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REVIEW

# Transcranial Doppler in children

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**Abstract** Transcranial Doppler US, a non-invasive tool for evaluating the cerebral arteries, has evolved significantly during the last two decades. This review describes the practical procedure, and summarises and illustrates its established and "work-in-progress" indications in children. Indications for a transcranial Doppler US examination include, but are not limited to: (1) evaluation of cerebral blood flow velocities in the circle of Willis in patients with sickle cell anaemia to guide transfusion therapy; (2) diagnosis and follow-up of vasculopathy, such as moyamoya disease; (3) diagnosis and monitoring of acute cerebrovascular disorders in intensive care patients, in particular following traumatic brain injury, and during cardiovascular surgery; and (4) confirmation of a clinical diagnosis of brain death by documentation of cerebral circulatory arrest.

**Keywords** Transcranial Doppler · Mean velocity · Circle of Willis · Sickle cell anaemia · Children

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## Introduction

Transcranial Doppler (TCD) is a non-invasive ultrasonographic technique with wide indications [1], using a 2-MHz probe placed on the temple anterior to the ear, that allows real-time evaluation of the cerebral arteries in adults, and in children with a closed anterior fontanel. First introduced by Aaslid in 1982 [2] as an effective tool for the diagnosis and management of vasospasm, its principal indications in adult patients are well established and include delayed vasospasm after subarachnoid haemorrhage, detection of intracranial arterial stenoses, evaluation of the risk of ischaemic stroke in patients with an extracranial carotid or vertebral narrowing or occlusion, diagnosis of brain death, intra operative monitoring of the cerebral circulation, arteriovenous malformations, and right-to-left cardiac shunts [3, 4]. In neonates, assessment of the intracranial circulation is performed via the anterior fontanel. In paediatrics, TCD has become an essential tool in the management of children with sickle cell disease. Its use as a cerebral circulation monitoring tool in the intensive care unit and during cardiac surgery is of growing importance. This review will not address the use of Doppler in neonates, which has been described by others [5, 6], but will focus on the different aspects of TCD in children after fontanel closure. The review is based on the experience of the author and on the increasingly rich literature in the field.

Two types of TCD devices are available. Non-imaging, or 'blind' TCD, performed with a small, portable, inexpensive device, was used in the initial publications. Arteries are identified in pulsed wave Doppler mode based on depth and direction of the blood flow. Modern colour Doppler imaging duplex TCD links pulsed Doppler sonography

and colour Doppler mapping, and this allows a more accurate identification of the arteries, and offers a shorter learning curve for the operator. This equipment is now widely available in radiology departments and intensive care units. The technique described in this paper is that of colour Doppler imaging TCD; however, the review of indications is based on published reports using either technique.

## Technique

The equipment used is a duplex US colour flow mapper. The probe is either a sector or phased array cardiac or dedicated probe with a small imaging footprint and a Doppler frequency of 1.8 or 2 MHz. The examination is performed with the patient in the supine position. Two acoustic windows are used: the temporal and the suboccipital [3, 5, 7–9].

For the temporal window, the examiner usually sits bedside on the patient's right, as for an abdominal scan; forearm resting on the patient's shoulder or chest to assure good stability and a little restraint of the child. The probe is placed just anterior to the tragus of the ear and superior to the zygoma (Fig. 1), and an axial grey-scale view of the base of the brain is obtained depicting the hypoechoic "gazelle track" or heart-shape cerebral peduncles and the echogenic star-shaped suprasellar cistern; these are the reference landmarks. In the colour mode, the circle of Willis projects anteriorly (Fig. 2). The middle cerebral artery (MCA), which is the most important artery with its 60–80% supply of the hemisphere, is coded in red with flow towards the transducer (Fig. 3). The colour scale setting should be optimized according to the actual velocities. After switching to the spectral Doppler mode, a 5-mm wide Doppler sample gate is placed on the internal carotid artery (ICA) bifurcation and moved towards the periphery along the MCA. At each depth, the recording is optimised by slightly tilting and sliding the transducer to attempt a parallel alignment of the axis of the vessel and the Doppler beam. Two to three velocity recordings are made from ICA bifurcation towards the periphery, and the highest velocity is recorded. Then the anterior cerebral artery is investigated by moving the Doppler gate deeper onto the A1 segment, which is blue-coded as it approaches the midline with flow away from the transducer. After angling the probe slightly downwards, the internal carotid artery is visualised, first in red in its terminal part, then in blue in the hairpin part located within the cavernous sinus. To obtain a good view, the transducer often needs to be slid posteriorly. The posterior cerebral artery is first coded red in its initial part, then blue as it courses around the cerebral peduncle. After completing insonation on one side, we repeat the procedure on the other side after asking the child to turn the head opposite.

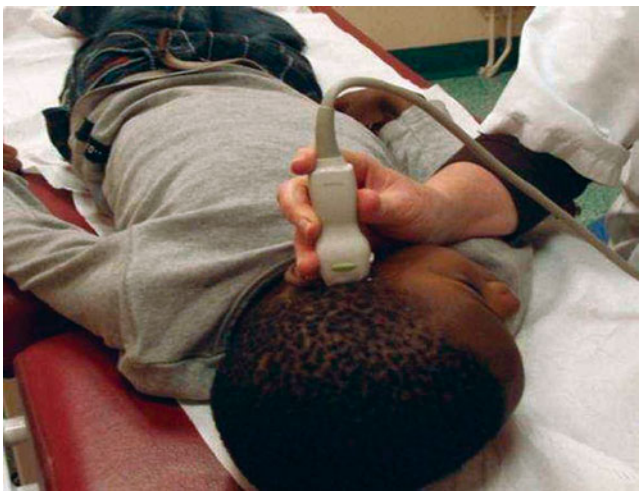


**Fig. 1** Left temporal acoustic window: a 2-MHz US probe is placed just anterior to the tragus of the ear

Terminal segments of the vertebral arteries and basilar artery can be visualised via the suboccipital window; the patient in decubitus position with the neck flexed so that the chin touches the chest. The transducer is then placed over the upper neck at the base of the skull and angled through the foramen magnum towards the nose. The Y-shaped confluence of the vertebral and basilar arteries, blue-coded, should be visible.

Angle correction should not be attempted because arteries are short and sinuous. Introducing an inappropriate angle correction would result in overestimation of flow velocities. The tracing is assumed to be obtained at an optimal angle of 0° [1, 8].

Although no side effects have been described with TCD, the lowest possible power output should be selected, complying with the ALARA principle [5].

## Doppler measurements

Three key parameters can be obtained from the Doppler spectrum: flow direction, velocities, and indices for arterial resistance. Flow direction can be assessed by the colour-code. By convention, flow towards the transducer is coded in red and is plotted above the baseline in the pulsed Doppler-spectrum; flow away from the transducer is coded in blue and plotted below the baseline.

The most commonly used velocity parameter is the **t**ime **a**verage **m**ean of the ma**x**imal velocities (TAMX), also called mean velocity, obtained by manual or automated outlining of the envelope of the spectral waveform over one cardiac cycle. The peak systolic velocity (VS) and end diastolic velocity (VD) can also be measured.

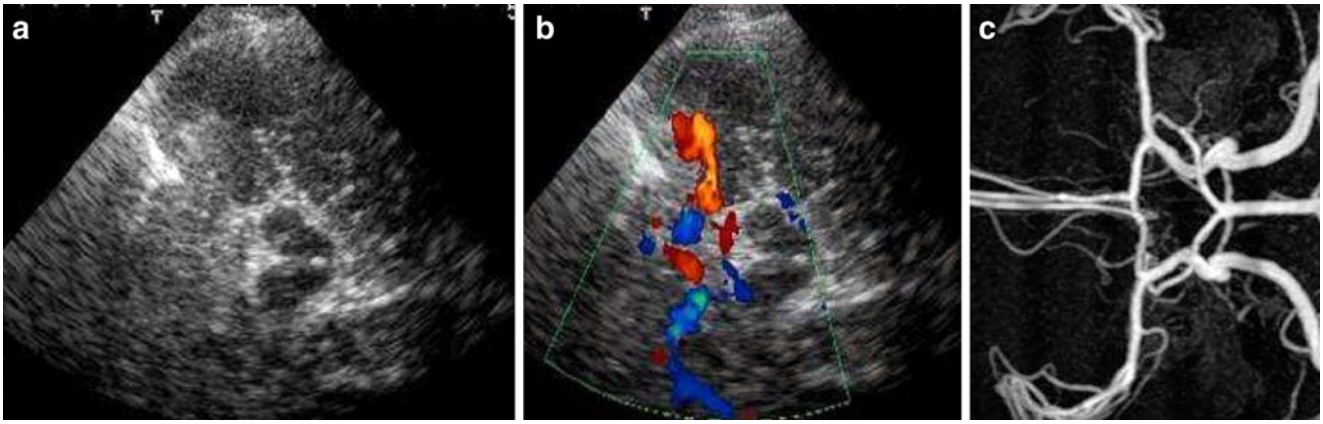



**Fig. 2** Temporal window. **a** Axial grey-scale view of the base of the brain depicts the hypoechoic "gazelle track" or heart-shape cerebral peduncles; the reference landmark. **b** In colour mode, the circle of Willis projects anteriorly. **c** Maximum-intensity projection of a 3D-time-of-flight MRI acquisition shows a corresponding axial view of the circle of Willis

Two indexes reflecting the downstream vascular resistance can be calculated. The pulsatility index (PI) is calculated as PI = (VS − VD) / TAMX. Normal PI is 0.7–1.1. The resistive index, RI, is equal to (VS – VD) / VS. Normal RI after the neonatal period is 0.5±15% (0.43–0.58) [10]. These two indices always change in the same direction. When a territory is less resistant to blood flow, there is a higher flow rate during diastole. A decrease of the indices is observed, e.g., downstream from a severe stenosis, related to the raise of $PCO_2$ in the ischaemic

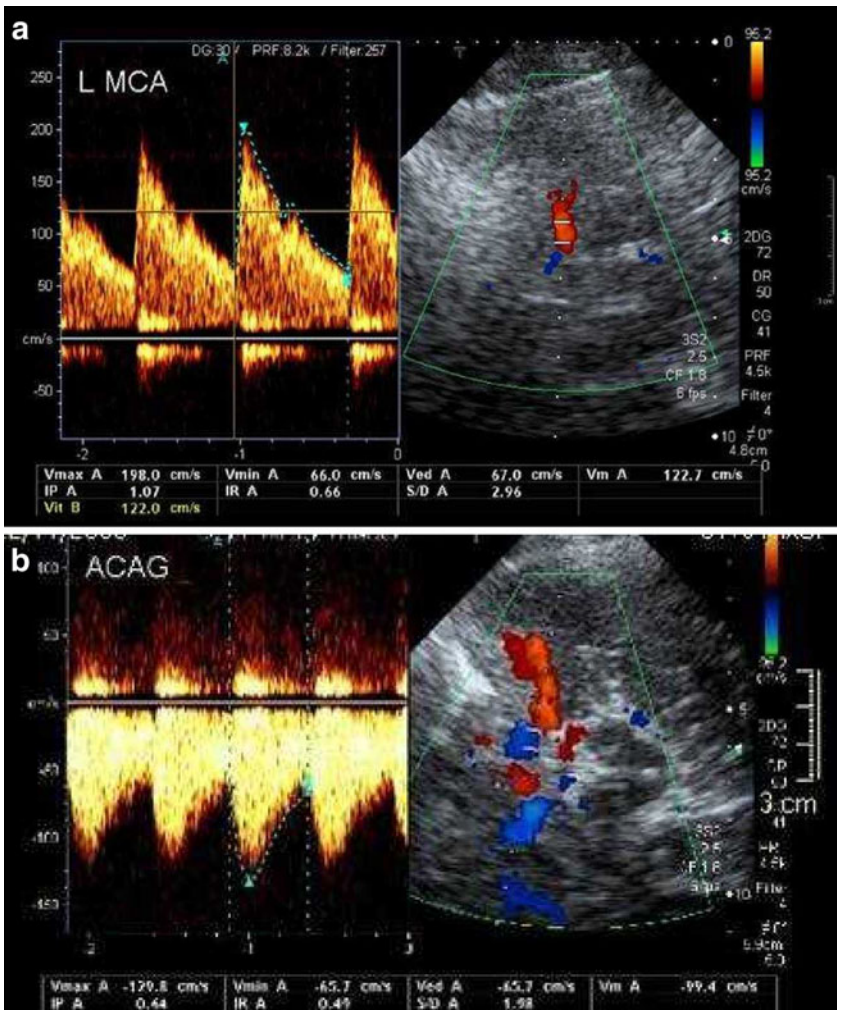



**Fig. 3** Temporal acoustic window. **a** The middle cerebral artery (MCA) is coded red, and the spectrum is above the baseline, as flow is towards the transducer. The time-averaged mean of the maximal velocities (TAMX) is related to the area under the curve of maximal velocities; therefore, it is possible to evaluate by placing a line at the midpoint of the spectrum. TAMX is 122 cm/s here. **b** The A1-segment of the ipsilateral anterior cerebral artery is coded blue, and the spectrum is below the baseline, as flow is away from the transducer towards the midline

territory, leading to reflex vasodilatation. Intracranial hypertension, on the contrary, induces an increase of these indexes via a diffuse increase of resistance to cerebral blood flow (CBF).

## Introduction to basic cerebrovascular haemodynamics

### Autoregulation

CBF depends on two factors: the cerebral perfusion pressure (CPP) and the cerebrovascular resistance (CVR), so that CBF = CPP / CVR. The CPP can be calculated from the mean arterial blood pressure (MAP) and the intracranial pressure (ICP), so that CPP = MAP − ICP. The CVR changes with constriction and dilation of arterioles in the brain.

Autoregulation of cerebral blood flow is mediated via calibre changes in cerebral arterioles in response to changes in blood pressure to maintain a constant cerebral blood flow. Autoregulation is effective at a mean arterial pressure from approximately 50 to around 150 mmHg; it generally responds within seconds to change in blood pressure. Outside this range, CBF changes linearly with blood pressure. Disease states, including traumatic brain injury, can impair cerebral autoregulation, rendering the brain susceptible to inadequate (ischaemic) or excessive (hyperaemic) CBF. Autoregulation can be evaluated bedside with TCD by capturing changes in velocity in response to changes in arterial carbon dioxide tension ($PaCO_2$) and MAP [11].

Velocity (V) in a rigid pipe equals the volume of fluid per time (Q) divided by the cross-sectional area (A) of the pipe, V = Q / A. Thus, the flow velocity in an artery depends on two factors: the cross sectional area of the vessel and the blood flow through it. In a narrowed vessel, as long as the blood volume flow is constant, the velocity increases at, and immediately downstream from, the stenosis. An increased velocity can also reflect increased flow volume without a change in luminal diameter, e.g. in anaemia, arteriovenous malformation, in a vessel functioning as a collateral for another occluded artery, or a combination of these. As proximal segments of intracranial arteries have limited vasodilatation capacity, low velocity always reflects low blood flow, e.g. downstream from a stenosis, or in case of increased vascular resistance (as in cerebral oedema). TCD parameters are influenced by different physiological and pathological factors, and by vasoactive substances.

Velocities vary with age. They rise rapidly after birth, then more slowly until the age of 6–8 years, after which there is a slow decrease to about 70% of the maximal velocities by the age of 18 years [12, 13] (Table 1). Maximum values in children with sickle cell anaemia are recorded at age 3–6 years [14]. Velocities are slightly higher in pubertal girls than in boys [11]. Velocities in the vertebro-basilar system are lower than in the carotid system.

### Others factors affect cerebral blood flow and velocities

There is an inverse linear relationship between haematocrit and velocity [15]. Velocities increase in anaemia due to increased cardiac output, decreased blood viscosity and decreased intracranial resistance, allowing sustained normal oxygenation of the brain. This explains why children with sickle cell disease have high velocities, even in the absence of a stenosis. Consequently, cut-off levels for normal/abnormal velocities are different in these children (Table 2).

Carbon dioxide ($CO_2$) is a powerful modulator of cerebral blood flow and intracranial velocities. The variation of velocities is about 4% per mmHg of $PaCO_2$ when autoregulation is normal. The partial pressure of oxygen ($PaO_2$) is another modulator, and velocities increase exponentially when $PaO_2$ decreases below 60 mmHg. Hyperventilation, via a reduction of $PaCO_2$ and hypocapnic alcalosis, induces constriction of distal intracranial arterioles, a significant decrease of intracranial velocities, and an increase of PI and RI. In turn, hypercapnia induces vasodilatation, a dramatic increase of velocities, and decrease of PI and RI. These mechanisms are mediated via changes in extracellular pH. Cerebral vaso-reactivity to $PaCO_2$ can be reduced or nullified by ischaemia, traumatic head injury, some forms of metabolic encephalopathy, and drugs, e.g. thiopenthal, acetazolamide, halothane. Halothane increases MCA velocities by 30% during general anaesthesia, whereas thiopenthal has a mild opposite effect. Sleep can increase velocities slightly due to hypercapnia. Crying can decrease velocities due to hypocapnia. Fever increases blood flow by about 10%. In clinical practice, interpretation of TCD should take into account these general causes of intracranial velocity variation.

Lesions producing large diastolic runoff (e.g., a large patent ductus arteriosus or aortic cardiac valve insufficiency) will decrease diastolic blood flow to the brain and consequently reduce the diastolic component of the Doppler spectrum.

## Indications

### Sickle cell anaemia

Sickle cell anaemia (SCA) is a serious genetic haemoglobinopathy caused by a beta globin gene mutation express-

**Table 1** Velocities in cm/s and standard deviation (SD) in healthy children in the middle cerebral artery (MCA), internal carotid artery (ICA), anterior cerebral artery (ACA), posterior cerebral artery (PCA) and basilar artery (BA) based on Bode [12, 13]

| Measurement | MCA | ICA | ACA | PCA | BA |
|---|---|---|---|---|---|
| TAMX | | | | | |
| 3–12 months | 74 (14) | 67 (10) | 50 (11) | | |
| 1–3 years | 85 (10) | 81 (8 | 55 (13) | 50 (17) | 51 (6) |
| 4–6 years | 94 (10) | 93 (9) | 71 (15) | 56 (13) | 58 (6) |
| 7–10 years | 97 (9) | 93 (9) | 65 (13) | 57 (9) | 58 (9) |
| 11–18 years | 81 (11) | 79 (12) | 56 (14) | 50 (10) | 46 (8) |
| VS | | | | | |
| 3–12 months | 114 (20) | 104 (12) | 77 (15) | | |
| 1–3 years | 124 (10) | 118 (24) | 81 (19) | 67 (18) | 71 (6) |
| 4–6 years | 147 (17) | 144 (19) | 104 (22) | 84 (20) | 88 (9) |
| 7–10 years | 143 (13) | 140 (14) | 100 (20) | 82 (11) | 85 (17) |
| 11–18 years | 129 (17) | 125 (18) | 92 (19) | 75 (16) | 68 (11) |
| VD | | | | | |
| 3–12 months | 46 (9) | 40 (8) | 33 (7) | | |
| 1–3 years | 65 (11) | 58 (5) | 40 (11) | 36 (13) | 35 (6) |
| 4–6 years | 65 (9) | 66 (8) | 48 (9) | 40 (12) | 41 (5) |
| 7–10 years | 72 (9) | 68 (10) | 51 (10) | 42 (7) | 44 (8) |
| 11–18 years | 60( 8) | 59 (9) | 46 (11) | 39 (8) | 36 (7) |

*TAMX* time-averaged mean of the maximal velocities, *VS* peak systolic velocity, *VD* end-diastolic velocity

ing haemoglobin S. The disease is very frequent in Africa, and among African descendants in Europe, North and South America, but it also exists around the Mediterranean, in the Middle East and in Asia. In developed countries, survival is no longer a major problem, due to early detection of the disease and high standards of care. Nevertheless, morbidity remains high with a stroke risk, in the absence of intervention, of 11% before the age of 18 years [16]. Most strokes are due to a macro-angiopathy affecting the terminal internal carotid arteries and proximal middle and anterior cerebral arteries, with smooth muscle hyperplasia and intimal fibrosis that lead to progressive stenosis and occlusion with moyamoya-like collateral development [17]. Chronic transfusions are effective in reducing the risk of (1) recurrent ischaemic stroke, and (2) a first stroke in children with HbSS who have abnormally high velocities on TCD [18].

TCD has become an essential tool in the management of SCA, recommended by the French Authority of Health and by the United States Department of Health and Human Services (type A, class I evidence) [1, 19, 20]. In children who have suffered a stroke, it detects arteriopathy with a sensitivity of 90% and specificity of 100% compared to cerebral angiography [21]. The most important application is in evaluation of stroke risk in neurologically asymptomatic SCA patients. In the 1990s, Adams et al. [22] demonstrated that an abnormal TCD is linked to high risk of a first stroke, and that chronic transfusions reduce this risk. One hundred ninety children were screened with TCD and followed for an average of 29 months; 23 had a TAMX >170 cm/s; strokes occurred in seven patients, including six among the 23 patients with abnormal TCD. This result was confirmed by a subsequent study [23] including 125 more children, which showed that a TAMX ≥200 cm/s in the terminal ICA, or in the MCA, indicates a 10% risk for stroke per year, compared to a 2% risk in patients with normal TCD.

**Table 2** Diagnostic groups at transcranial Doppler, and clinical impact in patients with sickle cell anaemia. Time average mean of the maximal velocities (TAMX), recorded without angle correction

| Groups | TAMX, cm/s | Clinical consequence |
|---|---|---|
| Normal | <170 | Re-scan annually |
| Conditional | 170–199 | Re-scan every 3 months |
| Abnormal | ≥200 | Start transfusions |

In the randomised multi-centre North American STOP I-study (stroke prevention trial in sickle cell anaemia) [18], 1,934 HbSS or HbSB0 children from 2 to 16 years old were screened with TCD. Children with TAMX ≥200 cm/s in the MCA or ICA were randomised into two groups. Sixty-three children received periodic blood transfusions or exchange transfusions designed to maintain their haemoglobin S level ≤30%. Sixty-seven children received standard supportive care with symptomatic treatment. After a year, ten children in the standard care group had a stroke, while only one child in the transfusion group had a stroke, indicating a 92% relative reduction in stroke rate ($P<0.001$). Subsequently, the National Institute of Health in the United States issued an alert recommending TCD-screening in children 2–16 years old with SCA, and long-term transfusion treatment in children with an abnormal TCD.

The efficiency of this stroke prevention protocol was later confirmed by several studies. Fullerton [24] observed a 5-fold decrease in the rate of first stroke in Californian children with sickle cell disease within 2 years following the implementation of the STOP-based protocol. In Memphis, the stroke rate decreased from 0.46 to 0.18 per 100 person-years after the TCD screening rate reached 99% [25]. In a newborn SCA-cohort of Creteil, France, including 217 SS/Sβ0 thalassaemia patients, early and annually screened with TCD since 1992, the cumulative stroke risk by age 18 was 1.9% (95% CI, 0.6–5.9) [14, 26, 27]. In Philadelphia, the incidence of overt stroke in the post-TCD period was 0.06 per 100 patient-years, compared with 0.67 per 100 patient-years in the pre-TCD period [28].

According to the French and U.S. guidelines [19, 20], children with SCA should be screened with TCD from the second year of life and then re-scanned annually until 16 years old if normal (i.e. highest TAMX of any artery <170 cm/s), quarterly if conditional (TAMX of at least one artery 170–199 cm/s), and regular transfusions should be initiated in case of abnormal TCD (TAMX in at least one artery ≥200 cm/s) (Table 2; Fig. 4). Correlation with magnetic resonance angiography (MRA) is useful in children with abnormal or inadequate TCD, e.g. where there is no useful acoustic window. It is worth noting that abnormal velocity does not equal angiographic stenosis. TCD is a more sensitive technique, and it detects arterial disease at an earlier stage than MRA. But children with abnormal TCD and abnormal MRA are at higher risk for stroke than those with an abnormal TCD alone [29] (Fig. 5).

In STOP-I [18], the diagnostic distribution at initial TCD examinations was: 67% normal, 17.6% conditional, 9.3% abnormal, and 6% inadequate. In a French cohort [14], TCD was abnormal in 21% of SCA-patients at a median age of 3.2 years (range, 1.3–8.3). In 44% of these, conditionally abnormal TCD had been observed earlier. The cumulative risk of abnormal TCD by age 14 in SS/SB0 patients was 29.6% (95% CI, 22.8–38.0%), with a plateau starting at age 9 years.

Conditional velocities are more likely to become abnormal when the child is younger and when velocities are close to 200 cm/s [14, 30]. In the French cohort, conditional TCD occurred in 58/217 patients and became abnormal in 20/58 patients (34.5% conversion rate). The median age of conditional TCD was 2.5 years (range, 1.2–5.5) and the median delay 1.1 years (range, 0.03–7). Age less than 4 years was a significant risk factor for conversion (OR = 6.7; 95% CI, 1.7–27). In the STOP study, the conversion risk was 97% in very young children with two consecutive conditional TCD examinations, and 13% in teenagers seen for the first time at the age of 14 years [31].

Since the objective of the examination is to detect focal acceleration of blood flow, it is important to carefully explore the entire arteries by sweeping the sample gate along the MCA and the ICA during spectral recording, and optimising the pulsed spectrum at each depth by slightly tilting the probe in order to get the highest velocity. Expert operators trust the sound signal: the higher the pitch, the higher the velocity.

## Monitoring cerebral haemodynamics in intensive care patients, particularly following traumatic brain injury

Traumatic brain injury (TBI) is an important factor in children's morbidity and mortality. Several important disturbances of cerebral haemodynamics follow TBI, including hyperaemia, cerebral ischaemia and vasospasm, which vary between patients, and from day to day in any

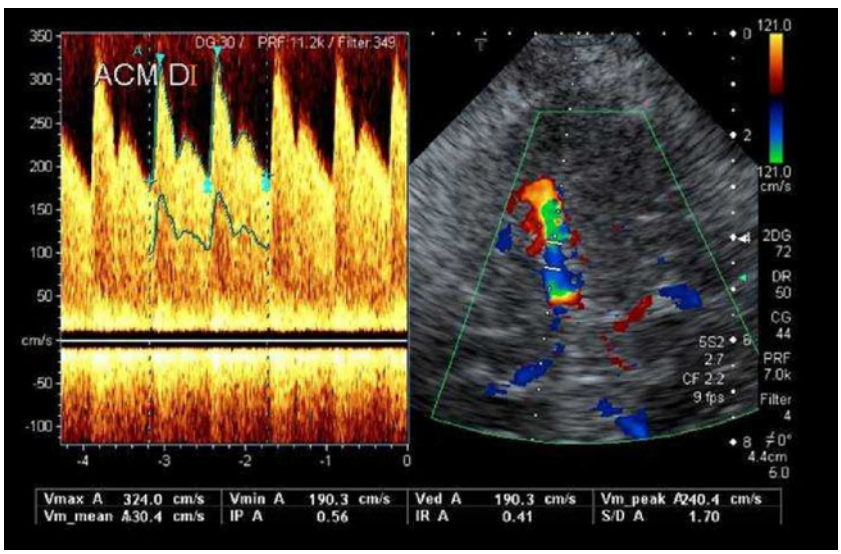



**Fig. 4** Sickle cell anaemia. Transtemporal recording of the right middle cerebral artery demonstrates a time-averaged mean of the maximal velocities of 240 cm/s, which is abnormally high, suggesting increased risk of stroke, and indicating need for chronic transfusions

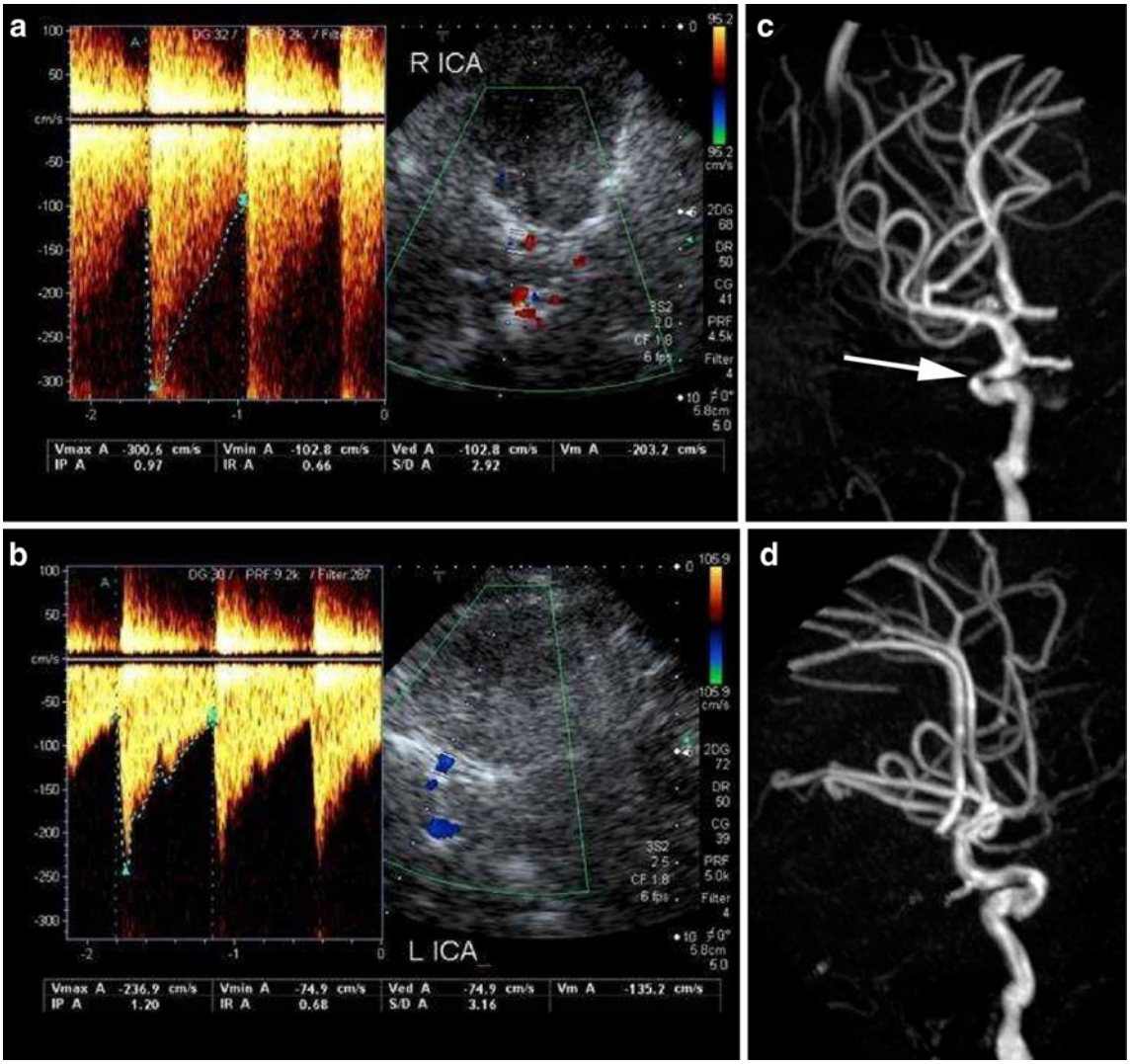



**Fig. 5** Sickle cell anaemia, temporal window. **a** Velocity of the right internal cerebral artery is abnormally high with a time-averaged mean of the maximal velocities (TAMX) of 203 cm/s. **b** TAMX in the left ICA is in the normal range for a child with sickle cell anaemia at 135 cm/sec. **c** Magnetic resonance angiography (MRA) confirms abnormality by demonstrating a short tight stenosis of the C2-segment of the right internal cerebral artery (*arrow*). **d** Normal MRA of the left internal carotid circulation

individual. TCD, in association with other tools available for monitoring cerebral haemodynamics, may help in understanding the pathophysiology and guide management. Among the different cerebral arteries available for evaluation, the MCA is easiest to locate, and it provides the most reproducible data. Moreover, it supplies the largest part of the hemispheres.

High cerebral blood flow is a main cause of diffuse cerebral swelling leading to increased intracranial pressure and poor outcome. Hyperaemia can occur a few hours after TBI, last two to four days, and be followed by Doppler patterns suggestive of high vascular resistance, consistent with elevated intracranial pressure [32, 33]. Hyperaemia has also been reported in the first hours following an ischaemic event, particularly in neonates and children [34]. In adults, it has been well described as cerebral hyperperfusion syndrome following carotid endarterectomy or carotid artery stenting. This can provoke intracerebral haemorrhage and is believed to be caused by loss of autoregulation. It has also been reported in children with diabetic ketoacidosis and cerebral oedema, and is seen on TCD as increased flow velocities (twice normal values), and decreased PI and RI [35–37] (Fig. 6).

Cerebral ischaemia is the main cause of secondary deterioration in patients following TBI. Because of its non-invasiveness and ease in use, TCD may be an ideal tool for detecting decreased CBF and for evaluating the course of treatment [38, 39]. An initial TAMX <28 cm/s corresponds to an 80% likelihood of early death [40]. For Goutorbe et al. [41], a diastolic velocity <20 cm/s is

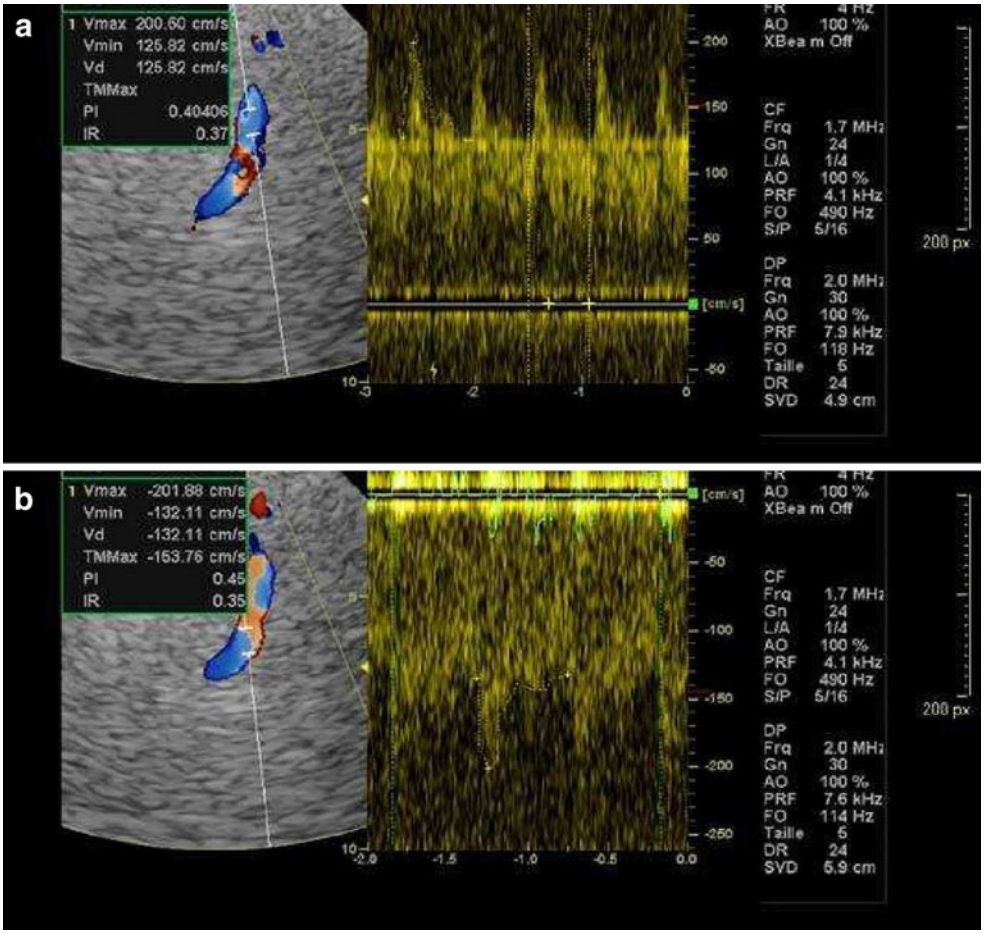



**Fig. 6** An 11-year-old boy in diabetic ketoacidotic coma. Intracranial flow velocities are abnormally high, and pulsatility index (PI) is low; this is consistent with hyperaemia. The time-averaged mean of the maximal velocities is 160 cm/s and the PI is 0.4 in the middle cerebral artery (**a**). Corresponding parameters in the anterior cerebral artery are 153 cm/s and 0.45 (**b**). MRI performed at day 7 (not shown) depicted several intracerebral haematomas

predictive of poor outcome. In a prospective paediatric study including 36 children with moderate or severe TBI, diastolic velocity <25 cm/s and PI >1.31 on TCD at admission but after the first resuscitation phase (correction of low blood pressure, anaemia, hypoxia, hypoventilation), was associated with poor prognosis [42] (Fig. 7). TCD may also be used to monitor treatment. For example [43], vasopressors used for increasing mean arterial pressure and/or decreasing intracranial pressure will decrease PI and increase diastolic velocity and TAMX. Thus, the target mean arterial pressure can be estimated by TCD. Mannitol increases CBF and hence flow velocities.

Most recent studies have stressed the role of impaired CBF autoregulation in the poor outcome of patients after TBI, and the need for evaluating autoregulation. In children, impaired autoregulation has been reported in about 40% after TBI [44]. However, the adequacy of the autoregulation varies with time after injury, and may even differ between the hemispheres; therefore, single measurements may not reflect the true state [45, 46].

Intracranial vasospasm is a classic complication to aneurysmal subarachnoid haemorrhage or TBI. Vasospasm typically occurs 48 hours after subarachnoid haemorrhage and may last for 12–16 days. In adults, TCD has been proved useful for the detection and monitoring of vasospasm in the basal segments of the intracranial arteries, especially the MCA and basilar artery, following subarachnoid haemorrhage (Type A, Class I-II evidence) [1]. With a TAMX >120 cm/s as cut-off, sensitivity is good (92%), but specificity very low (50%). In clinical practice, vasospasm is highly suspected when TAMX >200 cm/s. The Lindegaard ratio, also called Aaslid ratio (the ratio of peak systolic velocities between MCA or anterior cerebral artery, and the ipsilateral extracranial ICA), may help differentiate high velocities due to generalised hyperaemia from vasospasm [3, 4]. A Lindegaard ratio of 3–6 is considered a sign of mild spasm, and >6 a sign of severe spasm. A rapid increase of MCA velocity of 50–65 cm/s over a period <24 h, rather than an absolute value, is predictive of poor prognosis and ischaemic deficit. Only arteriography is universally accepted as a confirmatory test. Nevertheless, MRA or CT angiography is often used due to their accessibility and shorter examination times.

Vasospasm is uncommon in children following TBI [47, 48]. In a study evaluating changes in cerebral haemodynamics after head injury, Mandera et al. [48] did not diagnose vasospasm in any patient. In a study comparing the TCD pulsatility index and intracranial pressure in

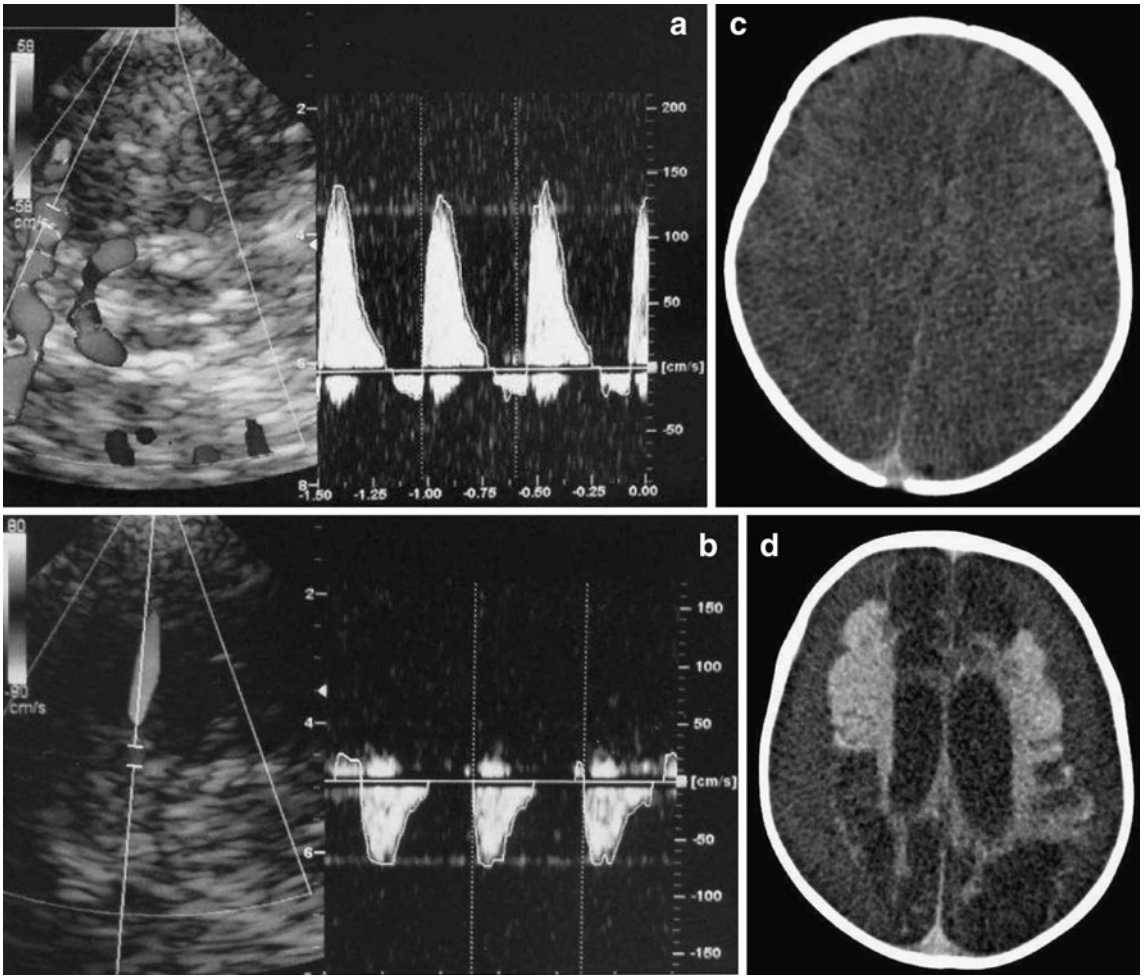



**Fig. 7** A 2-month-old boy with shaken baby syndrome and poor outcome. TCD at admission showed resistive (pulsatility index, PI= 2.66) slow (time-averaged mean of the maximal velocities, TAMX= 39 cm/s) flow, with reverse diastolic flow in the middle cerebral artery (**a**); no diastolic flow in the anterior cerebral artery (**b**). The spectra were normal at day 12 (not shown) with TAMX=94 cm/s and PI=1.1. CT on admission (**c**) showed diffuse brain swelling with loss of grey/white matter differentiation. CT done one month later (**d**) shows encephalomalacia and bilateral ex vacuo subdural hematomas

children with traumatic brain injury, Figaji et al. [49] reported an 11% incidence of vasospasm. In a series of 22 children aged 7 months to 14 years, with moderate to severe traumatic brain injury as indicated by a Glasgow coma score <12 and abnormality on brain imaging, 36.3% had, on day 3–5, a flow velocity in the MCA >120 cm/s and a Lindegaard ratio >3, indicative of mild to moderate vasospasm when applying the criteria used in adults [50].

## Brain death

Brain death denotes the complete and irreversible cessation of brain function due to a total arrest of cerebral blood flow. Diagnosis of brain death rests both on clinical criteria and confirmatory tests. In recent years, TCD has shown high sensitivity and specificity for determination of brain death in adults and children [51–54]. The proximal part of both MCA, and the basilar artery, are monitored at intervals. If the temporal window is not available, an orbital window can be used for the assessment of the carotid siphons. As cerebral oedema develops, cerebral perfusion pressure decreases, depicted by decreased diastolic velocities with no change of the systolic velocities, and raised RI and PI. When intracranial pressure is about the same as mean arterial pressure, diastolic flow velocity is zero with only high spiky systolic segments. This state may be reversible, if adequate treatment is possible. With a further fall in cerebral perfusion pressure to below mean arterial pressure, two patterns of flow can be recorded. (1) The "reverberating" or "oscillating" pattern of flow with short antegrade systolic, and reversed diastolic flow. The retrograde diastolic flow lasts longer, resulting in no net flow. (2) The "systolic spikes" with early antegrade systolic slow flow (<40–50 cm/s) of duration <200 ms, without diastolic

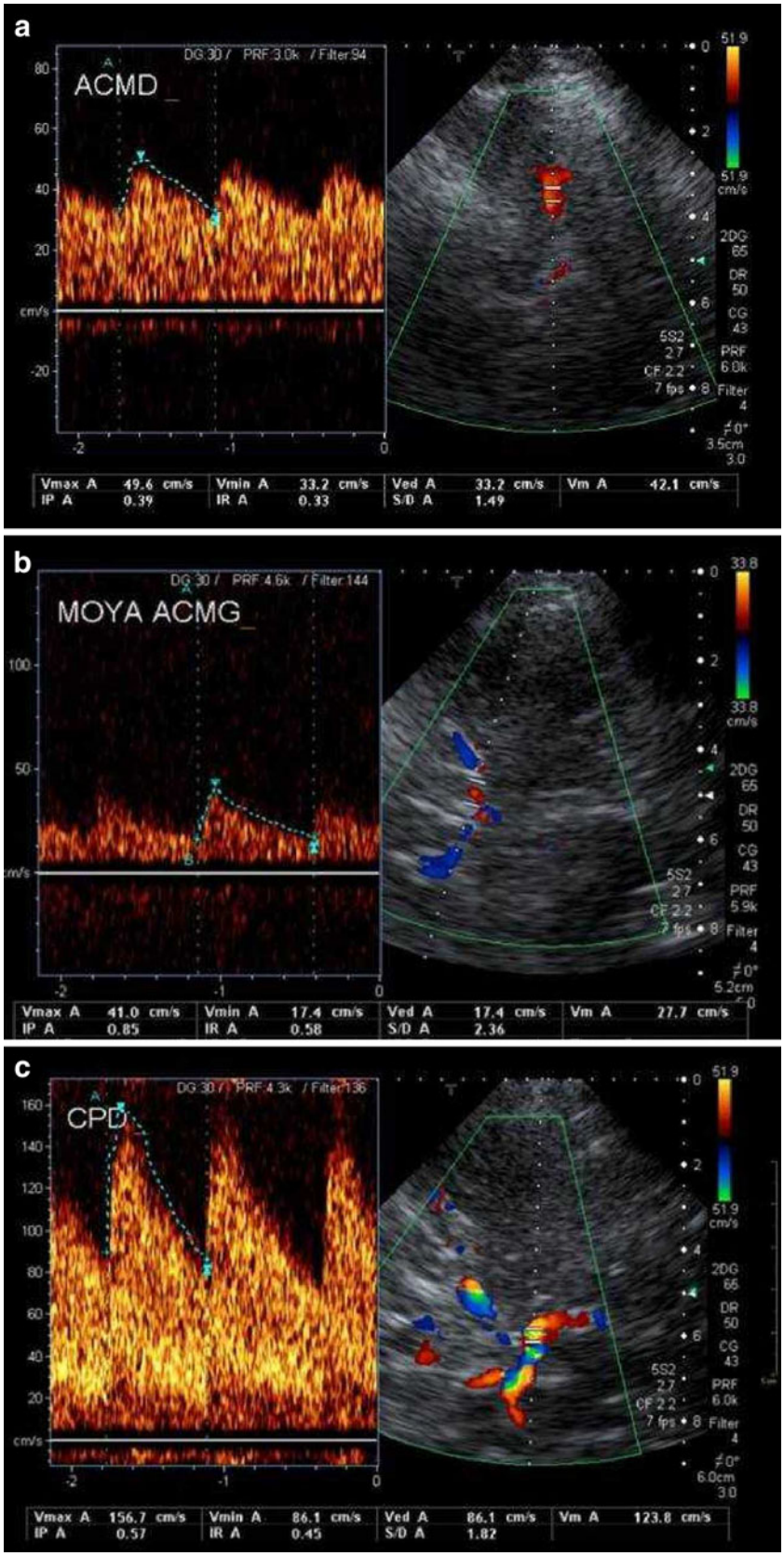
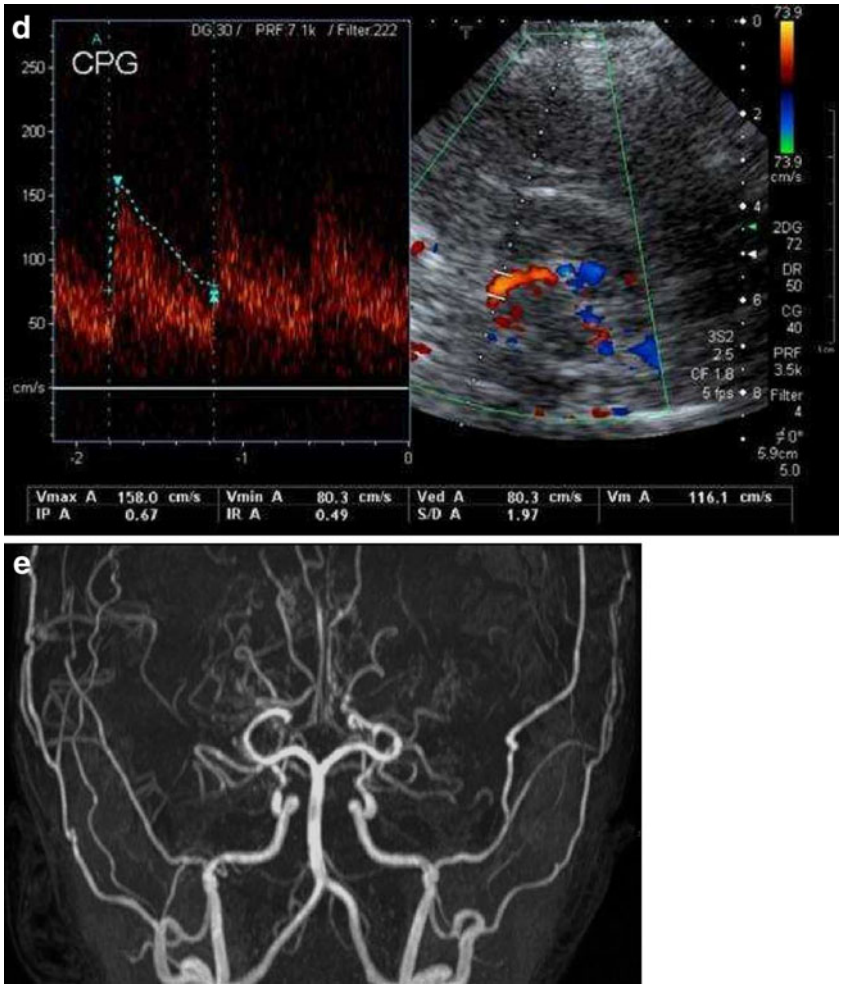



**Fig. 8** A 9-year-old girl with neurofibromatosis type 1 and moyamoya syndrome has occlusion of both middle cerebral arteries (MCAs) with slow flow (**a** and **b**) due to collateral vessels. High velocities (3–4 times that in the ipsilateral MCAs) are demonstrated in both posterior cerebral arteries (**c** and **d**). Coronal maximum-intensity projection of a magnetic resonance angiographic acquisition demonstrates the very abnormal intracranial arteries (**e**)

**Fig. 8** (continued)




flow, TAMX <10 cm/s. To be reliable, the abnormalities must be bilateral and unchanged over a 30-minute period. These two patterns are highly predictive of brain death (Type A, Class II evidence according to the American Academy of Neurology). Comparison with conventional arteriography has shown a 95% sensibility and 99% specificity [52]. In most countries, TCD is not used for confirming brain death, but it allows optimal timing of the formal confirmatory examination. There are a few pitfalls in the use of TCD in brain death, particularly in infants. Absent or retrograde diastolic flow can be found in children with systemic-to-pulmonary shunts, patent ductus arteriosus or aortic valve insufficiency [55]. Conversely, cerebrospinal fluid deviation, e.g. decompressive craniotomy, leading to a decreased intracranial vascular resistance, can cause persistence of normal flow patterns despite brain death. There can be a discrepancy between an abnormal MCA flow pattern and a non-conclusive basilar artery flow pattern. In this case, it is necessary to repeat the examination a few hours later and to perform the confirmatory examination only when the basilar artery flow becomes abnormal. In some cases, arrest of intracranial circulation may not occur at the same time in different arteries, and TCD waveforms can be different between the two MCAs, with more abnormal flow pattern on the more severely injured side, which emphasises the requirement for bilateral recording.

If no cerebral flow can be detected, technical problems, such as a poor acoustic window or non-optimal settings, must be excluded. The detection of a concomitant reversal of diastolic flow in the extracranial internal carotid artery could be a reliable sign of brain death [54].

## Evaluation of the cerebral vasculature in stroke

Arteriopathies are the most common cause of arterial ischaemic stroke in children. The spectrum differs from that in adults and includes moyamoya, vasculitis, dissection, and transient cerebral arteriopathy (TCA). TCA, first recognised as an important cause of childhood stroke in 1998 [56], is characterised by lenticulo-striate infarction due to non-progressive unilateral arterial disease affecting the supraclinoid internal carotid artery and its proximal branches. The course of the disease is characterised by the stabilisation, improvement or even normalisation of the

arterial lesions, sometimes after initial worsening during the first months. TCA is considered to a post infectious process, usually occurring in the 12 months after a *Varicella zoster* infection, but lately it has also been reported in association with other infectious agents, such as enterovirus, *Borrelia burgdorferi*, HIV, and West Nile virus [57]. TCA should be differentiated from moyamoya disease, which is a progressive arteriopathy affecting both carotid arteries (poorer prognosis), but which can be unilateral at presentation [58, 59]. TCD can make the evaluation of the arterial lesions in association with MRI and may be valuable in the follow-up of these patients, reducing the need for repeated MRI [60].

### Others indications

TCD has also been used in children in the detection of intracranial arteriopathies in genetic disease (neurofibromatosis type 1, Williams syndrome) (Fig. 8) [61] and in internal carotid artery dissection [62].

TCD has been tried in non-specific headache or orthostatic dysregulation [63] and in hydrocephalus, without conclusive results. By comparing TCD parameters of 12 children with hydrocephalus before and after cerebrospinal fluid drainage to 13 children with essential ventriculomegaly and ten control children, Galarza and Lazareff [64] demonstrated slightly lower velocities, and higher RI and PI, in the hydrocephalus group, although all parameters remained within normal range, making TCD inadequate in clinical practice.

In adulthood, TCD has in some cases been reported to depict large arteriovenous malformations as serpiginous structures, and to identify feeder vessels with elevated velocities and decreased PI and RI. However, the sensitivity is very low compared to MRI and CT. TCD may be used as a supplementary test, in particular for monitoring the effects of surgical or vascular intervention. TCD is also used as part of multimodality neurological monitoring during surgery for congenital heart disease, allowing the evaluation of cerebral blood flow variations as well as the presence of emboli during, before and after cardiopulmonary bypass [65].

## Conclusion

TCD is highly recommended in the management of children with sickle cell disease. Its use in intensive care is growing as it may allow a better adjustment of therapy in cerebrovascular disturbances to prevent, or reduce the effects of, acute cerebral oedema. TCD parameters should always be carefully correlated with clinical and biological findings.

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