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Transcranial color-coded duplex ultrasonography in routine cerebrovascular diagnostics

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Transcranial color-coded duplex ultrasonography;
Middle cerebral artery;
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Arteriovenous malformation

Summary Transcranial color-coded duplex ultrasonography (TCCS) enables the visualization of basal cerebral arteries through the intact skull by color-coding of blood flow velocity. The arteries of the circle of Willis can be identified by their anatomic location with respect to the brain stem structures and by the determination of the flow direction. TCCS is an important neuroimaging method due to its excellent time resolution. In addition to the diagnostics of intracranial vascular disease, this technique is valuable in intensive care and stroke units, e.g. for follow-up examinations in vasospasm after subarachnoid hemorrhage, and for intraoperative monitoring as well. In difficult anatomical conditions, the application of echo contrast agents can improve the diagnostic reliability of the examination. This paper reviews the examination technique and the clinical application of this method in routine cerebrovascular diagnostics.

Introduction

Seventy years ago, as early as 1942, the Austrian neurologist Karl Theodor Dussik published the first paper on medical ultrasonics. Inspired by a report on the application of ultrasound in radar underwater technology, together with his brother Fritz Dussik, he introduced in Vienna a device that was able to produce sonographic images of the head and brain [1,2]. This method, named hyperphonography, however, was not accepted as a possible diagnostic tool at that time, because ultrasonic waves were attenuated by the skull in a high extend.

In the early 1950s, echoencephalography was introduced. This technique made it possible to image the position of midline echoes of the brain [3—5]. Further development of ultrasonographic techniques enabled the two-dimensional B-mode imaging of cerebral parenchyma at the end of the 1970s. However, this was only possible through the fontanel in young children [6,7].

Parallel to this development, Aaslid presented transcranial Doppler (TCD) sonography for the examination of cerebral hemodynamics in 1982 [8]. Using a pulsed Doppler system with low transmitter frequency, this method allows blood flow velocities to be recorded from basal cerebral arteries through the intact skull. With this method, intracranial arteries are examined by using transtemporal, suboccipital and transorbital approaches. The Doppler signal obtained is assigned to a specific artery based on indirect parameters: the depth of the sample volume, the position of the transducer, and the flow direction [9]. Exact differentiation between individual vessels can be in some cases difficult using the TCD method. Mistakes can occur because of the lack of anatomical structures for orientation, especially in distinguishing between arteries of the same direction of flow, or in the presence of anatomical variations. To perform compression tests of the common carotid artery in this case, however, is not recommended because during the compression thromboembolic complications cannot be

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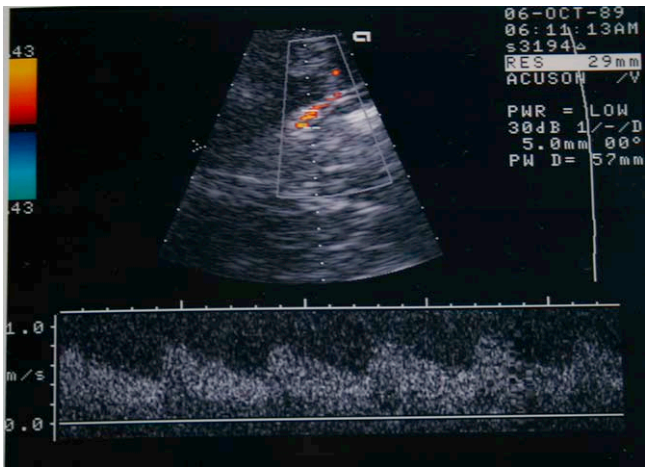

Figure 1 View of a color-coded image of the middle cerebral artery with a corresponding Doppler spectral analysis, performed under visual control using a transtemporal insonation in a healthy adult (the sample volume is placed in 57 mm depth). Documentation of this probably oldest printed image of a transcranial color-coded examination was performed on October 6, 1989 during the ''Dreiländertreffen 1989'' Congress in Hamburg.

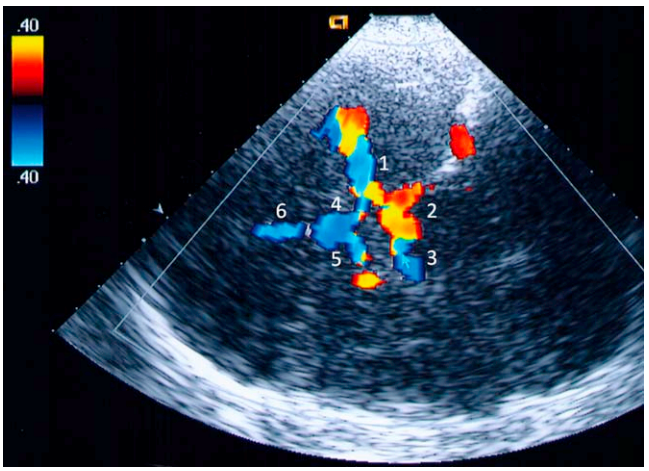

Figure 2 View of the basal cerebral arteries in the axial plane with transtemporal insonation. Color-coded duplex sonography of the ipsilateral middle cerebral artery (MCA) = 1, ipsilateral posterior cerebral artery (PCA) = 2, contralateral PCA = 3, A1 segment of the ipsilateral anterior cerebral artery (ACA) = 4, A1 segment of the contralateral ACA = 5, and A2 segment of the ipsilateral and/or contralateral ACA = 6. Due to insufficient resolution, a side differentiation of the A2 segments (of both sides) is not possible.

ruled out in patients with atherosclerotic vascular disease [10].

Transcranial color-coded duplex ultrasonography (TCCS), on the other hand, enables the visualization of the basal cerebral arteries through the intact skull by color-coding of blood flow velocity. TCCS was first applied in studies of children [11]. The development of high-resolution ultrasonic systems and high performance sector transducers has opened up new perspectives for transcranial examination in adults as well [12—14]. Fig. 1 demonstrates our very first recording of the blood flow in the middle cerebral artery in October 1989 using a high resolution Acuson XP equipment (Acuson, Montain View, CA).

Examination technique

A sector transducer with an operating frequency of 2.0—3.5 MHz with a small aperture size is used for imaging intracranial vessels. As in conventional TCD, three different approaches are used to insonate intracranial arteries: transtemporal, transnuchal (suboccipital), and transorbital.

Using the transtemporal approach the basal cerebral arteries can best be displayed in the axial scanning plane. An imaging depth of 140—160 mm is most convenient. At the 1998 meeting of the European Transcranial Color-Coded Duplex Sonography Study Group (TCCS Study Group) the following standard transtemporal axial scanning planes were recommended:

1. An axial scanning plane through the *mesencephalic* brain stem — achieved by scanning in the orbitomeatal axial plane
2. An axial scanning plane through the *diencephalon* — achieved by slightly angling the transducer 10 degrees apically
3. An axial scanning plane through the *cella media* — achieved by angling the transducer 30 degrees apically.

For easier anatomical orientation on the screen, firstly, the cerebral structures in the midline — the hypoechogenic butterfly-shaped mesencephalic brain stem, surrounded by the hyperechogenic basal cistern — are displayed with B-mode ultrasonography. Subsequently, the color mode can be added to render the basal cerebral arteries visible (Fig. 2). The arteries of the circle of Willis can be identified by their anatomical location to the brain stem structures and by the determination of their flow direction based on specific color coding of the blood flow velocity. The middle cerebral artery (MCA), along with the P1 and proximal P2 segments of the posterior cerebral artery (PCA), is coded red due to their flow direction toward the transducer. In contrast, the A1 and A2 segments of the ipsilateral anterior cerebral artery (ACA), and the distal P2 segment of the PCA are coded blue, because the flow in these vessels is directed away from the transducer. Accordingly, the contralateral A1 segment of the ACA is coded red and the contralateral MCA is coded blue.

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, the TCCS examination is technically not possible in 10—20% [15]. The inability to image intracranial vessels in these cases can be overcome with echo contrast agents [14].

The 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,

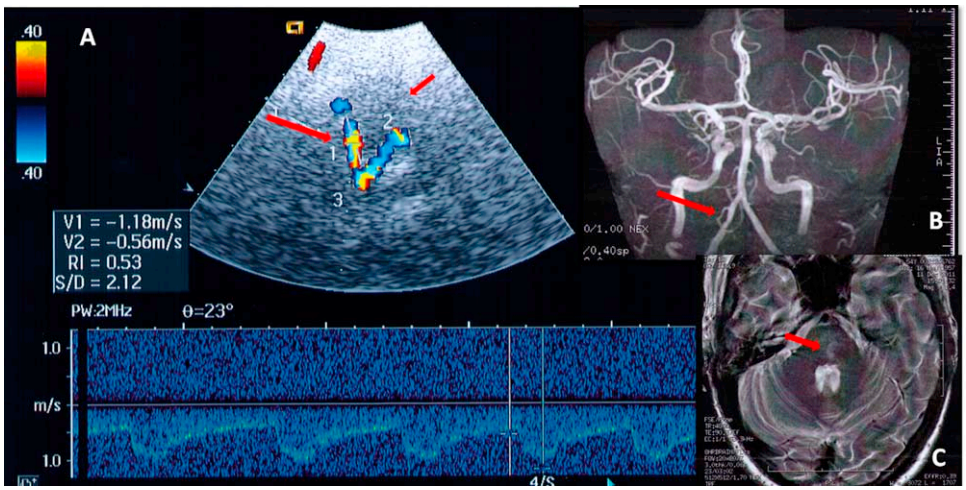

Figure 3 Imaging of the basal cerebral arteries by transnuchal (suboccipital) insonation in a 52-year-old woman with a left paramedian pons ischemia and a minor stenosis of the right vertebral artery. (A) Visualization of the right vertebral artery (VA) = 1, of the left VA = 2 and the basilar artery (BA) = 3 by insonating through the great foramen (short arrow). The spectral waveform of the right VA shows slightly increased blood flow velocities in the V4 segment (long arrow). V1 = maximum systolic velocity (118 cm/s). (B) Magnetic resonance angiogram (MRA) shows a moderate stenosis of the right VA in V4 segment (arrow). (C) Magnetic resonance image (MRI) of a left paramedian pons ischemia (arrow). (MRI, MRA images: Courtesy - Radiologie Dr. Sollfrank, München, with permission.)

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 (Fig. 3).

In the transorbital color-coded ultrasonography the acoustic power should be reduced to 10—15% of the power usually used in the transtemporal approach. The duration of the insonation should be kept to a minimum in order not to damage the eye lens. The examination enables visualization of the ophthalmic artery and the carotid siphon.

As compared to the conventional TCD, the advantages of TCCS are related especially to its imaging component. A complete circle of Willis is found only in 20% of the population [16]. Most often variations are observed in which one or several vascular segments may be hypoplastic or aplastic. Especially in the axial plane, these anatomical variations can be displayed easily using TCCS (Fig. 5b and c).

In addition, by using TCD, the angle between the insonated vessel and the ultrasonic beam is not known. Because the position of the pulsed sample volume and the insonation angle cannot be visually controlled, the flow velocity within the artery can be underestimated. With TCD, a small angle of insonation (0°—30°) is assumed [8]. Accordingly, if the angle of insonation ranges from 0° to 30°, the cosine varies between 1.00 and 0.86, yielding a maximum error of less than 15% [17]. Our data show that the angle of insonation is more variable than currently assumed [18,19]. Using TCCS the sample volume is placed under visual control in the vessel segment of interest, and the insonation angle can be measured by positioning the cursor parallel to the vessel course. The mean angle of insonation was less than 30° only in the basilar artery. Although values of angle corrected blood flow velocity are not absolute values, they are more precise than those obtained by conventional TCD examination. Nevertheless, in tortuous vessels the blood flow velocity increases in proportion to the increase in the angle of insonation. This is of considerable importance in assessment of blood flow velocities in pathological conditions, especially in quantification of the stenosis of an intracranial artery.

Clinical aspects

During the last two decades TCCS found its important role in the routine diagnostics of cerebrovascular diseases, despite the technical difficulties at the beginning of the transcranial duplex ultrasonography period.

In the second part of this article a short overview of the possible indications for TCCS in the clinical routine in the examination of the intracranial arteries will be presented. The imaging of the cerebral parenchyma disorders and the examination of the cerebral veins are described in other chapters of this book [20,21].

Findings in cerebral occlusive disease

Data concerning the sensitivity and specificity of TCCS in *intracranial stenosis* and normal values of flow velocities have been established by several investigators [22—25]. The classification is based on conventional TCD studies.

The degree of stenosis is estimated on the basis of the changes of the Doppler spectrum (increased flow velocities in the area of the stenosis, and flow disturbances upstream and downstream from the lesion). TCCS provides information on the localization of the stenosis. Using the frequency dependent color-coding, the site of the stenosis can be more easily recognized due to the aliasing phenomenon (Figs. 3 and 4).

An increase in flow velocity is also measured in the case of *vasospasm*. In 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

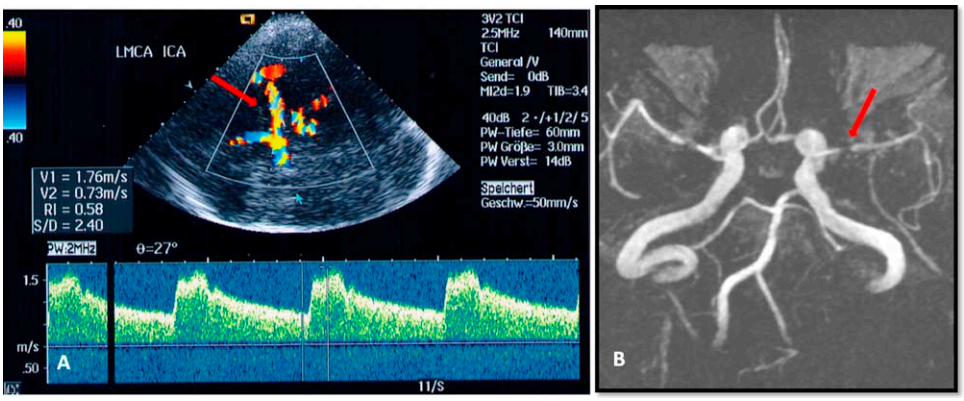

Figure 4 Bilateral MCA stenosis in the case of a 62-year-old-man with vasculitis. (A) Imaging of a moderate stenosis of the left MCA. The sample volume is placed in 60 mm depth (arrow), V1 = maximum systolic velocity (178 cm/s). An aliasing phenomenon can be seen in all visualized arteries because of the setting of the color scale by 40 cm/s mean blood flow velocity. (B) MRA of the bilateral MCA stenosis (the arrow indicates the sonographically examined artery). (MRA image: Courtesy - Radiologie Dr. Sollfrank, München, with permission.)

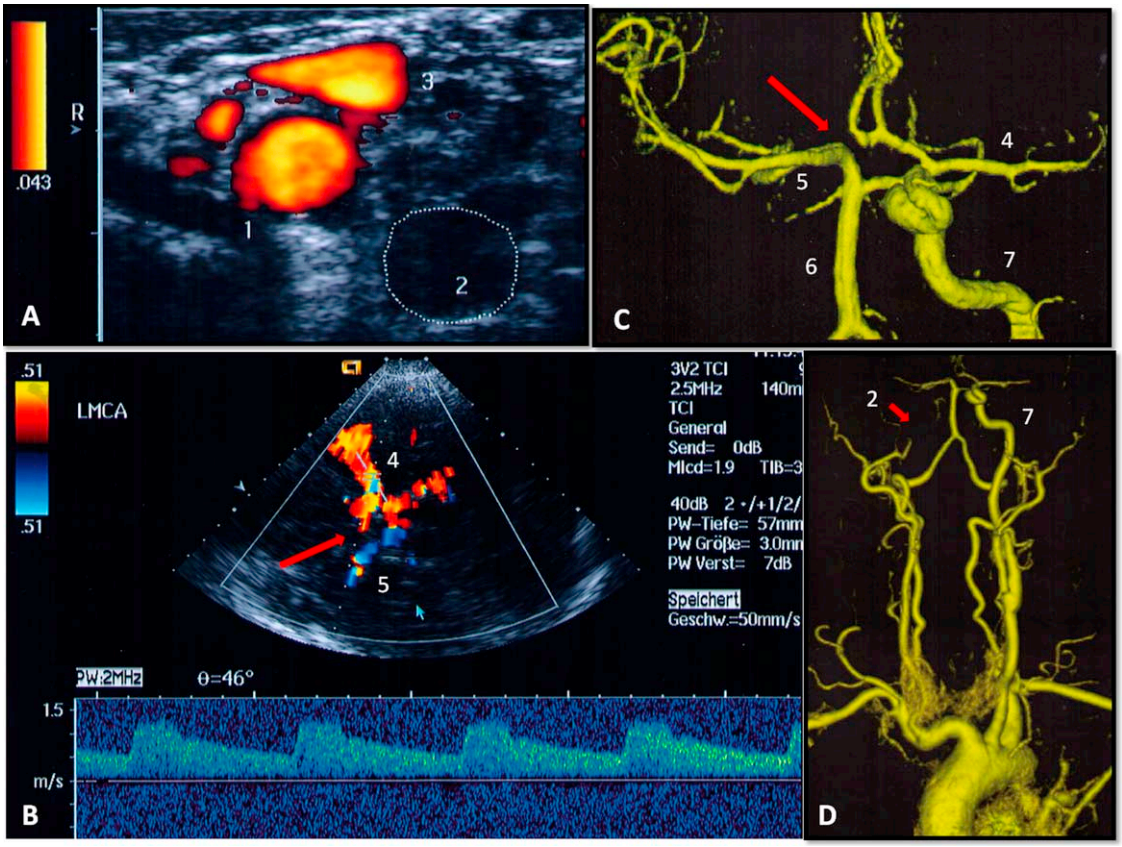

Figure 5 Intracranial collateral supply in the case of an occlusion at the origin of the right internal carotid artery (ICA) in a 67-year-old man without neurological symptoms. (A) Power mode image of the occlusion of the right ICA at the origin in transverse plane. The nonperfused lumen of the ICA [2] beside the perfused lumens of the external carotid artery (ECA) [1] and the jugular vein (JV) [3] can readily be delineated. (B) With transtemporal insonation of the left side a good collateral supply of the right hemisphere via the vertebrobasilar system can be visualized. The circle of Willis is incomplete in this patient — with an aplastic right anterior cerebral artery (arrow). (C) Intracranial MRA showing the aplastic right anterior cerebral artery (arrow), and a good collateral supply. (D) Extracranial MRA image of the occlusion of the right ACI at the origin (the arrow points at the ICA area without flow signal). 1: right ECA, 2: right ICA, 3: right JV, 4: left MCA, 5: right MCA, 6: BA, and 7: left ICA. (MRA images: Courtesy - Diagnoseklinik München, with permission.)

with a vasospasm several vessels are often affected simultaneously. This can be impressively demonstrated due to the aliasing phenomenon in all imaged vessels facilitating the differentiation between a stenosis and vasospasm [14].

Ultrasonographic diagnosis of an *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 diagnosis of MCA occlusion include lack of detectable flow in the MCA, a sufficient visibility of the other arteries (of the ipsilateral PCA, or ACA), or veins (deep middle cerebral vein), and the detection of a collateral flow.

TCCS has become a standard diagnostic technique to assess the intracranial status in acute stroke. It is increasingly used for the evaluation of prognosis and the success of revascularization in clinical trials. Recommendations on the methodology how examinations should be performed in the time limited situation of acute stroke, for monitoring of recanalization, and on documentation are summarized in the *''Consensus Recommendations for Transcranial Color-Coded Duplex Sonography for the assessment of Intracranial Arteries in Clinical Trials on Acute Stroke''* which were approved during a meeting of the consensus group in October 2008 in Giessen, Germany [26].

In an *extracranial* occlusion of the internal carotid artery the *presence of collateral pathways* imaged by transcranial sonography allow a prognosis to be made in the case of an acute vessel obstruction. To assess the effects of an extracranial occlusion of the internal carotid artery on cerebral hemodynamics, indirect extra- and intracranial findings must be considered (Fig. 5) [14,27].

Findings in cerebral vascular malformations

An *arteriovenous malformation* (*AVM, angioma*) is a massive collection of abnormal vessels in which the arterial circulation flows directly into the venous circulation, bypassing the capillary network. With TCCS, the pathological vascular convolutions of an AVM can be displayed directly on the screen. Furthermore, the typical Doppler spectrum of the angiomatous vessels can be recorded under visual control. Visualization of an AVM depends on its localization, rather than its size. The detection of AVMs located in the temporal and deep basal brain regions, in particular, is usually highly successful. AVMs located near the parietal, frontal, occipital or cerebellar cortex, on the other hand, are difficult to image, even if their diameters are larger [28].

If an AVM cannot be visualized directly, detection of feeding arteries in the circle of Willis makes the diagnosis very probable. Hereby, especially the low pulsatility of the Doppler spectrum is typical.

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 inversely directed flow: Half of the aneurysm is coded blue, and the other half is coded red, with the colors corresponding to the direction of in- 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 localization and size (>5 mm). 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. Special software, such as three-dimensional reconstruction tools, can make these lesions assessable in a high number of patients [29]. In addition, power Doppler imaging can be useful in detecting low flow velocities within aneurysms. The reliability of the investigation can also be improved by using echo contrast agents [30].

TCCS should not be used for screening of AVM. On the other hand, as a noninvasive method this technique is suitable for postoperative follow-up examination and for *embolization monitoring* in patients with intracranial angioma or fistulae. After embolization, a decrease of vascular convolutions, a reduction in flow velocities, and an increase of the reduced pulsatility indices can be observed [14].

Conclusion

Transcranial color-coded duplex ultrasonography is an important neuroimaging method due to its excellent time resolution. In addition to the diagnostics of intracranial vascular disease, this technique is valuable in intensive care and stroke units for follow-up examinations in vasospasm after subarachnoid hemorrhage and for intraoperative monitoring. In difficult anatomical conditions, the application of echo contrast agents can improve the diagnostic reliability of the examination. Based on advances in computer and transducer technology TCCS as a noninvasive method has a great potential in further innovative imaging and therapeutic solutions such as cerebral perfusion imaging, sonothrombolysis, and site targeted ultrasound contrast agents for drug delivery to the brain.

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