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Chapter 2

Transcranial duplex scanning in the evaluation of carotid artery stenosis

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Introduction
Over the past decades much attention has been paid to the intrinsic characteristics of carotid lesions which contribute to the risk of cerebral ischemia and consequent neurological deficits. Plaque morphology and luminal diameter reduction as risk factors for thromboembolic and hemodynamic causes of cerebral ischemia have been thoroughly investigated. Although it has become clear that in patients with symptomatic high-grade carotid artery stenoses carotid endarterectomy (CEA) is superior to medical therapy\textsuperscript{1,2}, there is still much debate whether symptomatic patients with a lesser degree of stenosis or asymptomatic patients with high-grade stenoses might also profit from CEA. In the ongoing search for optimal treatment of carotid artery occlusive disease it is recognized that aside from the severity of the carotid lesion other factors, such as the cerebral hemodynamic state, may have a significant influence on clinical outcome as well. Increasing evidence has been generated on the important role of collateral blood flow and cerebrovascular reserve capacity in protecting the endangered hemisphere against ischemia.

Nowadays, duplex scanning of diseased vessels is common practice in vascular laboratories all over the world. For a long time, however, the intact skull remained a severe obstacle to measuring blood flow velocities in the basal cerebral arteries. Conventional Doppler instruments operating in the range from 5- to 10-MHz are unable to penetrate the skull, because the ultrasound wave is strongly attenuated by bone. It was not until 1982 when Aaslid et al for the first time succeeded in obtaining backscattered Doppler signals from the basal cerebral arteries.\textsuperscript{3} This result was achieved using a Doppler instrument emitting a frequency wave of 2-MHz. Operating at this frequency, attenuation of the ultrasound wave in bone and soft tissue is considerably reduced. The thin temporal bone appeared to be a satisfactory ‘acoustic window’ for the identification of the anterior, middle and posterior cerebral arteries according to depth, direction and velocity of the Doppler signal recorded.

In 1990, Bogdahn et al first reported on real-time transcranial color-coded duplex ultrasonography.\textsuperscript{4} Color-coding of the Doppler signal permits visualization of blood flow and direction and allows direct identification of the basal cerebral arteries within the black-and-white B-mode image of the brain parenchyma.

Cerebral hemodynamics and stroke risk assessment
After the publications of studies on the benefits of CEA for symptomatic high-grade carotid artery stenosis as opposed to medical treatment only, the longing for a well-designed treatment algorithm of asymptomatic carotid artery disease has become even more intense. Over the
years several randomized clinical trials on CEA for asymptomatic carotid artery stenosis have been performed. In the Asymptomatic Carotid Atherosclerosis Study (ACAS) the five-year cumulative stroke risk in patients randomized to surgery was 5.1% (including perioperative stroke and death) compared with 11% in the medical group. If all patients who underwent surgery had received arteriography as part of the surgical treatment, the absolute risk reduction would have been from 11% to 5.6%. Thus, to prevent one stroke over 5 years about 16-19 CEAs have to be performed. By identifying patient subsets at higher risk of stroke, this ratio will decrease and cost effectiveness of CEA can be improved.

Not only the severity of a carotid artery stenosis is a risk factor for developing neurological deficits. There is considerable evidence that intracerebral hemodynamics play an important role as well. Although the predominant mechanism of stroke is considered to be of thromboembolic origin, a subset of patients with severe extracranial occlusive disease exists who suffer from strokes due to the inability of their cerebral hemodynamic system to counteract reduced cerebral blood flow. There are indications that patients with progressive carotid artery disease and an incomplete circle of Willis and/or an exhausted cerebral autoregulation, have an increased risk of stroke. Deviations of the 'normal' Willisian polygon are not rare. Anatomical studies of normal brains have revealed that a typical polygon configuration is present in only 20-50% of the population (Figure 1). The anomalies most frequently found were hypoplasia of one or more of the component vessels and persistence of the embryonic origin of the posterior cerebral artery from the internal carotid artery. The association of Willisian polygon anomalies with cerebral infarcts has already been assumed several decades ago, when it was demonstrated that deviations in the circle of Willis were present more frequently in infarcted brains than in normal brains. More recently it was shown that hypoplastic or absent ipsilateral posterior communicating arteries are a risk factor for ischemic cerebral infarction in patients with internal carotid artery occlusion.

In another study patients with uni and bilateral internal carotid artery occlusions were investigated with conventional transcranial Doppler ultrasonography and CO₂ reactivity measurements. Cerebral vasomotor reactivity was lowest and low-flow infarctions were most frequent in those patients whose collateral hemispheric blood supply was from the ophthalmic artery alone as opposed to patients with a complete or nearly complete circle of Willis. From the foregoing studies it became clear that there is a strong pathophysiological relation between the severity of internal carotid artery stenosis, the integrity of the circle of Willis, the cerebral vasomotor reactivity and the neurological status of the patient.
Chapter 2

The potential role of transcranial ultrasound techniques
During the last fifteen years transcranial examination with ultrasound has become a useful tool in clinical and experimental settings, due to its effectiveness in assessing cerebral blood flow and cerebral hemodynamics. Especially in the field of carotid artery disease and carotid surgery a variety of clinical applications has been found. In patients with hemodynamically significant carotid artery stenosis it can provide information about additional factors on clinical outcome, such as the functional integrity of the circle of Willis, the cerebral reserve capacity or the presence of intracranial arterial stenosis.

![Diagram of the Circle of Willis](image)

**Figure 1.** Typical normal polygon configuration of the circle of Willis. A1, precommunicating part of the anterior cerebral artery; P1 and P2, pre and postcommunicating parts of the posterior cerebral artery.

Continuous monitoring of the cerebral circulation during CEA is another important clinical application, which will possibly lead to a better understanding of the relation between cerebral blood flow changes and brain function. The addition of transcranial ultrasound techniques is expected to produce further information on the clinical relevance of microemboli and to help developing better criteria for the use of a shunt. It is anticipated that transcranial ultrasound techniques can help neurologists and vascular surgeons in distinguishing which
patients with carotid artery lesions are really stroke-prone, so that in the future surgical therapy, especially when performed for prophylactic reasons, will be offered only to those patients who will maximally benefit from it.

The development of transcranial color-coded duplex scanning is a further move in the right direction to improve accurate assessment of cerebral blood flow as conventional transcranial Doppler techniques lack the possibility of direct imaging of the blood vessels.

Advantages of transcranial color-coded duplex scanning over conventional transcranial Doppler ultrasonography

Visualization of arteries

The use of a transcranial color-coded duplex scanner is not yet applied worldwide. Therefore, a considerable amount of clinical and experimental neurovascular imaging is still performed with conventional Doppler techniques. Broad application of transcranial color-coded duplex scanning, however, will just be a matter of time when its advantages become better known. Conventional transcranial Doppler, for the identification of the basal cerebral arteries solely relies on the spatial relations between and the flow direction within them. Because transcranial color-coded duplex scanning directly visualizes the cerebral arteries as opposed to the ‘blind’ identification of conventional Doppler, it enables correct vessel identification, especially when interpretation is difficult. This is the case if there are anatomical anomalies in the circle of Willis, for example a tortuous course of the basal cerebral arteries, or if collateral flow is present. Furthermore, one can imagine that spatial relations between vessels change when intracranial pathology is present and that blind identification can become rather unreliable in such cases. With transcranial color-coded duplex scanning exact localization of the sample volume within the course of a basal cerebral artery is possible. In this manner, direct information concerning flow disturbances due to for example intracranial stenosis or vasospasm (a complication seen with subarachnoid hemorrhage) can be obtained.

Angle correction

In studying cerebral hemodynamics, which often implies comparison of data between individuals, blood flow velocities must be determined as precisely as possible. In 1982 Aaslid et al already identified the problem that the angle between the intracranial arteries and the ultrasound beam is unknown. They assumed that the angle between the ultrasound beam and the direction of the blood flow in the intracranial arteries was sharp, so that accurate determination of blood flow velocities was possible. The maximum error of the
velocity measurement is less than 15% if the angle of insonation ranges between 0° and 30°, as its cosine will vary between 1 and 0.86. However, recent data of blood flow velocity measurements with transcranial color-coded duplex scanning showed that the angle of insonation is much greater and more variable than has currently been assumed. The measurement of angle-corrected blood flow velocities is an important additional feature of transcranial color-coded duplex scanning and enables estimation of blood flow velocities that are closer to the 'true' values than those obtained with conventional Doppler. Depending on the magnitude of the mean angle of insonation, the difference in velocities between conventional transcranial Doppler and transcranial color-coded duplex scanning can be as great as 30% in favor of the latter.¹

**Examination technique**

**General considerations**

Blood flow velocities in the basal cerebral arteries are directly influenced by the partial carbon dioxide pressure (pCO₂). Carbon dioxide (CO₂) is a potent vasodilator of the cerebral precapillaries and hypercapnia results in a marked increase of cerebral blood flow. In order to avoid major fluctuations in pCO₂, patients are examined in a supine and comfortable position. Before transcranial investigation is started, complete routine duplex examination of the extracranial carotid and vertebral arteries is performed to detect and grade stenoses of the cerebropetal vessels. With this knowledge, asymmetry in flow velocities can be explained and the presence of functional collaterals can be anticipated.

**Acoustic windows**

Transcranial investigation is performed with low-frequency (2.0-MHz to 2.5-MHz) transducers, which emit high output energies to achieve the tissue penetration that is needed to insonate the deep-set basal cerebral arteries. The technique makes use of relatively thin areas of the skull or natural foramina, which can be penetrated with ultrasound. These are the so-called acoustic windows. Usually three acoustic windows are recognized: the transtemporal window, the suboccipital window and the transorbital window. The transtemporal window (Figures 2 and 3) is situated above the zygomatic arch immediately anterior and slightly superior to the tragus of the ear conch. This window is used to insonate the middle cerebral artery, the anterior cerebral artery and sometimes the distal-most segment of the internal carotid artery. When the probe is placed slightly dorsal the posterior cerebral artery can be insonated. Placing the probe between the squama ossis occipitalis and the
Figure 2. Insonation through the right temporal bone window.

Figure 3. Intracranial B-mode image from the right temporal bone window with color-coding of the basal cerebral arteries, showing the anterior and posterior part of the circle of Willis. Red indicates flow towards the probe and blue indicates flow away from the probe. The typical butterfly configuration of the mesencephalic brain stem is encircled. ACA, anterior cerebral artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; P1, precommunicating part of posterior cerebral artery; P2, postcommunicating part of posterior cerebral artery.

Figure 4. Insonation through the suboccipital window.
spinous process of the first cervical vertebra approaches the suboccipital window (Figures 4 and 5), so that the ultrasound beam can be directed through the foramen magnum. In this way, the intracranial parts of both vertebral arteries and the basilar artery can be insonated. Placing the probe over the eyeball and directing the signal through the supra or infraorbital fissure or the optic canal uses the transorbital window. This route is used mostly for the study of flow in the ophthalmic artery, but the carotid siphon and the precommunicating part of the contralateral anterior cerebral artery can be insonated as well.

Examination of the basal cerebral arteries is considered adequate if the vessel of interest can be visualized with color-flow and a representative Doppler signal can be obtained for the calculation of peak-systolic, mean and end-diastolic velocities and the pulsatility index (Figure 6).
Limitations of transcranial examination with ultrasound

One of the main shortcomings of examining cerebral arteries with ultrasound is the increased energy loss in the skull and consequent reduced acoustic quality of the temporal bone in black people and older people, especially older women. This results in the absence of suitable acoustic windows in a considerable number of patients. Martin et al reported absence of suitable temporal windows in normal volunteers in 1% of 47 subjects aged 20-39 years, in 19% of 36 subjects aged 40-59 years and in 14% of 32 subjects aged 60 years and older.\(^1\)

The use of intravenously administered ultrasound contrast agents might overcome the problem of unsuitable windows and will possibly enable visualization of more distal arterial segments, although this has still been studied insufficiently.

Like conventional transcranial Doppler examination, transcranial color-coded duplex scanning is not an 'easy to learn' ultrasonographic technique. It makes a strong appeal to the knowledge, skill, and experience of the vascular technologist. Furthermore, if visualization is difficult due to suboptimal acoustic windows or anatomical variations, complete examination of the circle of Willis is time consuming, which puts the vascular technologist's patience and stamina to the test. After an intensive learning period, however, most vascular technologists should be able to master the technique.

Applications

Assessment of collateral function

As has been previously outlined, there seems to be a strong relation between the severity of extracranial stenosis, the presence of an incomplete circle of Willis, an exhausted cerebral reserve capacity and the neurological status of patients. Furthermore, collateral cerebral blood flow plays a major role during CEA, as it protects the endangered hemisphere from ischemia during cross-clamping. Although cerebral angiography is still considered the 'gold-standard' for the assessment of collateral cerebral blood flow, it is acknowledged that selective cerebral angiography can only demonstrate the patency of potential collateral channels and does not measure quantitative flow through them.

Functional patency of the Willisian collaterals, the anterior and posterior communicating arteries (Figure 1), can be assessed accurately with transcranial ultrasound techniques, when compared with angiography (Table 1). Although in rare cases transcranial color-coded duplex scanning can actually visualize the anterior and posterior communicating arteries, for reliable assessment of true collateral flow common carotid artery compression must be applied for several seconds. To avoid a systemic cardiovascular reaction during this manoeuvre, gentle
Table 1. Accuracy of TCD and TCCD in Assessing the Collaterals of the Circle of Willis in Patients with Carotid Artery Occlusive Disease.

<table>
<thead>
<tr>
<th>Author</th>
<th>Population</th>
<th>Method</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindegaard et al¹⁵</td>
<td>49 patients*</td>
<td>TCD + compression tests</td>
<td>AcoA 93</td>
<td>AcoA 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PcoA 86</td>
<td>PcoA 92</td>
</tr>
<tr>
<td>Müller et al¹⁶</td>
<td>40 patients§</td>
<td>TCD + compression tests</td>
<td>AcoA 95</td>
<td>AcoA 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PcoA 87</td>
<td>PcoA 95</td>
</tr>
<tr>
<td>Baumgartner et al¹⁷</td>
<td>117 patients‡</td>
<td>TCCD + compression tests</td>
<td>AcoA 98</td>
<td>AcoA 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PcoA 84</td>
<td>PcoA 94</td>
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</table>

TCD, transcranial Doppler ultrasonography; TCCD, transcranial color-coded duplex ultrasonography; AcoA, anterior communicating artery; PcoA, posterior communicating artery. *25 patients with <90% ICA stenosis, 11 patients with 90-99% ICA stenosis, 13 patients with ICA occlusion, §40 patients with ICA occlusion, ‡117 patients with 70-99% ICA stenosis and occlusions.

Compression is applied low in the neck, away from the carotid sinus and only in patients without serious common carotid artery pathology as assessed by prior duplex scanning. After all, it is not inconceivable that this manoeuvre could lead to iatrogenic embolization, when serious plaque formation at the site of compression is present. A photoplethysmograph must be attached to the earlobe on the side of the compressed artery to check the adequacy of compression.

Collateral supply (Table 2) through the *anterior communicating artery* (AcoA) is indicated

Table 2. Detection of Functionally Patent Willisian Collaterals.

<table>
<thead>
<tr>
<th></th>
<th>AcoA</th>
<th>PcoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No carotid lesion</td>
<td>Flow reversal in A1 during ilce</td>
<td>Direct visualization</td>
</tr>
<tr>
<td></td>
<td>Velocity increase in A1 during clce</td>
<td>Velocity increase in P1 during ilce</td>
</tr>
</tbody>
</table>

*High-grade stenosis or carotid occlusion*

<table>
<thead>
<tr>
<th></th>
<th>Reversed flow in ipsilateral A1</th>
<th>Direct visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity decrease in ipsilateral MCA during clce</td>
<td>Velocity in P1 &gt; mean P1 velocity +2 SD of age and sex-matched normals</td>
</tr>
</tbody>
</table>

AcoA, anterior communicating artery; PcoA, posterior communicating artery; A1, precommunicating part of the anterior cerebral artery; P1, precommunicating part of the posterior cerebral artery; MCA, middle cerebral artery; ilce, ipsilateral carotid compression; clce, contralateral carotid compression; SD, standard deviation.
First by reversed blood flow in the precommunicating part of the anterior cerebral artery (A1) ipsilateral to the compressed common carotid artery, and second by an enhanced blood flow velocity in the ipsilateral precommunicating part of the anterior cerebral artery during contralateral common carotid artery compression (Figures 7-9). If a high-grade stenosis or occlusion of the internal carotid artery is present, collateral supply through the AcoA is indicated by a reversed high blood flow velocity in the A1-segment ipsilateral to the stenosed internal carotid artery. This may also become manifest by a prompt reduction of the blood flow velocity in the precommunicating part of the anterior cerebral artery.

Figure 7a and b. Schematic drawings of blood flow reversal and flow enhancement in the left A1 during compression of the ipsilateral and contralateral common carotid artery (expressed by the black square in the drawing) indicating a functionally patent anterior communicating artery.

Figure 8. Transcranial color-coded ultrasonogram of the anterior part of the circle of Willis before (left hand picture) and during (right hand picture) ipsilateral carotid compression. Reversal of flow (right hand picture) in the ipsilateral A1 is demonstrated by the change of color from blue to red. Note the aliasing effect in the contralateral A1 and M1 indicating strongly enhanced blood flow velocities.
Figure 9a. Doppler spectrum showing reversal of flow in the ipsilateral A1 during carotid compression.

Figure 9b. Doppler spectrum showing velocity enhancement in the contralateral A1 during carotid compression.

Flow velocity in the middle cerebral artery ipsilateral to the stenosed internal carotid artery during compression of the contralateral common carotid artery. When none of these characteristic findings are demonstrable, a patent AcoA is excluded.

Presence of collateral flow through the posterior communicating artery (PcoA) is demonstrated if the vessel can actually be visualized with color flow. In most cases, however, the PcoA cannot be detected directly and collateral flow through the PcoA is ascertained if blood flow velocity in the precommunicating part of the posterior cerebral artery (P1) is significantly enhanced during ipsilateral common carotid artery compression. This velocity enhancement is a result of the pressure gradient between the anterior and posterior circulation caused by the compression manoeuvre (Figures 10-12).

Figure 10. Schematic drawing of blood flow velocity enhancement in the precommunicating part (P1) of the right posterior cerebral artery during ipsilateral common carotid artery compression, indicating a functionally patent right posterior communicating artery.
Figure 11. Transcranial color-coded ultrasonogram of the posterior part of the circle of Willis before (left hand picture) and during (right hand picture) ipsilateral carotid compression. Reversal of flow (right hand picture) in the ipsilateral PcoA is demonstrated by the change of color from blue to red. Note the aliasing effect in the ipsilateral P1 indicating a strongly enhanced blood flow velocity.

Figure 12. Doppler spectrum showing velocity enhancement in the P1 during ipsilateral carotid compression.

A significant flow increase in the P1-segment during compression is defined as an increase of more than 20% from precompression levels, this value being twice as much as expected from normal variation and measurement error. In case of severe obstructive internal carotid artery disease a functional PcoA is indicated by a peak-systolic velocity in the ipsilateral P1 higher than the mean P1 velocity +2 SD of age- and sex-matched normals.17 Another way to assess the functional patency of the PcoA is to perform compression tests of the vertebral arteries at the mastoidal slope high in the neck. Due to its technical difficulty and unreliability, however, we do not recommend this technique. Moreover this manoeuvre causes discomfort to the patient. Persistence of the embryonic origin of the posterior cerebral artery from the internal
carotid artery can be revealed when blood flow velocity in the posterior cerebral artery strongly decreases during ipsilateral common carotid artery compression.

Assessment of cerebrovascular reserve capacity
Another parameter for the identification of patients who are at risk for hemodynamic strokes is the detection of a depleted cerebrovascular reserve capacity (CVR). CVR can be defined as the brain’s potential ability to compensate for a drop in perfusion pressure due, for example, to progressive carotid artery stenosis. The main defense mechanism of the brain in countering low-flow states is vasodilatation of the cerebral precapillary arteries. The capability of the precapillary vessels to dilate in response to a decrease of cerebral blood flow is defined as the cerebral vasomotor reactivity (VMR). The VMR of the precapillary arteries can be measured by assessing the peak-systolic velocity in the middle cerebral artery with transcranial ultrasound techniques before and after provocation tests with acetazolamide (Diamox) or carbogen gas (a mixture of 95% O$_2$ and 5% CO$_2$). The intravenous administration of acetazolamide or the inhalation of carbogen through an anesthesiologic mask causes dilatation of precapillary arteries and produces a blood flow velocity increase in the middle cerebral artery. In case of maximal dilatation of the precapillary vessels to compensate for a critically reduced cerebral perfusion pressure, the administration of vasodilating stimuli will have no additional effect and no velocity enhancement in the middle cerebral artery will be registered. This reflects an exhausted cerebral reserve capacity and a considerable risk of stroke. Measurement of VMR, which reflects cerebrovascular reserve capacity, helps to identify patients with reduced cerebral perfusion pressure and quantifies the hemodynamic impact of extracranial occlusive lesions of the brain-supplying arteries. It has been reported that low-flow infarctions are significantly associated with a reduced VMR in patients with high-grade stenosis or occlusion of the internal carotid artery. Patients with such lesions have a higher rate of future ipsilateral stroke compared to patients with normal or only slightly disturbed vascular reserve. Furthermore, the VMR was found to be dramatically reduced in patients with symptomatic uni or bilateral internal carotid artery occlusions and incomplete circles of Willis.

Detection of intracranial stenoses
Intra-arterial angiography still is the gold-standard for detection of intracranial stenoses. However, clinicians are hesitant to apply a potentially dangerous technique for screening purposes especially if the incidence of the disease is low. A reliable noninvasive method will therefore be of great help in optimal treatment of patients at risk for developing disabling
neurological deficits due to intracranial stenosis. Noninvasive assessment of the intracranial arteries seems particularly clinically relevant if CEA without any preceding angiographic evaluation is performed. This is, because additional neurological events after successful CEA may be associated with the presence and degree of intracranial stenotic lesions.

A lot of research on transcranial color-coded duplex scanning must still be conducted to establish its value in diagnosing intracranial arterial stenosis. It can provide important information in that respect, as the technique enables visualization and velocity measurements of places where such stenoses are most likely to occur: the carotid siphon and the main stem of the middle cerebral artery. However, before ultrasonographic grading of intracranial stenoses can be routinely applied, hemodynamic criteria are needed which can be obtained from comparative studies with cerebral angiography. Nevertheless, false-positivity and false-negativity are major problems when rigid velocity criteria are used for the diagnosis of intracranial arterial occlusive disease, as velocities vary with age, sex, cerebral vascular resistance, degree of extracranial occlusive disease, etc. Several factors can lead to an incorrect diagnosis. For example, the erroneous diagnosis of vasospasm as stenosis or the wrong interpretation of high blood flow velocities for stenosis in arteries supplying Willisian collaterals or leptomeningeal anastomoses. Because of these typical pitfalls, one must be cautious with the use of pure velocity data or flow characteristics for the assessment of intracranial stenoses and occlusions. Conclusive data regarding the detection of intracranial occlusive disease with transcranial color-coded duplex scanning is lacking and therefore the true value of this new technique in this particular diagnostic field remains to be elucidated.

Conclusion

Transcranial color-coded duplex scanning is a completely noninvasive technique for accurately determining cerebral hemodynamics. In contrast with the classic radiological technique of intra-arterial digital contrast angiography or modern techniques like magnetic resonance angiography or computed tomographic angiography, transcranial duplex scanning is the only technique that allows real-time assessment of cerebral hemodynamics. Influences of intra or extracranial vascular obstructions and influences of exogenous stimuli on cerebral blood flow can be immediately assessed. This cerebral vasculature imaging technique offers considerable possibilities for clinical and experimental use. In the broad field of carotid surgery, it will contribute to a better understanding of pre and postoperative hemodynamic phenomena and it is anticipated that in the future transcranial color-coded duplex scanning may have additional value in determining which patients will benefit most from carotid endarterectomy. Nevertheless,
as with other new diagnostic tools, to acquire widespread acceptance, transcranial color-coded duplex scanning will have to demonstrate its usefulness in daily clinical practice. To establish its true value, a lot of research still has to be done.

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