Chapter 24
Aneurysmal Subarachnoid Hemorrhage and Endovascular Treatment: Usefulness of Transcranial Doppler (TCD/TCCS) for Cerebral Hemodynamic Monitoring

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Key Points

1. Subarachnoid hemorrhage (SAH) is a devastating disease with high morbidity and mortality. Delayed cerebral ischemia due to vasospasm is one of the main hemodynamic complications. Up to 30% of patients may develop delayed cerebral ischemia related to vasospasm. Early detection can guide clinical decisions at patient's bedside.
2. Transcranial Doppler (TCD/TCCS) is an accessible and reproducible tool, applicable for the monitoring of cerebral blood flow velocities (CBFVs) and hemodynamic indexes derived from them.
3. The use of Echo-contrast may increase the sensitivity of the detection of unruptured intracranial aneurysms and their recanalization after endovascular treatment.
4. New technologies of TCD can improve its sensitivity. It allows intraoperative and continuous monitoring in patients at high risk of developing vasospasm.

24.1 Introduction

Transcranial Doppler (TCD/TCCS) is a non-invasive method with numerous clinical applications in critically ill patients with acute brain injury (ABI). In addition to diagnostic and monitoring of vasospasm in patients with SAH, the use of TCD has recently been extended to the detection and characterization of intracranial aneurysms.

TCD is performed by a low-frequency transducer (≤2 MHz) through acoustic window in the skull (bone window or natural hole), allowing visualization of basal cerebral arteries and measuring CBFVs in different clinical scenarios [1] (Fig. 24.1).

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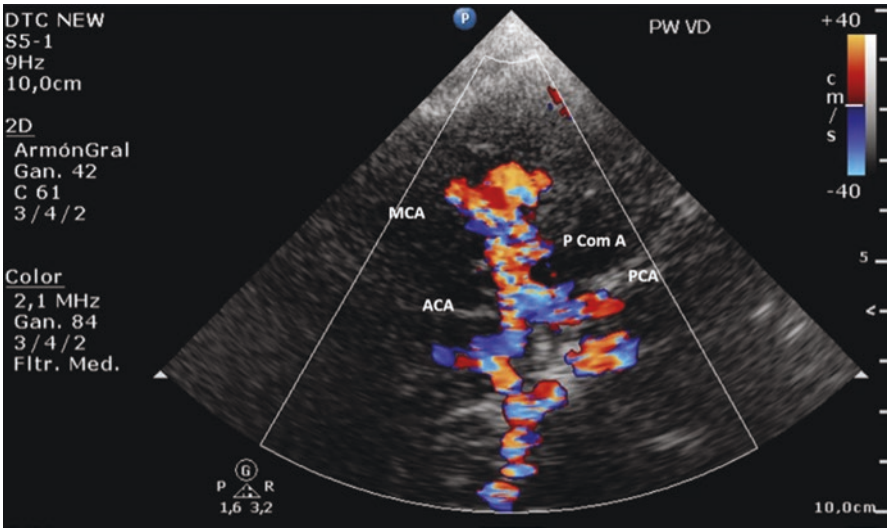

Fig. 24.1 Image obtained by TCCS: transtemporal acoustic window showing the circle of Willis in a patient with SAH. MCA middle cerebral artery, ACA anterior cerebral artery, PCA posterior cerebral artery, PcomA posterior communicating artery

24.2 Subarachnoid Hemorrhage (SAH): Epidemiology and Pathophysiology

Subarachnoid hemorrhage (SAH) is a disease with high morbidity and mortality with high social impact [2]. SAH is the third most common cerebrovascular disorder (after intracranial hemorrhage and acute ischemic stroke). Approximately 80% of spontaneous, non-traumatic SAH result from aneurysm rupture [2, 3]. Worldwide, incidence is approximately 9.1/100,000 adults. In the USA, the incidence of SA is higher in woman (2:1), African Americans, Hispanics, and above 55-year-olds.

After SAH triggers the activation of numerous deleterious mechanisms: (1) increased intracranial pressure; (2) decreased cerebral blood flow (CBF); (3) impairment of cerebral auto-regulation (CA); and (4) exposure to inflammation and cerebral metabolism changes. All of these clinical circumstances can lead to the appearance of early secondary brain injury, occurring most commonly in the first 72 h after bleeding [3, 4].

SAH patients are at high risk for multiple complications in the weeks following their initial bleed. Delayed cerebral ischemia (usually present after the first 72 h from symptom onset) is the second most common cause of morbidity and mortality after the early brain injury of the initial SAH and is most commonly due to arterial vasospasm. Both early and delayed cerebral ischemia have been established as important predictors of poor prognosis [2], and it is accepted that their pathogenesis is multifactorial. The exact underlying pathophysiological mechanisms remain unknown.

24.2.1 Vasospasm

Vasospasm, the leading cause of delayed cerebral ischemia, is one of the major complications of SAH. Vasospasm is defined as a CBF reduction induced by vasoconstriction of intracranial arteries not attributable to: atherosclerosis, spasm induced by catheter manipulation, or vessel hypoplasia. It occurs in up to 70% of patients between 3 and 14 days after initial bleeding (has been reported up to 21 days). Vasospasm becomes symptomatic in 20–40% of patients and is considered responsible for 20% of morbidity and mortality in SAH [5].

The main risk factors for the appearance of vasospasm include initial clinical severity, the amount of bleeding, and the presence of intraventricular hemorrhage (IVH) [6]. Therefore, vasospasm has a multifactorial origin.

Digital subtraction angiography (DSA) is considered the gold standard technique for vasospasm detection (CT angiography may be a valid option). However, DSA is an invasive technique and therefore not applicable if serial monitoring is required. On the other hand, TCD/TCCS is a non-invasive, repeatable, and low-cost method that allows the diagnosis and daily monitoring of vasospasm of critically ill patients in the ICU.

TCD/TCCS is a useful and reliable method for the detection of hemodynamic changes. Therefore, it is considered a suitable tool for daily monitoring of vasospasm and early diagnosis of neurological worsening related to vasospasm.

In many institutions, TCD (as a blind technique) has been used as a tool for cerebral vasospasm monitoring due to its reproducibility and ability to detect variations in cerebral hemodynamics. However, TCD is an operator-dependent technique and that the measurement can be influenced by the angle of insonation, giving rise to under- or overestimates of CBFVs values.

The hemodynamic parameters most commonly measured are: (1) CBFVs (Peak systolic velocity (PSV), end-diastolic velocity (EDV), and mean flow velocity (MFV)), (2) direction of CBFVs, (3) spectral Doppler waveform analysis (flow patterns), (4) sound (turbulence or attenuation cerebral blood flow), and (5) hemodynamic indexes/ratios: pulsatility index (PI), resistance index (RI), and Lindegaard ratio (LR).

In recent years, most centers have incorporated transcranial color-coded duplex sonography (TCCS) methodology. The main advantage of TCCS is the visualization of intracranial vessels (B-mode), which allows for a targeted evaluation of each arterial segment and its corresponding CBFVs [7, 8]. The direct visualization of the cerebral basal arteries (circle of Willis) through color-Doppler mode allows the detection of segments in main arteries of anterior and posterior circulation, facilitating the detection of hemodynamic alterations secondary to vasospasm [9].

The MFV in cerebral basal arteries is directly proportional to CBF and inversely proportional to the section area of the insonated vessel, where any clinical situation that causes a variation of vessel diameter will affect the MFV. Hence, vasospasm is one of the most common causes of increased MFV after SAH. CBFVs that define the severity of vasospasm are clearly established for the MCA, but not for the ACA, PCA, and BA [10].

Progressive or persistent elevation in CBFV may be due to hyperemia or vasospasm, where LR (relationship of MFV between MCA and extra cranial portion of

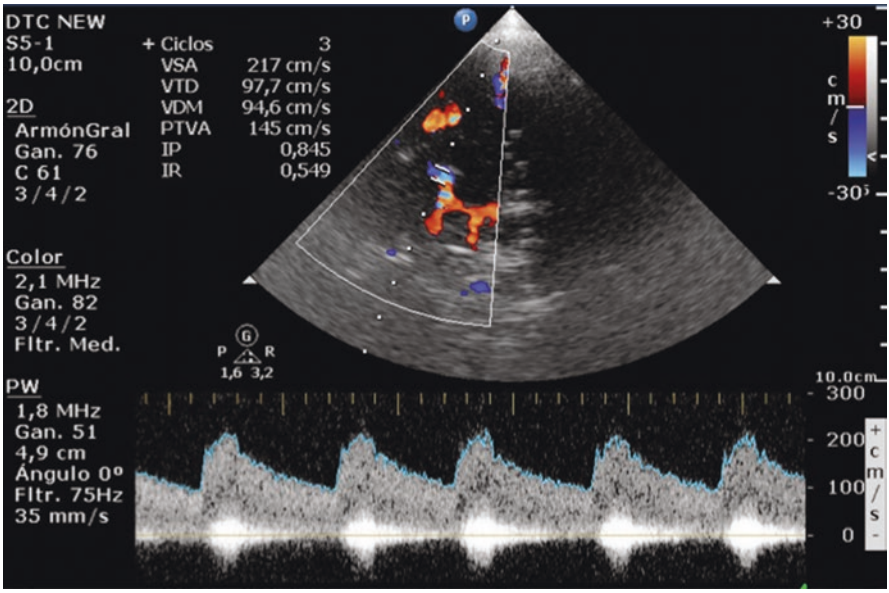

Fig. 24.2 TCCS insonation performed on a patient with aneurysmal SAH (MCA) in which moderate vasospasm and artifact corresponding to the presence of the coils used are observed

ICA) allows for the differentiation between them, while helping to classify the vasospasm severity (Fig. 24.2).

There have been reports in the literature of another ratio obtained by TCD/TCCS that correlates better with vasospasm than MFV measurement in patients with SAH.

This ratio has been calculated from the relationship between MFV in the ipsilateral MCA (defined ipsilateral MCA where highest CBFV) and MFV of the contralateral MCA (ipsilateral MFV_{MCA}/contralateral MFV_{MCA}). The value of this ratio to predict DCI was more auspicious than MFV measurement. The cut-off value that best discriminated the risk of DCI was 1.5 [11].

24.2.2 Vasospasm Diagnostic Criteria

Adapted from Marshal et al. [12].

24.2.2.1 Diagnostic Criteria of Vasospasm (VSP) by TCD/TCCS in MCA

Major (severe vasospasm):

- Change in MFV with respect to baseline greater than 50 cm/s
- Mean flow velocity (MFV) >200 cm/s
- Lindegaard ratio >6

Minor (moderate vasospasm):

- Mean flow velocity (MFV) >120 cm/s
- Lindegaard ratio >3

It is necessary to consider the appearance of a decrease in the CBFV in the poststenotic segment and the appearance of CBF turbulence when the degree of stenosis, secondary to vasospasm, is higher than 50% of diameter of the insonated vessel [10].

Due to the segmental nature of vasospasm and the need for daily monitoring by TCD/TCCS, it is important to identify the arterial segment affected. Therefore, it is convenient to record the MFV measurement corresponding to the depth of each segment of each cerebral basal artery insonated for a real-time control at the patient's bedside in the ICU.

In patients with SAH admitted to the ICU, daily monitoring using TCCS methodology can be useful to define the need for neuroimaging (CT, MRI, CTA, DSA) to evaluate brain parenchyma impact and/or decide intra-arterial therapy (angioplasty or drug administration) [13].

The prevalence of early angiographic vasospasm, defined as the appearance of angiographic vasospasm in the first 48 h after SAH, is estimated at around 10%. In some studies, the presence of vasospasm on admission has been identified as an independent prognostic factor in this patients [14, 15]. Patients with intracerebral hematoma, intraventricular hemorrhage, large aneurysm size (>12 mm), and MCA aneurysms appear to have a greater risk of early vasospasm [16].

24.3 TCD/TCCS: Cerebral Vasoreactivity

Dilatation of the cerebral arterioles results in a reduction in cerebrovascular resistance (CVR) allowing CBF to increase in the proximal segments of the cerebral basal arteries. While arteriolar vasoconstriction increases CVR and therefore causes CBF reduction. Cerebral vasoreactivity is the vasoconstriction and vasodilatation capacity of intracranial vessels after stimulus (e.g. vasoactive drugs) and is a measure of the integrity of CA. Vasoreactivity can be assessed measuring by CBFV changes. Those hemodynamic changes can be measured by TCD/TCCS [17, 18].

Cerebral vasoreactivity can be assessed by TCD/TCCS after acetazolamide administration in patients with ruptured intracranial aneurysms [19, 20]. In these trials, vasoreactivity was normal in both brain hemispheres, and the location of the aneurysm did not influence the final results. Likewise, the development of vasospasm in the acute stage of SAH did not cause an alteration in cerebral vasoreactivity.

Since the influence of cerebral vasoreactivity on vasospasm development has been proposed, researchers evaluated the existence of differences in hemodynamic response of cerebral basal arteries after acetazolamide administration in a group of 37 patients with unruptured cerebral aneurysm [21] and detected no differences

between affected and non-affected brain hemisphere or between subjects with aneurysm compared to healthy subjects.

These results suggest that patients with unruptured aneurysm have no alterations in cerebral vasoreactivity after aneurysm treatment (e.g., clipping, coiling).

24.4 TCD/TCCS: Intraoperative Monitoring

Several intraoperative monitoring modalities, including indocyanine angiography, electrophysiological studies, and micro-Doppler ultrasonography, are used to verify correct positioning of the surgical clip to secure cerebral aneurysm. Siasios et al. in 2012 [22] studied a series of 19 patients in whom micro-Doppler had been performed during surgery. In all of these patients, the high diagnostic capacity of this technique was demonstrated.

Given the technical difficulties of microsurgery for ruptured intracranial aneurysms and the accessibility and reliability of intraoperative ultrasonography, its use as a complementary tool during aneurysm clipping could be considered with the intention to minimize the risk of intraoperative complications or improper clip placement.

24.5 Detection of Intracranial Aneurysms and Recanalization of Treated Aneurysms

Recanalization of the aneurysmal neck is a complication that can appear after treatment, so long-term follow-up and detection of this recanalization is relevant.

Power Doppler mode is an accessible and non-invasive technique for anterior circulation aneurysms detection, but less sensitive than other diagnostic methods (e.g. DSA, CTA, MR angiography). The sensitivity of power Doppler is low for small aneurysms (<5 mm). Also, the terminal segment of the ICA is the most difficult to interpret [23] (Fig. 24.3).

The use of non-invasive imaging techniques such as TCD/TCCS, capable of detecting the residual neck in a secured aneurysm, would significantly reduce diagnostic costs, as well as potential complications, radiation exposure, and the use of radiological contrast.

Turner et al. in 2005 [24] evaluated the ability of TCCS with and without an echo-contrast to detect aneurysmal neck recanalization in patients with secured intracranial aneurysms by coiling. The authors reported that their results compared with those of the arteriography. The sensitivity of TCCS was approximately 80% for the detection of occluded aneurysms and, in the case of recanalized aneurysms, TCCS sensitivity increased as the degree of recanalization of the neck increases.

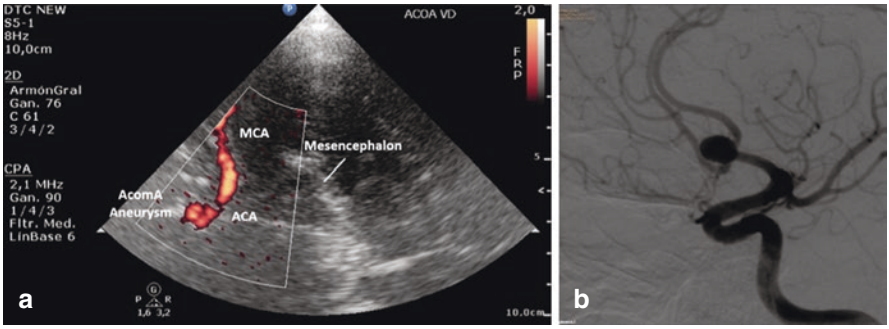

Fig. 24.3 (**a**) TCCS: Power Doppler mode image of an anterior communicating artery aneurysm (AcomA). (**b**) Diagnostic arteriography of the same patient in which the AcomA aneurysm of 7 mm maximum diameter is visualized

The administration of the echo-contrast contributed to the diagnosis of other recanalized aneurysms that had not been detected without it. Hence, TCCS and echo-contrast could be useful to monitoring the recanalization of aneurysmal neck reducing the use of invasive monitoring methods such as cerebral arteriography.

The use of flow-diverter stents for the treatment of unruptured aneurysms and ruptured aneurysms, where surgical clipping or coiling is not possible, has been increasing. Several studies have reported on the probability of long-term stenosis after deployment of flow-diverter stents. Therefore, TCD/TCCS should be considered as a useful monitoring tool to detect stenosis of flow-diverter stents [25, 26].

24.6 Cerebral Aneurysms and Cerebral Blood Flow: Other Techniques

Non-invasive monitoring of the brain microcirculation by means of a laser-Doppler flowmeter system allows for the availability of sensitive and real time information of the brain microcirculation during the surgery. In a small number of patients, it was evaluated how the detection of local pathological changes in the microcirculation would act as a predictor of post-operative prognosis, validating these intraoperative findings with other monitoring techniques such as somatosensory evoked potentials (SSEPs) [27].

Recent advances in robotics have contributed to the development of transcranial Doppler probes incorporating automated algorithms for flow rate detection and optimization of the signal recorded in the MCA (Delica EMS 9D robotic TCD system®). Today, this technique is beginning to be applied in the management and monitoring of patients with traumatic brain injury (TBI). Indeed, a new field of study in SAH is opening. This type of probe allows for the automatic recording CBFVs of both MCA continuously for 4 h and correlates these values with other systemic hemodynamic parameters [28, 29]. This technology has not been applied

at present in SAH patients. A possible limitation of this technique includes the detection of vasospasm from arteries other than the middle cerebral artery, which should be evaluated further (more details see Chap. 66).

24.7 Conclusion

Subarachnoid hemorrhage (SAH) is a devastating disease with high morbidity and mortality. The most frequent neurological complication, after the acute effects of initial SAH, is delayed cerebral ischemia due to vasospasm, which can appear in up to 70% of patients, with an incidence peak between days 4 and 14, and can last until day 21 after bleeding. Up to 30% of cases can be associated with focal neurological deficits.

Transcranial Doppler (TCD/TCCS) is a non-invasive, reproducible technique performed at the bedside, which allows for the monitoring of CBFVs. TCD/TCCS also allows for the daily detection and monitoring of vasospasm, even in patients admitted to ICU.

In addition to the absolute values of MFV (MCA, ACA, PCA, and BA) defined as vasospasm, it is important to keep in mind that an increase of MFV greater than 50 cm/s from the previous day must be considered as a vasospasm criterion.

In unruptured aneurysms, no alterations in cerebral vasoreactivity have been detected in cerebral basal arteries.

The power Doppler mode allows for the detection of intracranial aneurysms (diameter >5 mm). The use of echo-contrast increases diagnostic sensitivity both for the identification of unruptured aneurysms and for the detection of neck recanalization in secured aneurysms.

New techniques are being developed that incorporate Doppler as a diagnostic tool and could be applied in normal clinical practice, such as laser-Doppler for intraoperative monitoring and/or robotic-TCD for the detection and monitoring vasospasm in patients with SAH.

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