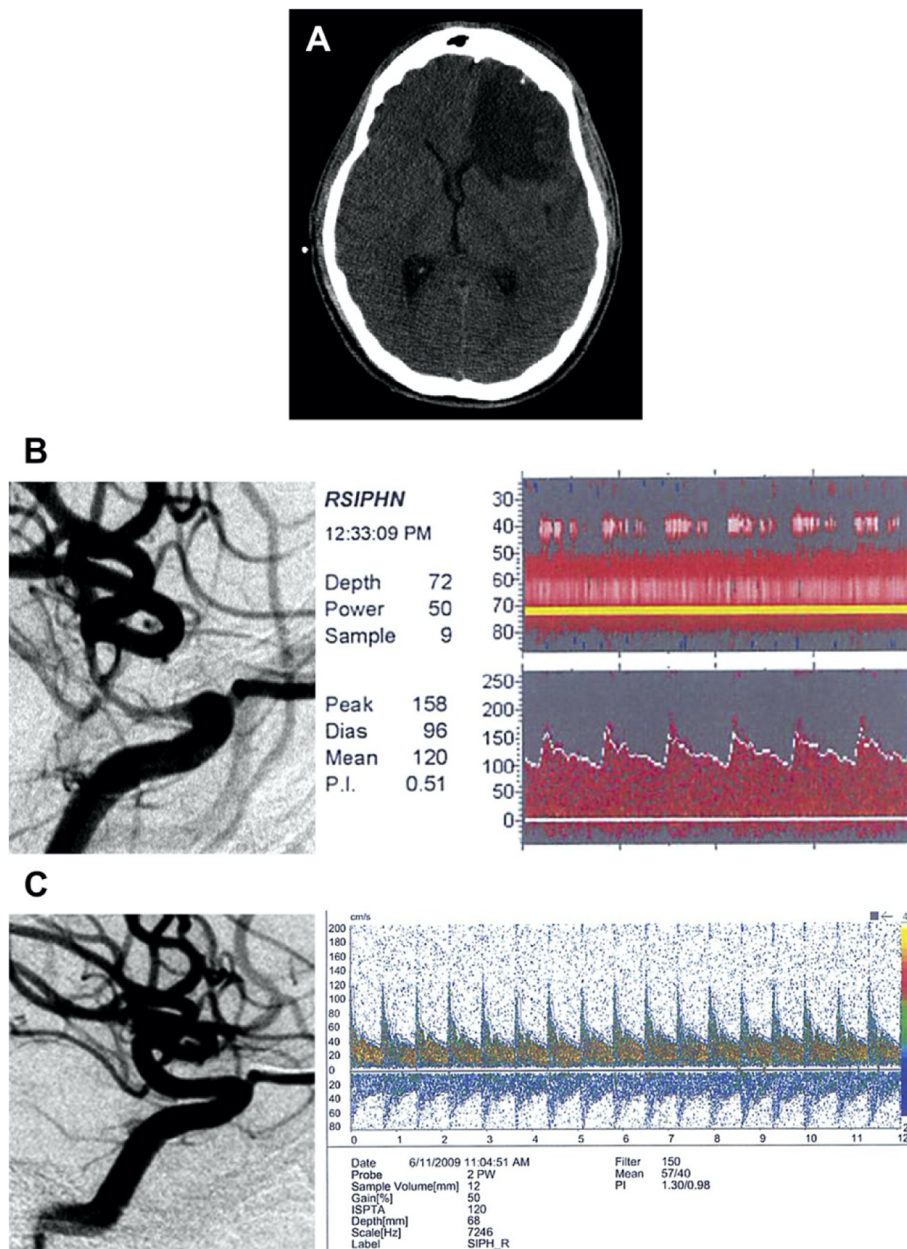


Fig. 3 Patient with right side contusion. **a** CT scan demonstrating contusion. **b** Right common carotid artery injection showing severe vasospasm affecting right carotid siphon before angioplasty and corresponding TCD measured CBFV in the right carotid siphon. **c** Resolution of vasospasm after transluminal angioplasty and TCD showed CBFV normalization after angioplasty [5]

these changes should be assessed by noninvasive bedside TCD [39–42].

Assessment of AVM using TCD

AVMs are often supplied by distinct high-flow shunts and are characterized by decreased or absence of vasomotor reactivity. These features make it possible for TCD to differentiate AVM feeding arteries from healthy cerebral vessels, and specificity of TCD has high sensitivity in detection of medium-sized and large AVMs, but

its sensitivity decreases in detection of AVM less than 2.5 cm [43].

The most commonly used TCD parameters in evaluation of basal cerebral arteries and those of AVM are velocity and pulsatility index (PI). By using these parameters, AVM feeding arteries are characterized by the presence of high velocity and low PI. So, we can differentiate between them and normal cerebral arteries. Most of studies concluded that the AVM size affects velocity and PI measurements. In large AVM, there is an

increase in mean velocity and diminish in PI with progressive increase in volume of AVM [39, 44].

TCD assessment following AVM intervention

TCD evaluation of AVM after intervention either by surgical resection or embolization revealed a reduction in mean flow velocity and an increase in PI in the former feeding arteries when compared to preoperative values. Firstly, normalization of PI occurs over the first few days after intervention while normalization of mean velocity takes much longer (1–3 weeks) [45].

A study by Petty et al. compared TCD parameter changes following surgical resection with embolization. They found that there was dramatic change in mean velocity and PI in surgically treated group [41].

In embolization, different results may emerge depend on whether the embolization is partial or staged. In first and subsequent stages of staged embolization, there is an increase in the mean velocity of the feeding artery. Thus, it may be due to increase in collateral flow, absence of diameter reduction, or due to recanalization of previously canalized feeders [38].

The changes in TCD parameters with the use of radiosurgery in AVM occur more gradually and have of latency period from 1 to 2 years [46].

Role of transcranial Doppler (TCD) in traumatic brain injury (TBI)

Traumatic brain injury represents a major health problem and a leading cause of death and disability all over the world. As a result of direct trauma, there is disruption of normal brain function leading to primary brain injury and is usually followed by secondary brain injury especially in moderate and severe TBI; it includes cerebral infarction, hydrocephalus, brain edema, raised intracranial pressure, and infection [47, 48].

Several methods were used to monitor TBI patients in intensive care unit as monitoring of ICP via intraventricular catheter or subdural, intraparenchymal, and subarachnoid probes. Also, brain oxygen extraction in the brain can be evaluated through jugular venous oxygen saturation [49, 50].

Transcranial Doppler (TCD) allows a bed side, noninvasive evaluation of monitoring of ICP (measured by pulsatility index (PI) values of the middle cerebral and other cerebral vessels), cerebral blood flow mean (through measurement of mean blood velocity) and cerebral perfusion pressure (CPP). Also, TCD may be used for detection and monitoring of cerebral vasospasm after traumatic SAH (Fig.3) [51, 52]

Role of TCD in carotid endarterectomy

Carotid endarterectomy is usually associated with perioperative hemodynamic disturbance, e.g., intraoperative

hypoperfusion that may lead to brain ischemia or postoperative hyper perfusion that may cause intracerebral hemorrhage [53, 54].

Early postoperative detection of cerebral hyper perfusion can prevent the occurrence of serious complications because lowering of blood pressure helps in prevention of progression of cerebral hyper perfusion [53, 55].

Intraoperative assessment of the difference in mean flow velocity of MCA before and after carotid declamping by TCD is the gold standard in detection of cerebral hyper perfusion. An increase of > 100% in MCA velocity after declamping is usually associated with cerebral hyper perfusion [54, 56].

Recent studies concluded that postoperative assessment of MCA velocity within 2 h postoperatively and compare it with the preoperative measurement help in detection of cerebral hyper perfusion in up to 41% of patients [57].

Role of TCD in diagnosis and monitoring of intracranial hypertension and brain death evaluation

Diagnosis of brain death is an important social and legal issue, and it is usually confirmed by physical examination and some technical modalities such as angiography, EEG, and radionuclide scan. TCD offers some valuable information beside these modalities and can be performed bedside with less time consumed. Transcranial Doppler detects velocity flow and shape of waveform, and differentiate between systolic and diastolic CBFV [58, 59].

Progressive increase in intracranial pressure is associated in reduction in diastolic CBFV; when ICP exceed end diastolic blood pressure, CBFV became nil and thus associate with appearance of small systolic spikes followed by absent of flow in both systolic and diastolic direction. With continued presence of this pattern, brain death is confirmed [59, 60].

Role of TCD in disease of brain parenchyma and brain tumor

The use of transcranial ultrasonography in parenchymal brain disease and brain tumors is limited to the neonates because of the presence of open fontanelle help in proper isolation of brain parenchyma [61].

Despite these limitations, transcranial ultrasonography may give some useful information. In Parkinson's disease, the substantia nigra shows increase in echogenicity than in normal individuals. Also, there is a reduction in echogenicity in raphe nuclei in patients with unipolar depression [62, 63].

In high-grade glioma, TCD shows abnormal arterial and venous pattern indicating high vascularity of these tumors; these patterns are absent or mild in low-grade glioma [61, 64].

Conclusion

In the critically ill patients with ischemic stroke, SAH, and TBI in which there are disturbance of cerebral hemodynamics, neuromonitoring should be extended. TCD is noninvasive, repetitive, easily available at the bedside, radiation free, and can help prevent delayed neurologic deficits [6].

The use of TCD helps tools in the early detection of cerebral vasospasm following SAH before it became clinically manifested helping in early incorporation of the specific treatment measure for vasospasm [17].

In patients with hyperacute stroke, TCD helps in detection of ischemic stroke and in monitoring of efficacy of treatment especially with those with arterial occlusion [34].

Also, TCD is very useful in early diagnosis of hyper perfusion syndrome after carotid endarterectomy, confirmation of brain death, and monitoring of AVM after definitive treatment [6, 40].

Limitations of the TCD

Although the presence of many advantages to the use of TCD in intensive care patient's status post-SAH and in many situations mentioned before, there are some limitations of TCD.

- It is highly operator dependent, with the handheld technique requiring detailed three-dimensional knowledge of cerebrovascular anatomy and its variations [6]
- Measurements of velocity may be affected by others factors such as age, gender, hematocrit value, differences in the partial pressure of CO₂ within the blood, and thickness of skull bone [42].
- TCD measurements are also limited to the large basal arteries and can only provide an index of global rather than local cerebral blood flow velocity [42].
- Also, in AVM monitoring by TCD site of AVM can be an obstacle; many studies concluded that superficial AVM and those located in the parietal, occipital, and cerebellar regions are difficult to be detected [40].

Abbreviations

TCD: Transcranial Doppler ultrasonography; RI: Resistant Index; CBFV: Cerebral blood flow velocity; ICP: Intracranial pressure; PI: Pulsatility index; MCA: Middle cerebral artery; FVm: Mean flow velocity; BA: Basilar artery; BI: Traumatic brain injury; CNS: Central nervous system; AVM: Arteriovenous malformation; SAH: Subarachnoid hemorrhage; PSV: Peak systolic velocity; CPP: Cerebral perfusion pressure; EDV: End diastolic velocity; CT: Computed tomography; CTA: Computed tomography angiogram; DWI: Diffusion-weighted image

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Author's contributions

Mohammed F. A Ali: data interpretation and analysis, and writing the paper. The author(s) read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The author declares no competing interests.

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