ELSEVIER

European Journal of Ultrasound 16 (2002) 47–57

EUROPEAN JOURNAL OF ULTRASOUND

www.elsevier.com/locate/ejultrasou

Review article

The axial imaging plane—the main domain of the transcranial color-coded duplex ultrasonography?

Eva Bartels *

Department of Clinical Neurophysiology, University Hospital, Georg-August University of Göttingen, Robert-Koch-Straase 40, D-37075 Göttingen, Germany

Abstract

Transcranial color-coded duplex ultrasonography (TCCS) makes possible the visualization of basal cerebral arteries through color-coding the flow velocity information. This method is well established in the clinical routine for the diagnostics of pathological processes in cerebrovascular disease. The present review describes the examination technique, normal and pathological findings, such as stenosis and occlusion of intracranial arteries, as well as intracranial vascular malformations focussing on the advantages of the examination in the axial imaging planes.

Keywords: TCD; Color-coded transcranial duplex sonography (TCCS); Axial imaging plane; Intracranial stenosis; MCA occlusion; Arteriovenous malformation; Aneurysm

1. Introduction

In the early 1950s attempts were made to investigate intracranial structures through intact bone using echo encephalography. Information was obtained from the shift in the midline echo (French et al., 1951; Leksell, 1954).

In the early 1980s, transcranial Doppler sonography (TCD) was introduced which enabled to measure the blood flow velocities of the arteries of the Circle of Willis (Aaslid et al., 1982). However, the differentiation between individual vessels can be difficult using the TCD method, since this method has no imaging component. The Doppler signal obtained is assigned to a specific artery on the basis of indirect parameters: depth of the sample volume, position of the transducer, direction of the blood flow and compression tests (Arnolds and von Reutern, 1986). In addition, with use of the TCD method, the angle between the insonated vessel and the ultrasonic beam is not known.

The introduction of new, high resolution ultrasound systems and high performance sector transducers has opened up new perspectives for transcranial examination (Furuhata, 1989). By color-coding the Doppler signal it is possible not only to render blood flow in intracranial vessels visible through the intact skull in adults, but also to display their anatomical course, to perform more exact, angle-corrected measurements of blood flow velocities and to evaluate pathological

* Tel.: +49-89-297-216; fax: +49-89-2421-7799
E-mail address: bartels.eva@t-online.de (E. Bartels).

0929-8266/02/$ - see front matter
PII: S0929-8266(02)00067-8

intracranial conditions (Bogdahn et al., 1990; Bartels, 1993).

2. Examination technique

A sector transducer with an operating frequency of 2–3.5 MHz with a small aperture size (approximately 19 mm) is used for imaging intracranial vessels. As in conventional TCD, three different approaches are used to insonate the intracranial arteries: *transtemporal*, *suboccipital* and *transorbital*.

3. Transtemporal examination

The basal cerebral structures should be imaged as far as possible in reproducible planes; this is especially important for follow-up examinations. The following *axial scanning planes* are recommended by the TCCS Study Group.

- Plane through the *mesencephalic* brain stem—achieved by scanning in the orbitomeatal axial plane.
- Plane through the *diencephalon* at the level of the thalamus—achieved by slightly angling—(10°) the transducer apically.
- Plane through the *cella media*—achieved by maximally tilting (30°) the transducer apically.

Examination in the *coronal plane* is performed by turning the transducer by 90° and changing the scanning angle anteriorly and posteriorly. The standard planes are anterior, middle and posterior coronal planes—orientated according to the anatomy of the brain stem and the basal cerebral arteries.

The basal arteries can best be displayed in the *axial scanning plane* through the mesencephalic brain stem, which is given by the orbito–meatal line. An imaging depth of 140–160 mm is convenient. Correct anatomical orientation is achieved by demonstrating the cerebral structures in the midline—the hypoechogenic butterfly-shaped mesencephalic brain stem, surrounded by the hyperechogenic basal cisterns—are displayed with B-mode ultrasonography. Subsequently, the color mode can be switched on to render the basal cerebral arteries visible (Bartels, 1999).

The arteries of the circle of Willis can be identified by their anatomic location with respect to the brain stem structures and by determination of the flow direction.

Transnuchal (*suboccipital*) *insonation* is used for the examination of the proximal portion of the basilar artery and the intracranial segment of the vertebral arteries. To make the orientation on the screen easier, first the hypoechoic structure of the foramen magnum is visualized on the B-mode image. In the next step, switching to the color mode—the two vertebral arteries appear on both sides within the foramen magnum. Since their direction of flow is away from the transducer, these arteries are coded blue. Additionally, sagittal planes can be used to render abnormal vertebrobasilar hemodynamics visible.

Transorbital examination is feasible, nevertheless it should not be performed routinely and the acoustic energy should be reduced to a maximum of 10–15% in order not to damage the eye lens.

4. Flow velocity measurements

To record the Doppler spectrum, the sample volume is placed under visual control in the vessel segment of interest, and the cursor for measuring the insonation angle is adjusted parallel to the vessel course. Although angle corrected blood flow velocity values are not absolute values, they are more precise than those obtained by conventional transcranial Doppler examination. Reference values for the blood flow velocities of the basal cerebral arteries of the anterior and posterior cerebral circulation have been reported (Martin et al., 1995; Bartels and Flügel, 1994). Intra- and interobserver reproducibility have been shown to be good.

The *limitations* of the transtemporal insonation are mainly related to an unfavorable acoustic 'bone window', in particular with elderly people. In middle-aged patients, similar to the conventional TCD method, the examination is technically not possible in 10–20% (Grolimund and Seiler,

1988). Under unfavorable examination conditions, ultrasound contrast agents improve transcranial scan quality by increasing the intensity of Doppler signals obtained from intracranial vessels (Bogdahn et al., 1993).

The limitations of the suboccipital duplex sonography are greater. Besides the unfavorable bone window, the tortuous course of the basilar artery can render the examination difficult. Further examining problems can arise due to a difficult anatomical approach in obese patients or in patients with a cervical syndrome. Nevertheless, it is a well established procedure for the assessment of the posterior circulation rendering reliable results in cerebrovascular disease (Kaps et al., 1992; Schöning and Walter, 1992).

5. Pathological findings

In the second part of this review the typical findings of pathological vascular processes are described. Based on the everyday program of a neurosonological laboratory the most frequent diagnostic questions were selected to demonstrate the role of TCCS in the clinical routine. The indication for a TCCS evaluation of the anterior circulation occurred far more often than for one of the posterior circulation, where the pathological findings could be assessed the best in the axial scanning planes. The typical sonographic features of vascular processes in the anterior circulation using the transtemporal approach focus on the axial plane, and are summarized in the following section.

5.1. Findings in cerebral occlusive disease

It is technically relatively easy to detect a *stenosis in the proximal segment of the arteries of the Circle of Willis*. These arteries can be imaged the best with the transtemporal insonation in the mesencephalic axial plane. In this plane, the midline structures (brain stem, basal cisterns) can be found at a depth of approximately 80 mm, and the ipsi- and contralateral arteries are visualized at a depth from 45 to 90 mm. This region can be examined at an optimum resolution using color-coded sonographic equipment. And, of course, these areas are the focus of interest in the diagnostics of patients with acute cerebrovascular symptoms based on the atherosclerotic vessel wall changes, in order to optimize the therapeutic decision.

Data concerning the sensitivity and specificity of TCCS in the diagnosis of *stenosis of the middle cerebral artery* (*MCA*) remain limited. Furthermore, no criteria for the quantification of intracranial stenosis by TCCS are available. The classification is based on conventional TCD studies.

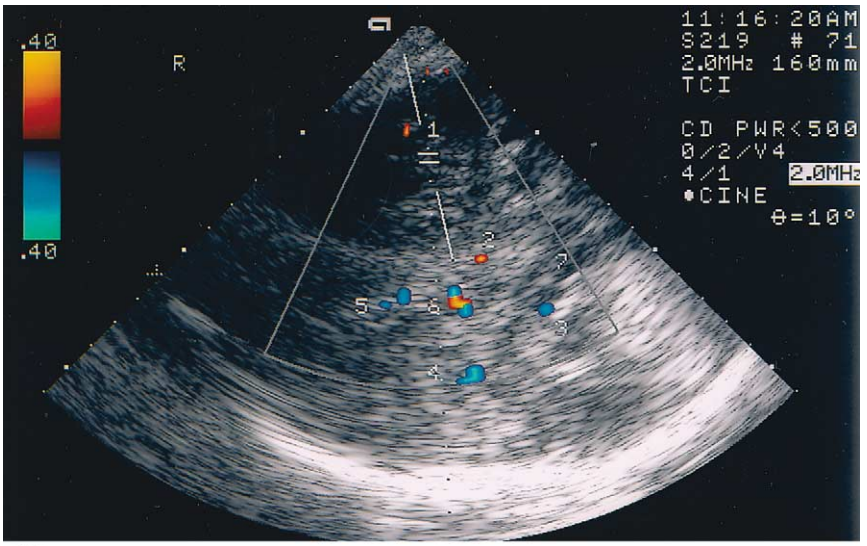
In the case of stenosis of the MCA a peak systolic flow velocity of over 160 cm/s, or mean value over 90 cm/s, is considered pathological (Rorick et al., 1994). A difference in mean flow velocity of at least 30 cm between the two sides is also indicative of a stenosis (Ley-Pozo and Ringelstein, 1990).

The *degree of stenosis* is estimated on the basis of the changes of the Doppler spectrum (increased angle-corrected blood flow velocities and spectral broadening in the site of the stenosis, flow disturbances upstream and downstream from the lesion, reduced maximum and mean flow velocities distal to the stenosis). TCCS provides information on the localization of the stenosis. Using frequency-dependent color-coding, the site of the stenosis can be more easily recognized due to the aliasing phenomenon (Becker et al., 1994). Additionally, the thickened vessel wall in the area of the stenosis can be imaged in B-mode due to its higher echogenicity (Seidel et al., 1995).

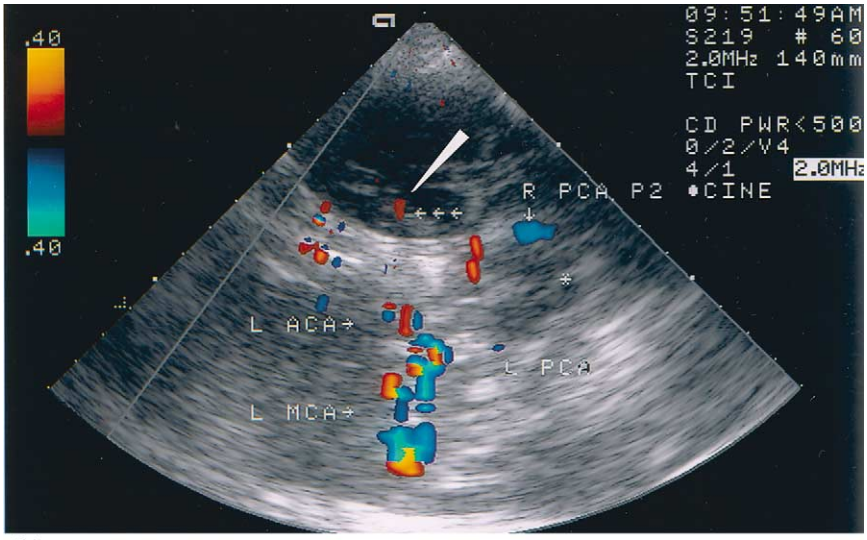
Differentiating between a stenosis and a *vasospasm* can sometimes be difficult.

In the case of a stenosis the aliasing phenomenon is usually visible in a circumscribed, short section of the vessel, corresponding to the extension of the stenotic segment, whereas, with a vasospasm several vessels are often affected.

Increased flow velocities can also be registered in the case of obstructive lesions in the contralateral hemisphere or in extracranial carotid disease due to a *compensatory increase in blood flow through collateral vessels*. Diagnostic errors can be avoided by considering the findings with all arteries supplying the brain (Baumgartner et al.,

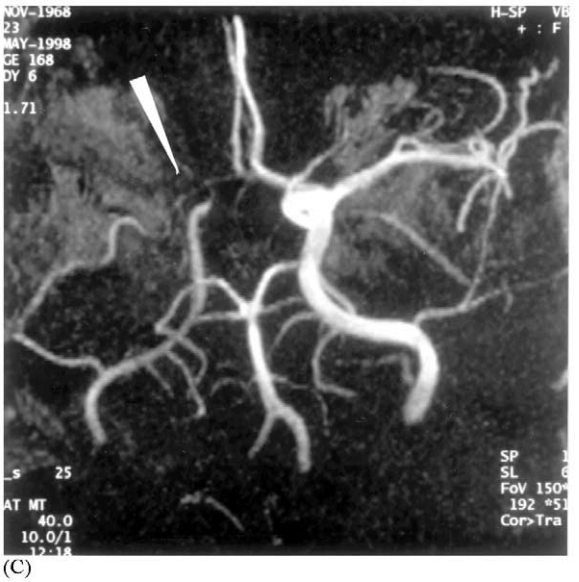


(A)



(b)

Fig. 1. Occlusion of the right MCA in 26 years old patient with a dissection of the right internal carotid artery. (A) Native transcranial color-coded image using a right transtemporal approach with an unfavorable temporal bone window. The visualization of the basal cerebral arteries is of insufficient quality, only fragments of the arteries are visible. (1) No detectable signal of the right MCA; (2) signal of the right posterior communicating artery; (3) left PCA; (4) left MCA; (5) A2 segment of the left ACA. (B) Using echo contrast agent Levovist good visualization of the contralateral (left) MCA and ACA and ipsilateral (right) PCA. There is no signal registered for the right MCA (arrow). MCA, middle cerebral artery; PCA, posterior cerebral artery; ACA, anterior cerebral artery; *, brain stem. (C) Magnetic resonance angiogram of an occlusion of the right MCA (arrow). The intracranial segment of the right internal carotid artery shows a weak signal due to a dissection at the origin.



(C)

Fig. 1 (*Continued*)

1997b; Giller, 1994; Sitzer et al., 1994). For easier spatial assessment of intracranial stenoses contrast-enhanced three-dimensional sonography can be used (Klötzsch et al., 2002).

Of particular clinical relevance is an *occlusion of the MCA*. It can arise due to a local thrombosis in an atherosclerotic lesion, or occasionally vasculitis, moyamoya diasease, or coagulopathy. Most often, however, it is caused by embolism, with either arterial or cardiac sources for the emboli (Ringelstein, 1995). An early diagnosis in patients with cerebral ischemia is crucial for the therapeutic strategy—especially in the decision for a thrombolysis.

Sonographic diagnosis of *occlusion* of a cerebral artery can be made when a color-coded signal cannot be obtained at depths of insonation corresponding to that artery, although neighboring arteries can be imaged well. Criteria for the sonographic diagnosis of MCA occlusion in the axial plane include lack of detectable flow in the MCA, good visualization of the ipsilateral posterior cerebral artery (PCA), and detection of collateral flow.

In patients with acute stroke **contrast enhancement** is valuable, especially in those patients whose baseline scans are not of good quality (Baumgartner et al., 1997a; Ries et al., 1997; Postert et al., 1997). In such a situation it is important for further diagnostic steps and for therapy to be able to determine whether failure to visualize a cerebral vessel is due to methodological problems or to an occlusion of a cerebral artery (Nabavi et al., 1998; Fig. 1).

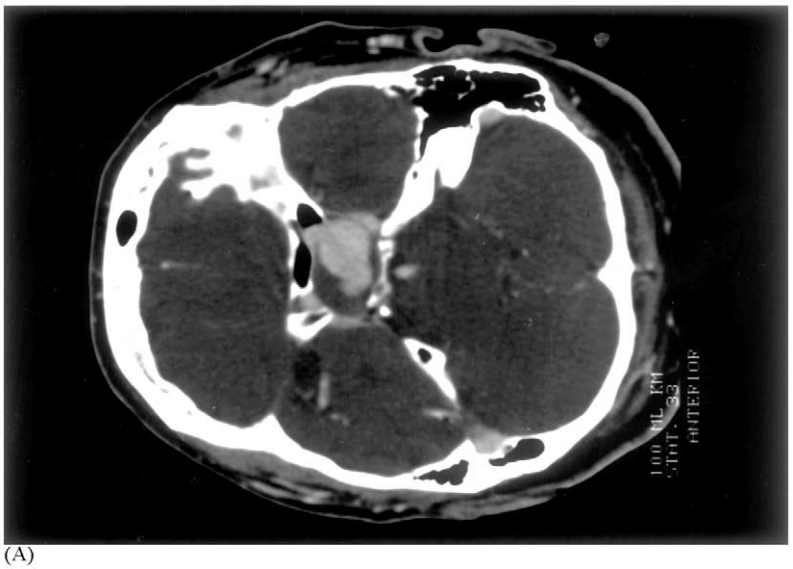
5.2. Findings in vascularized tumors

The ability to image vascularized tumors (e.g. meningioma) depends more on their degree of vascularization than on their size. With the exception of angiomas there are no typical tumor-specific hemodynamic parameters. Sometimes a spectral analysis reveals a low pulsatility of the spectral waveform. The location of the tumor is important for its imaging. The tumors located in the axial plane are easy to image and can sometimes even be detected incidentally (Bartels, 1999).

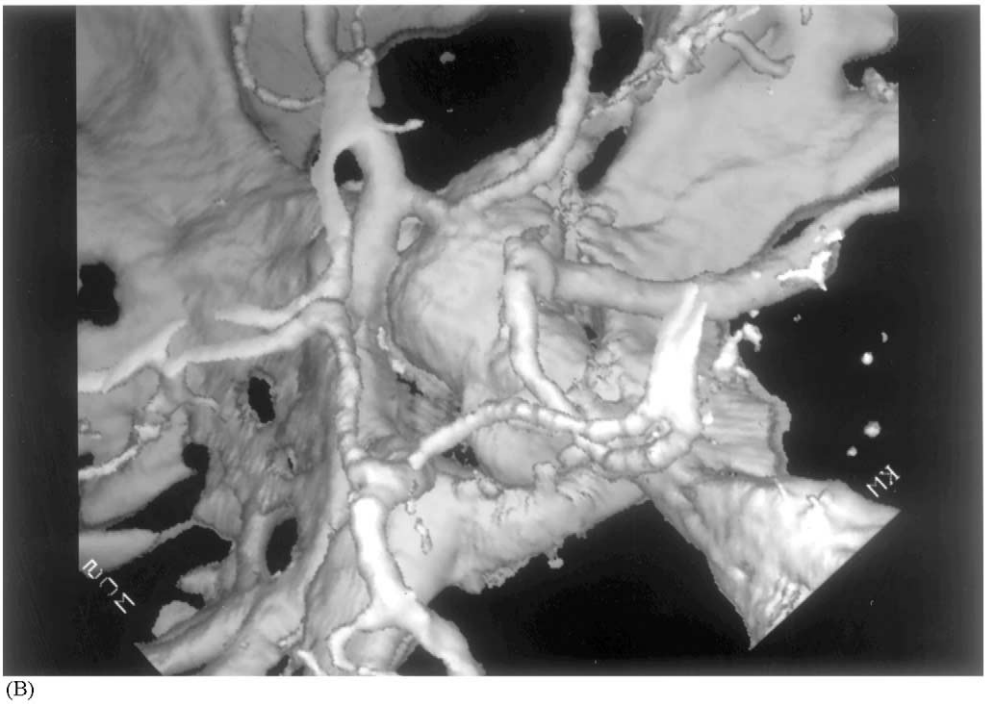
5.3. Findings in cerebral vascular malformations

5.3.1. Cerebral aneurysms

An aneurysm is imaged as a color-coded appendix next to a normal vessel. The most typical color-coded feature is the presence of two areas with

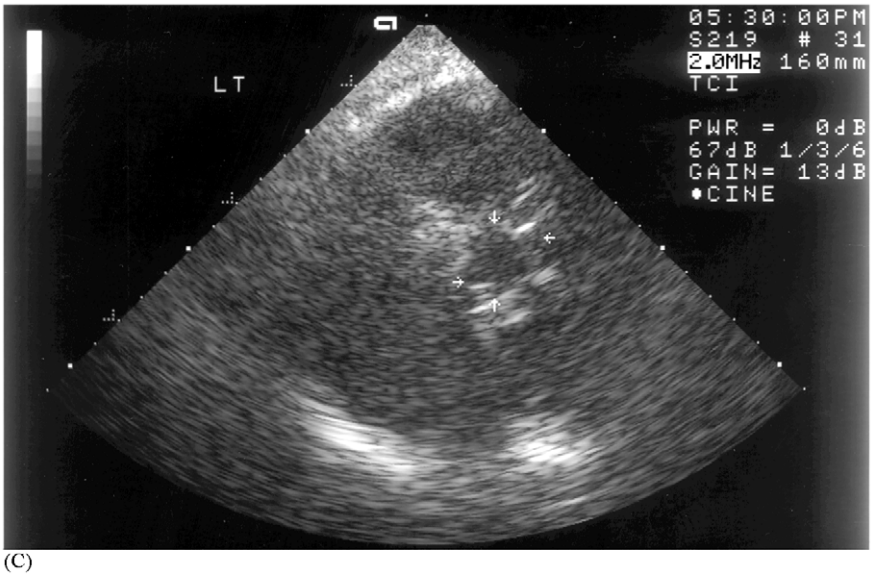


(A)

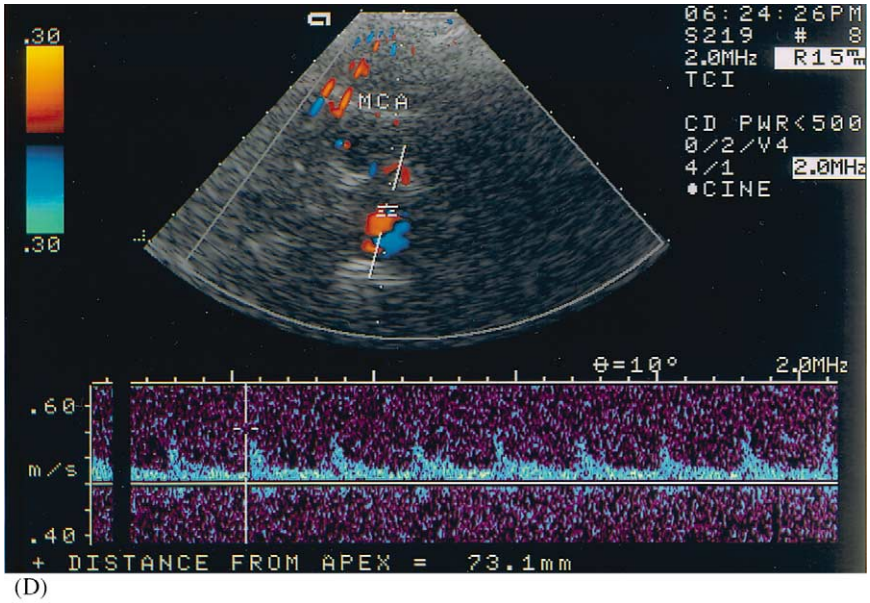


(B)

Fig. 2. Cerebral aneurysm visible in the axial plane of the CT scan (A) and in a three-dimensional computed tomography reconstruction (B). (C) Transtemporal B-mode image showing the hypoechoic aneurysm surrounded by a hyperechoic signal (arrows). (D) Doppler spectrum and a color-coded image of this aneurysm located in the midline in the axial plane in 73.1 mm depth. Due to the reversal of flow in the aneurysm, half of it is coded red, and the other half blue. The color-coded zones are separated by a black line.



(C)

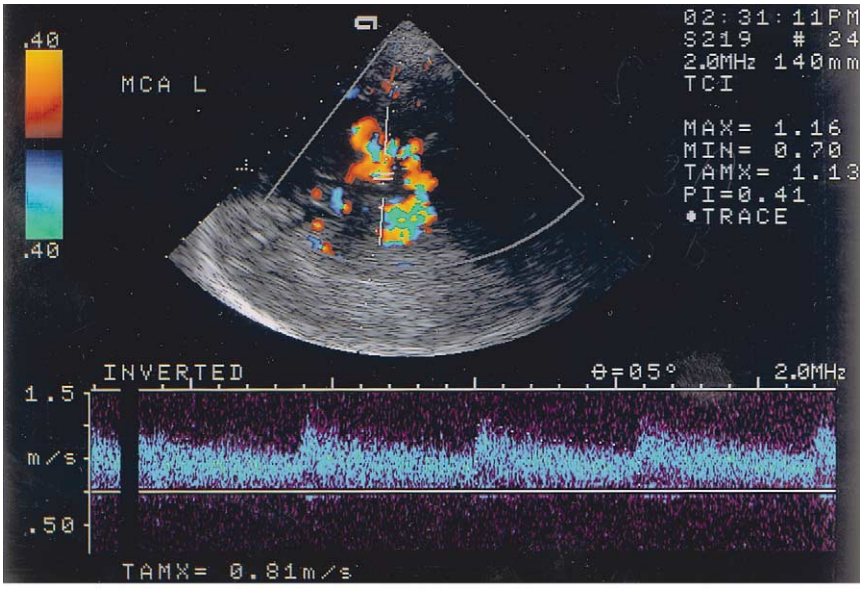


(D)

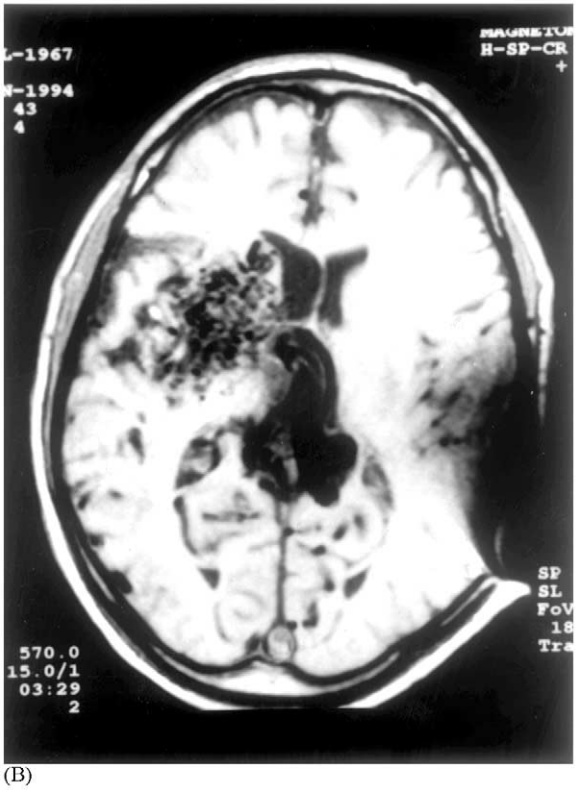
Fig. 2 (*Continued*)

inversely directed flow: half of the aneurysm is coded blue, and the other half is coded red. The colors correspond to the direction of inflowing and outflowing blood. Between these two areas, a black separation zone without color coding and with undetectable blood flow, can be recognized.

Visualization of an aneurysm depends on its location and size (>5 mm; Baumgartner et al.,



(A)



(B)

Fig. 3. View of a large fronto-temporo-basal angioma. (A) With transtemporal insonation the characteristic color-coded signal of an angioma with a mosaic pattern and aliasing is observed. The spectral waveform recorded from the vessel loops of the angioma shows a reduced pulsatiliy (Pulsatility Index, PI = 0.41). (B) Magnetic resonance image of the angioma.

1994). In 50% of cases of subarachnoid hemorrhage, aneurysms are found in the anterior communicating artery (Mumenthaler, 1990). For the imaging of these arterial segments the axial plane is most convenient. Aneurysms located in the proximal segment of the arteries of the circle of Willis can be recognized more easily than those situated in the periphery (Fig. 2). The reliability of the investigation can also be improved by using echo contrast agents. In addition, power Doppler imaging can be useful in detecting low flow velocities within aneurysms (Bartels et al., 1997; Wardlaw and Cannon, 1996).

With a tortuous course of an artery it is often not possible to distinguish between an aneurysm and a diagonally sectioned vessel branch or a vessel loop (Uggowitzer et al., 1999). Smaller, and more peripherally located, aneurysms can escape detection. In addition, visualization of a partially thrombosed aneurysm is also difficult. For these reasons color-coded duplex sonography should not be used as a screening procedure. In follow-up, after treatment with platinum coils, hyperechogenic signals of the clips with reverberation artifacts can be observed (Klötzsch et al., 1996).

5.3.2. Arteriovenous malformations

An arteriovenous malformation (AVM) is a massive collection of abnormal vessels in which the arterial circulation flows directly into the venous circulation. With TCCS, the pathological vascularity of an AVM can be displayed directly on the screen and show a lively dramatic pattern (Fig. 3). This variation in color represents the different flow directions of the vascular loops as well as the increased blood flow velocities in the angiomatous vessels (Becker et al., 1990, 1992; Klötzsch et al., 1995; Schreiber et al., 2002). Furthermore, the typical Doppler spectrum of the feeding arteries can be recorded under visual control. The diastolic component of the spectral waveform is increased more than the systolic component because of the reduced peripheral resistance in an angioma. This is manifested by a low pulsatility index. Using these parameters it is also possible to determine which arteries of the circle of Willis located outside of the angioma nidus participate in the blood supply. The closer the examination area to the angioma, the clearer the hemodynamic changes. The following flow values are given as a guidance: maximum systolic flow velocity >140 cm/s, end-diastolic flow velocity >100 cm/s, pulsatility index <0.6 (Bartels, 1998).

Using correlation with cerebral angiography and magnetic resonance imaging, angiomas can be visualized directly according to the above-mentioned criteria with a sensitivity of 77.7% (Bartels, 1999). Imaging angiomas located near the cortex -in the parietal, occipital, high frontal, and cerebellar regions can be difficult. In contrast, in a subgroup of patients with temporobasal, parietobasal, and frontobasal angiomas, which were located in the axial insonation plane, the sensitivity of detection was 90%. The size of the angioma was less important than the location: the smallest angioma imaged was 1 cm in diameter.

TCCS can detect angiomas as an incidental finding, however, it should not be used as a screening procedure. This method is particularly suitable for the follow up of postoperative and postembolization patients.

6. Conclusion

Color-coded duplex ultrasonography is increasingly accepted as a valuable method in neurovascular diagnostics. In the hands of an *experienced examiner*, it is a reliable tool in the evaluation of cerebrovascular diseases. For technical and methodological reasons, pathological processes, especially those located in the parietobasal, frontobasal and temporobasal subcortical brain regions, are best diagnosed using the axial imaging planes via the transtemporal approach. The main limitation of TCCS, like that of conventional TCD, is the need for an adequate acoustic window which can be overcome with echo contrast agents.

The examination of the pathological processes in the posterior fossa is not the object of this review. Nevertheless, it is clear that the imaging of the vertebrobasilar system using suboccipital insonation, must also be considered a routine part of the transcranial examination.

References

Aaslid R, Markwalder T-M, Nornes H. Noninvasive transcranial Doppler ultrasound recording of flow velocity in basal cerebral arteries. J Neurosurg 1982;7:769–74.

Arnolds BJ, von Reutern G-M. Transcranial Dopplersonography, examination technique and normal reference values. Ultrasound Med Biol 1986;12:115–23.

Bartels E. Transcranial colour-coded duplex ultrasonography. Comparison with conventional transcranial Doppler ultrasonography. Ultraschall Med 1993;14:272–8.

Bartels E. Aneurysms and Arteriovenous Malformations (AVMs). In: Bogdahn U, Becker G, Schlachetzki F, editors. Echoenhancers and Transcranial Color Duplex Sonography. Berlin: Blackwell, 1998:276–97.

Bartels E. Color-Coded Duplex Ultrasonography of the Cerebral Vessels/Atlas and Manual; Farbduplexsonographie der hirnversorgenden Gefäße/Atlas und Handbuch. Schattauer Stuttgart 1999.

Bartels E, Flügel KA. Quantitative measurements of blood flow velocity in basal cerebral arteries with transcranial color Doppler imaging. J Neuroimag 1994;4:77–81.

Bartels E, Rodiek S-O, Lumenta C, Flügel KA. What advantages has power Doppler imaging in comparison with transcranial color-coded duplex ultrasonography in the evaluation of cerebral aneurysms. In: Klingelhöfer J, Bartels E, Ringelstein EB, editors. New Trends in Cerebral Hemodynamics and Neurosonology. Amsterdam: Elsevier, 1997:320–5.

Baumgartner RW, Mattle HP, Kothbauer K, Schroth G. Transcranial color-coded duplex sonography in cerebral aneurysms. Stroke 1994;25:2429–34.

Baumgartner RW, Arnold M, Gönner F. Contrast-enhanced transcranial color-coded duplex sonography in ischemic cerebrovascular disease. Stroke 1997a;28:2473–8.

Baumgartner RW, Baumgartner I, Mattle HP, Schroth G. Transcranial color-coded duplex sonography in the evaluation of collateral flow through the circle of Willis. Am J Neuroradiol 1997b;18:127–33.

Becker GM, Winkler J, Hoffmann E, Bogdahn U. Imaging of cerebral arterio-venous malformations by transcranial colour-coded real-time sonography. Neuroradiology 1990;32:280–8.

Becker G, Perez J, Krone A, Demuth K, Lindner A, Hofmann E, Winkler J, Bogdahn U. Transcranial color-coded real-time sonography in the evaluation of intracranial neoplasms and arteriovenous malformations. Neurosurgery 1992;31:420–8.

Becker G, Lindner A, Hofmann E, Bogdahn U. Contribution of transcranial color-coded real-time sonography to the etiopathogenetic classification of middle cerebral artery stenosis. J Clin Ultrasound 1994;22:471–7.

Bogdahn U, Becker G, Winkler J, Greiner K, Perez J, Meurers B. Transcranial color-coded real-time sonography in adults. Stroke 1990;21:1680–8.

Bogdahn U, Becker G, Schlief R, Reddig J, Hassel W. Contrast-enhanced transcranial color-coded real-time sonography. Results of a phase-two study. Stroke 1993;24:676–84.

French LA, Wild JJ, Neal D. The experimental application of ultrasonics to the localisation of brain tumors. J Neurosurg 1951;8:198–203.

Furuhata H. New evolution of transcranial tomography (TCT) and transcranial color Doppler tomography (TCDT). Neurosonology 1989;2:8–15.

Giller CA. Is angle correction correct? J Neuroimag 1994;4:51–2.

Grolimund P, Seiler RW. Age dependence of the flow velocity in the basal cerebral arteries: a transcranial Doppler study. Ultrasound Med Biol 1988;14:191–8.

Kaps M, Seidel G, Bauer T, Behrmann B. Imaging of the intracranial vertebrobasilar system using color-coded ultrasound. Stroke 1992;23:1577–82.

Klötzsch C, Henkes H, Nahser HC, Kühne D, Berlit P. Transcranial color-coded duplex sonography in cerebral arteriovenous malformations. Stroke 1995;26:2298–301.

Klötzsch C, Nahser HC, Fischer B, Henkes H, Kühne D, Berlit P. Visualization of intracranial aneurysms by transcranial duplex sonography. Neuroradiology 1996;38:555–9.

Klötzsch C, Bozzato A, Lammers G, Mull M, Noth J. Contrast-enhanced three-dimensional transcranial color-coded sonography of intracranial stenoses. Am J Neuroradiol 2002;23:208–12.

Leksell L. Kirurgisk behandling av skallskador. Meeting of Svenska Läkarsällskapet, Stockholm, 7 Dez 1954.

Ley-Pozo J, Ringelstein EB. Noninvasive detection of occlusive disease of the carotid siphon and middle cerebral artery. Ann Neurol 1990;28:640–7.

Martin PJ, Evans DH, Naylor AR. Measurement of blood velocity in the basal cerebral circulation: advantages of transcranial color-coded sonography over conventional transcranial Doppler. J Clin Ultrasound 1995;23:21–6.

Mumenthaler M. Neurologie. Stuttgart: Thieme, 1990.

Nabavi DG, Droste DW, Kemény V, Schulte-Altedorneburg G, Weber S, Ringelstein EB. Potential and limitations of echocontrast-enhanced ultrasonography in acute stroke patients. Stroke 1998;29:949–54.

Postert T, Federlein J, Przuntek H, Büttner T. Insufficient and absent acoustic temporal bone window: potential and limitations of transcranial contrast-enhanced color-coded sonography and contrast-enhanced power-based sonography. Ultrasound Med Biol 1997;23:857–62.

Ries S, Steinke W, Neff KW, Hennerici M. Echocontrast-enhanced transcranial color-coded sonography for the diagnosis of transverse sinus venous thrombosis. Stroke 1997;28:696–700.

Ringelstein EB. Skepticism toward carotid ultrasonography. A virtue, an attitude, or fanaticism. Stroke 1995;26:1743–6.

Rorick MB, Nichols FT, Adams RJ. Transcranial Doppler correlation with angiography in detection of intracranial stenosis. Stroke 1994;25:1931–4.

Schöning M, Walter J. Evaluation of the vertebrobasilar-posterior system by transcranial color duplex sonography in adults. Stroke 1992;23:1280–6.

Schreiber SJ, Franke U, Doepp F, Staccioli E, Uludag K, Valdueza JM. Doppler sonographic measurement of global cerebral circulation time using echo contrast-enhanced ultrasound in normal individuals and patients with arteriovenous malformations. Ultrasound Med Biol 2002;28:453–8.

Seidel G, Kaps M, Gerriets T. Potential and limitation of transcranial color-coded sonography in stroke patients. Stroke 1995;26:2061–6.

Sitzer M, Fürst G, Siebler M, Steinmetz H. Usefulness of an intravenous contrast medium in the characterization of high-grade internal carotid stenosis with color Doppler-assisted duplex imaging. Stroke 1994;25:385–9.

Uggowitzer MM, Kugler C, Riccabona M, Klein GE, Leber K, Simbrunner J, Quehenberger F. Cerebral arteriovenous malformations: diagnostic value of echo-enhanced transcranial Doppler sonography compared with angiography. Am J Neuroradiol 1999;20:101–16.

Wardlaw JM, Cannon JC. Colour transcranial power Doppler ultrasound of intracranial aneurysms. J Neurosurg 1996;84:459–61.