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# Transcranial Doppler in Extracranial Cerebrovascular Disease

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## PRINCIPLES AND DEVELOPMENT OF TRANSCRANIAL DOPPLER

Transcranial Doppler (TCD) has expanded the capabilities of Doppler ultrasound to include examination of the intracranial circulation.[1] The use of ultrasound to measure blood flow velocity is based on the Doppler principle. As discussed in Chap. 11, the Doppler principle describes the frequency shift of a wave when the source of the wave and the receiver of the wave are moving with respect to each other. To measure the velocity of flowing blood, one can use the frequency shifts of an ultrasound beam reflected from flowing blood. These shifts are directly proportional to the blood flow velocity.

Satomura and Kaneko first described this application of ultrasound.[2,3] One of their goals

was actually to record blood flow velocities from the intracranial vessels. However, they concluded that the skull would be too much of a barrier to useful recordings; therefore, they concentrated their attention on the extracranial circulation. Further developments in this field have led to the many applications and the widespread use of Doppler ultrasound in the cardiovascular system.

The first transcranial Doppler recordings were made by Dr. Rune Aaslid in 1981 using a 2 MHz pulsed Doppler manufactured by Vingmed.[4] Subsequently, the transcranial Doppler methodology was developed at the Department of Neurosurgery in Berne, Switzerland. The initial application of this technology concentrated on the diagnosis of cerebral vasospasm caused by subarachnoid hemorrhage. Subsequent refinements in this technology were made possible by small portable microprocessor–controlled equipment (TC264, Eden Medical Electronics, Uberlingen, Germany). This instrumentation consisted of a 2 MHz pulsed range-gated Doppler with analog and digital output of the velocity waveform.

Pulsed Doppler is essential for TCD purposes, since a small sample volume is required to locate the different arteries in the basal human cerebral circulation in and around the circle of Willis. The low frequency used for the Doppler system is required for maximum penetration through the natural cranial windows. Initial identification of the individual intracranial vessels was accomplished by knowledge of the anatomy and flow characteristics of the intracranial circulation and was performed using a freehand technique.[1,5] Subsequently, additional techniques have been described for improved vessel identification.

The applications of TCD have expanded greatly. In addition to its widely accepted use in detecting cerebral vasospasm,[6] other applications continue to develop. Detection of intracranial stenosis from a variety of pathologic conditions has been described,[7] as well as the assessment of intracranial hemodynamics, which can be affected by many disease processes.[8] Monitoring of intracranial blood flow velocity also can be performed, and this can be used to study cerebral blood flow changes during autoregulatory responses,[9] $CO_2$ changes[8] in response to some medications, and brain activation.[10] Monitoring of the intracranial velocity changes during vessel clamping and other surgical procedures is also being used for research and clinical purposes. Further development of time-sequenced Dopplers allows monitoring of more than one vessel simultaneously.[4] Multichannel Doppler enables comparisons between cerebral hemispheres during vessel clamping, cerebral activation, autoregulation, and $CO_2$ reactivity.

During the last several years, the ability to detect intracranial microemboli has been recognized and further refined. It is now possible to detect cerebral arterial emboli caused by entry into the circulation during open heart surgery, peripheral vascular surgery, and catheter procedures. The microemboli that occur during surgical procedures are largely due to air bubbles, but also may arise from intravascular formed elements.[11,12] In addition, intracranial emboli composed of formed elements have been detected in many asymptomatic patients with intravascular pathology and have been observed in patients experiencing transient ischemic attacks (TIAs).[11,13] The development of automated detection and quantitation devices for intracranial microemboli is now underway. The two major capabilities of TCD that are useful in patients with extracranial cerebrovascular disease are the ability to detect intracranial emboli and the ability to determine the intracranial hemodynamic effects of proximal vascular lesions.

## EXAMINATION TECHNIQUES

The initial transcranial Doppler recordings were made through the temporal window or

the thin portion of the squamous part of the temporal bone.[1] It has been observed in most humans that in the temporal region of the skull, the inner and outer tables can be either fused or closely approximated, which allows the transmission of ultrasound (Fig. 12-1). The thicker portions of the cranium have a middle layer of cancellous bone, or diploe, which contains bone spicules that have a tendency to scatter ultrasound in many directions. Most of the skull is composed of this type of bone and therefore is less suitable for ultrasound penetration.

Three acoustical windows for TCD examination have been described: the transtemporal window; the transorbital window; and the transforamenal window (Fig. 12-2). The transtemporal window is located directly superior to the zygomatic arch. In this location, there may be several areas in the temporal squama where ultrasound can penetrate, and therefore several temporal windows which can be used for examination. Grolimund found that probably less than 35 percent of the original ultrasonic power is transmitted through the temporal bone during TCD examination.[14] Through amplification techniques and enhancement of signal-to-noise ratio, smaller fractions of the original ultrasonic intensity can be used to record useful spectral signals. Approximately 90 percent of

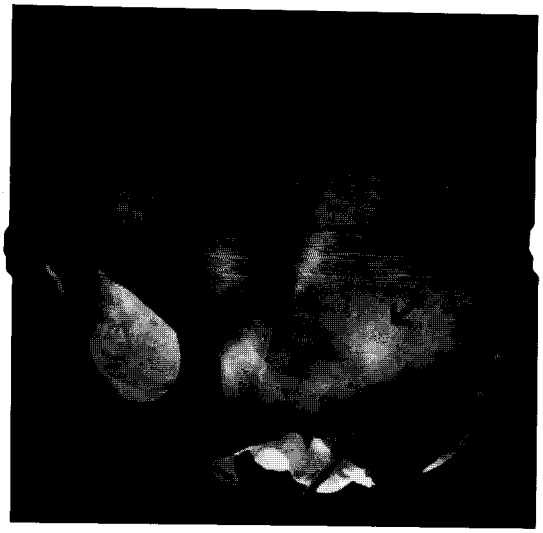


Figure 12-1. Transillumination of the human skull illustrating thin portions of the temporal bone (*arrow*) where ultrasound penetration using transcranial Doppler is possible. The inner and outer table of the skull are often fused in this region. This feature allows the penetration of low frequency ultrasound.

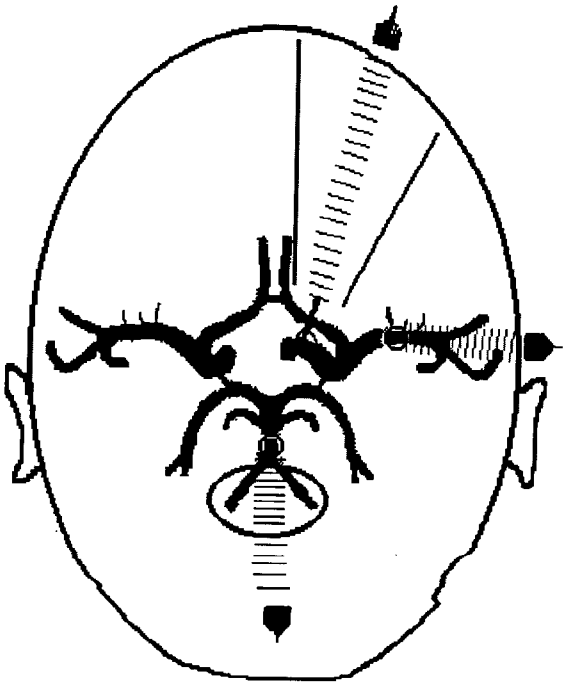
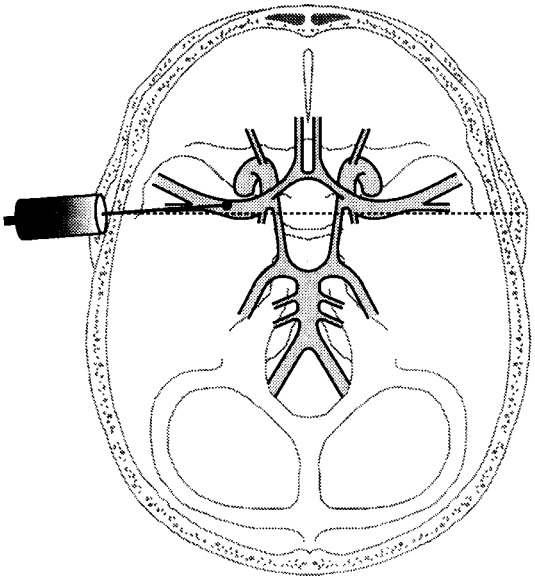


Figure 12-2. The three windows for transcranial Doppler examination of the basal cerebral vessels. Anteriorly, the transorbital window is used to examine the carotid siphon as well as the ophthalmic artery. On the lateral portion of the skull is the transtemporal window used to examine the middle cerebral artery, proximal anterior cerebral artery, distal internal carotid artery, and proximal posterior cerebral artery. The third window is the transforamenal window, which can be used to examine the posterior circulation vessels. The two vertebral arteries and basilar artery are easily examined using this window. The posterior inferior cerebellar arteries can also usually be examined.

subjects can be examined through the temporal window.[5] However, hyperostosis of the temporal bone may make it impossible to perform a complete examination of some individuals. Elderly females are particularly prone to having poor temporal windows. The temporal window can be used to examine the middle cerebral artery (MCA), proximal anterior cerebral artery (ACA), terminal internal carotid artery (ICA), proximal posterior cerebral artery (PCA), anterior communicating artery, and occasionally the posterior communicating artery (Fig. 12-3).

The most accurate determination of flow velocity is accomplished when an artery is parallel to the direction of the ultrasound beam. Generally, as arteries become more perpendicular to the ultrasound beam, they can no longer be examined adequately. Therefore, the standard TCD examination usually is limited to the basal cerebral arteries. It is not typically possible to examine the MCA branches as they become vertically oriented in the Sylvian fissure. Other arterial segments which are normally beyond the range of TCD are the ACA distal to the anterior communicating artery as it becomes vertically oriented in the interhemispheric fissure, and the PCA as it curves laterally around the brain stem and becomes oriented perpendicular to the ultrasound beam from the temporal window. The transorbital route can be used to examine the ophthalmic artery, the carotid siphon, and occasionally the ACAs. The transforamenal window utilizes the natural cranial opening through the foramen magnum. It can be used to examine both vertebral arteries (VA) as well as the basilar artery (BA). Branches from the vertebral arteries, particularly the posterior inferior cerebellar artery (PICA), also can be examined through these windows.

Vessel identification is accomplished through



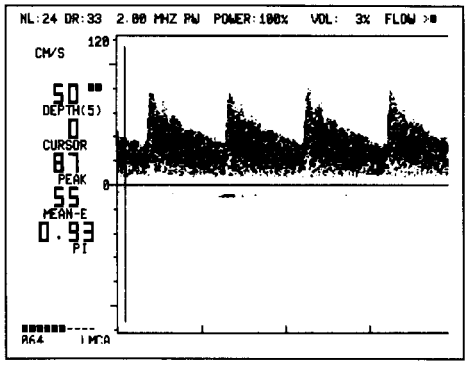



**Figure 12-3.** Recordings from the middle cerebral artery through the transtemporal window. Note that the spectral tracing is that of a low resistance vascular bed, which is typical of the intracranial circulation. Normally, the middle cerebral trunk is found at a depth of 55 mm from the scalp at the temporal window.

several techniques. The original and most widely used method for vessel identification involves the freehand technique, which utilizes six criteria to identify the intracranial vessels.[5] These are:

1. The cranial window used
2. The depth of the sample volume
3. The direction of flow in relation to the transducer
4. The spatial relationship of the vessel under examination to the internal carotid artery bifurcation
5. The relative flow velocity
6. The response to compression and oscillation maneuvers

Successful use of the freehand technique requires an ultrasonographer who is extremely familiar with the normal and abnormal intracranial vascular anatomy and who has performed multiple examinations on normal and abnormal subjects. Further technical developments in TCD equipment have led to the use of other modalities to facilitate vessel identification, such as vessel mapping and color-flow TCD.

The transcranial mapping technique was developed by Aaslid in cooperation with Eden Medical Electronics.[15] The principle behind transcranial vessel mapping is a computer-generated display produced by mapping the movement of the Doppler sample volume at different locations along the basal cerebral arteries. The computer saves a record of the placement of the sample volume as a three-dimensional plot with color-coded dots. With the aid of a vessel map, the branch points can be identified and the intracranial vessel anatomy can be reconstructed. Spectral waveforms saved from each of the dots may then be evaluated. In this way, one may record and provide positive documentation for the location of each waveform.

A more recent development for vessel identification is called transcranial color-coded real-time ultrasonography (TCCU).[16] This technology provides a B-mode image with a two-dimensional color-coded image of the basal cerebral arteries. Positive vessel identification is achieved using TCCU by enabling the sonographer to scan the basal vessels and obtain a real-time color-coded map of the vascular anatomy (Fig. 12-4). This technique also provides visualization of such intracranial landmarks as the sphenoid wing and the petrous ridge. Landmarks are useful reference points to locate the various intracranial vessels. Certain intracranial mass lesions can be identified at the same time and their effects on the normal vasculature can be evaluated.

The TCCU method involves scanning the intracranial basal vessels through the same three windows used in freehand examinations. The color-coded blood flow maps are then used to direct the sample volume to specific intracranial vessels. The color-coded map is renewed every two seconds during the scanning phase. Once a vessel is chosen for examination, the probe is held in the same position where optimal vessel visualization is achieved. Then the Doppler mode is selected and the sample volume is placed on the previously obtained color-flow map to record from each intracranial vessel. The TCCU technique is useful in providing documentation of the site at which recordings are obtained. It is also helpful in cases of difficult vessel identification or when vascular anomalies are present.[16–18] The equipment used for color-flow is currently more cumbersome than that commonly used for the freehand technique.

## INTRACRANIAL STENOSIS

Intracranial arterial stenosis may be caused by a variety of pathologic processes. The devel-

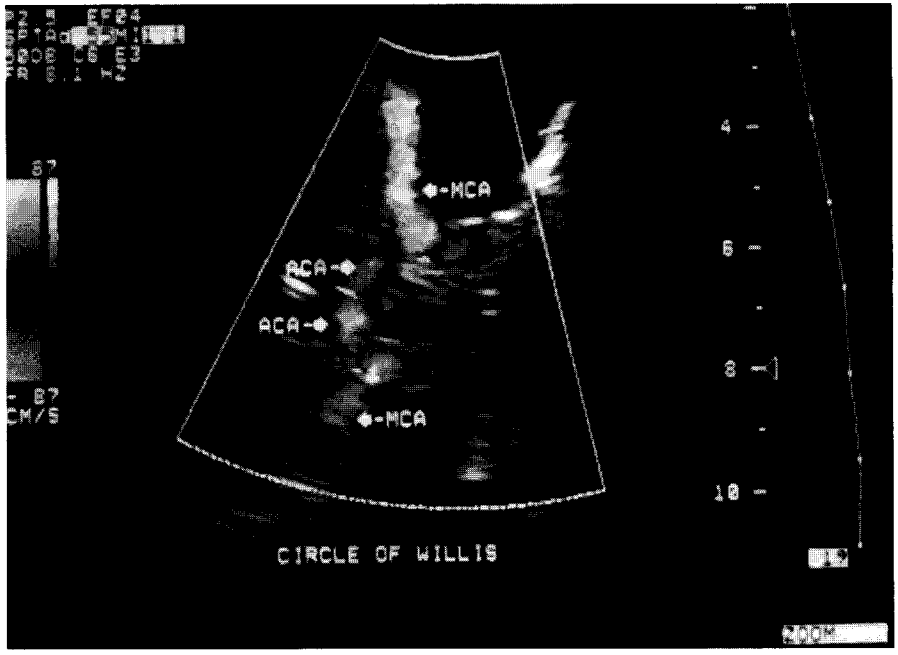



**Figure 12-4.** This is a sector scan from a color-flow Doppler instrument. This black and white illustration shows the major components of the circle of Willis. When the scan is obtained, the examiner can place the Doppler sample volume on preidentified vessels to record the blood flow velocity. This method provides the examiner with increased confidence for correct vessel identification.

opment of TCD ultrasonography has extended the capability of Doppler ultrasound to diagnose this condition reliably.[19–24] Reversible intracranial vessel narrowing is commonly caused by vasospasm following subarachnoid hemorrhage[6] and also can be seen in certain forms of vasculitis.[25] The most common cause of fixed intracranial stenosis in patients presenting with symptoms related to cerebrovascular disease is atherosclerosis involving the basal intracranial vessels.[22,26] Other conditions that can cause intracranial arterial stenosis include moyamoya disease, intracranial arterial dissection, sickle cell disease,[27] and arterial to arterial emboli undergoing various stages of recanalization.

Atherosclerotic disease of the intracranial vessels has received much less attention than lesions of the extracranial cerebral vessels. Probably one reason for this is that a noninvasive method was not available prior to the development of TCD to diagnose and follow the natural history of these lesions. Despite the fact that intracranial arterial stenosis due to atherosclerosis is less common than extracranial stenosis in western populations, the stroke rate from intracranial lesions can be significant. Bogousslavsky and coworkers[28] have analyzed the natural history of patients with MCA stenosis or occlusion entered into the extracranial–intracranial bypass study group. During a follow-up period of 42 months, recurrent cerebrovascular events (TIA and stroke) were experienced by 11.7 percent of the patients per year. The study found that atherosclerotic disease of the MCA was more common in Asian patients than in their Caucasian counterparts. A recent autopsy study comparing the sever-

ity of intracranial to extracranial atherosclerosis in Hong Kong Chinese also found that atherosclerosis of the intracranial cerebral vessels was more severe than that of the extracranial cerebral vessels in this population.[29]

The criteria for diagnosis of intracranial stenosis using TCD has been the subject of recent studies. The MCA, in addition to being commonly involved in intracranial atherosclerosis, is also the best suited for TCD examination. This is because it usually is parallel to the ultrasound beam and is considered an end artery in most cases. Leptomeningeal collateral vessels can be present; however, the collateral capacity of these vessels in humans is highly variable. Since increased velocities can be due either to stenosis or increased flow from collateral sources, four criteria have been established for making a positive identification of MCA stenosis.[7]

*Criterion 1*: Blood flow velocity increased to levels above those found in normal subjects.

*Criterion 2*: Localized increase in velocity at particular segments of the MCA.

*Criterion 3*: Side to side differences exceeding those encountered in normal subjects.

*Criterion 4*: Sonographic sounds of disturbed flow.

These criteria can also be applied to the other vessels commonly involved with intracranial atherosclerosis, namely, the distal ICA, and the other basal cerebral vessels (ACA, PCA, VA, BA). However, these arteries may be more likely than the MCA to have moderate increases in velocity when conducting increased collateral flow.

The differential diagnosis of intracranial stenosis includes vasospasm, feeding arteries to arteriovenous malformations, collateral circulation in the circle of Willis due to arterial occlusions, and carotid cavernous fistulas. Other less common occurrences include aneurysms, which can produce turbulence, and intracranial dissections, which may produce an intimal injury and stenosis.

Analysis of the accuracy of TCD for the diagnosis of intracranial stenosis has been reviewed by several authors.[19–21,23,24] Spencer and Whisler[24] compared carotid siphon stenosis assessed by angiography and TCD. In a group of 33 carotid siphons visualized angiographically, 11 demonstrated stenosis ranging from 30 to 75 percent. Comparison examinations using TCD revealed a sensitivity of 73 percent and specificity of 95 percent. Ley-Pozzo and Ringelstein[20] compared intra-arterial digital subtraction angiography to TCD in detecting occlusive disease of the carotid siphon and MCA. Sixteen of 17 cases of carotid siphon stenosis were correctly identified. Another study comparing TCD with angiography in a population of 196 patients reported the correct identification of stenosis using TCD in 16 of 21 cases documented angiographically.[21]

## INTRACRANIAL HEMODYNAMICS

Using TCD to evaluate intracranial hemodynamics has added much new information concerning the control of the cerebral circulation. In addition to being able to evaluate intracranial stenoses by observing focal accelerations in the blood flow velocity, TCD can be used to measure relative changes in blood flow in the basal intracranial vessels. The use of TCD for this purpose is based on the principle that changes in velocity will be proportional to changes in flow through a vessel if the vessel diameter is constant. When using TCD to evaluate blood flow changes, a constant insonation angle (angle between the ultrasound beam and the vessel) is insured by the use of a fixed monitoring probe. Changes in blood flow velocity through the MCA can be used to assess relative changes in blood flow in that artery due to changes in $CO_2$ concentration or moderate changes in arterial blood pressure. Using these principles, the functional capacity of the distal regulating vessels in the cerebral circulation can be assessed.

The maintenance of adequate cerebral blood flow depends on sufficient cerebral perfusion pressure through the inflow vessels. Sufficient cerebral perfusion is dependent on the blood pressure, the anatomy of the extracranial and intracranial vasculature, and compensatory mechanisms when the vasculature or blood pressure becomes compromised. Under normal circumstances the human cerebral circulation contains two paired inflow arterial networks, the carotid and vertebral systems. At the base of the brain a normally configured circle of Willis will function as a manifold to normalize the perfusion pressure to the distal vessels if one or more extracranial vessels becomes occluded or hemodynamically compromised due to stenosis.

The collateral capacity of the circle of Willis normally allows nearly complete compensation "side-to-side" in cases of carotid occlusion.[30,31] The major pathways that compensate for a carotid occlusion are (1) crossover through the anterior communicating artery with reversed flow in the proximal anterior cerebral artery ($A_1$) ipsilateral to the occlusion; (2) reversed flow (forward flow) in the posterior communicating artery ipsilateral to the occlusion; and (3) reversed flow in the ipsilateral ophthalmic artery. The major pathways that normally compensate for hemodynamically significant posterior circulation occlusions are the posterior communicating arteries, which provide "front-to-back" collateral flow. The posterior communicating arteries also can provide "back-to-front" collateral flow in cases of bilateral carotid occlusion or severe stenosis. However, major differences in the functional capacity of the circle of Willis are found in the general population. It has been estimated that less than 50 percent of individuals possess an anatomically normal circle.[32] Figure 12-5 illustrates the normal configuration of the circle of Willis and common variants seen.

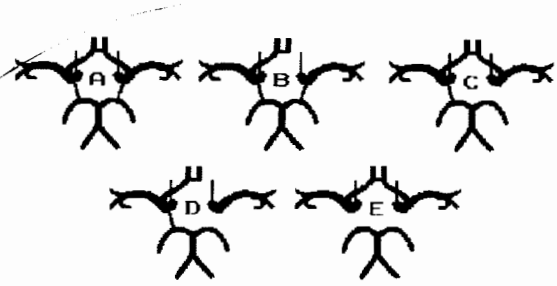



**Figure 12-5.** The common variations seen in the circle of Willis. *A.* Normal circle which can provide adequate collateral circulation to the distal cerebral vasculature with extracranial arterial occlusions. *B.* Functional impairment of the anterior crossover pathway due to an absent or atretic proximal anterior cerebral artery (*A1*). *C.* Functional impairment of anterior and posterior communication on one side due to an absent or atretic posterior communicating artery. *D.* Isolated carotid artery due to an inadequate anterior crossover pathway as well as inadequate posterior to anterior communication. The middle cerebral artery territory in this configuration is highly dependent on the flow through the ipsilateral internal carotid artery as well as the retrograde pathway through the ophthalmic artery. *E.* Absence of anterior to posterior communication due to bilateral agenesis or atresia of the posterior communicating arteries.

The effect of extracranial occlusive disease on intracranial hemodynamics and cerebral blood flow (CBF) is largely dependent on two factors: (1) the extent of the extracranial occlusive disease; and (2) the intracranial vascular anatomy and functional capacity of each individual patient. When the cerebral perfusion pressure is compromised owing to an acute extracranial arterial occlusion or a drop in blood pressure in the presence of extracranial occlusive disease, the collateral capacity of the circle of Willis will determine the distribution of perfusion to the intracranial vessels. Cerebral autoregulation then serves to dilate the distal regulatory vessels. This will effectively lower cerebrovascular resistance in an attempt to maintain cerebral blood flow. When this mechanism can no longer compensate and CBF begins to fall, increased extraction of oxygen from the blood by the brain can serve as

an additional mechanism to maintain cerebral metabolism. When all these mechanisms are exhausted, cerebral ischemic symptoms or stroke on a hemodynamic basis can ensue.

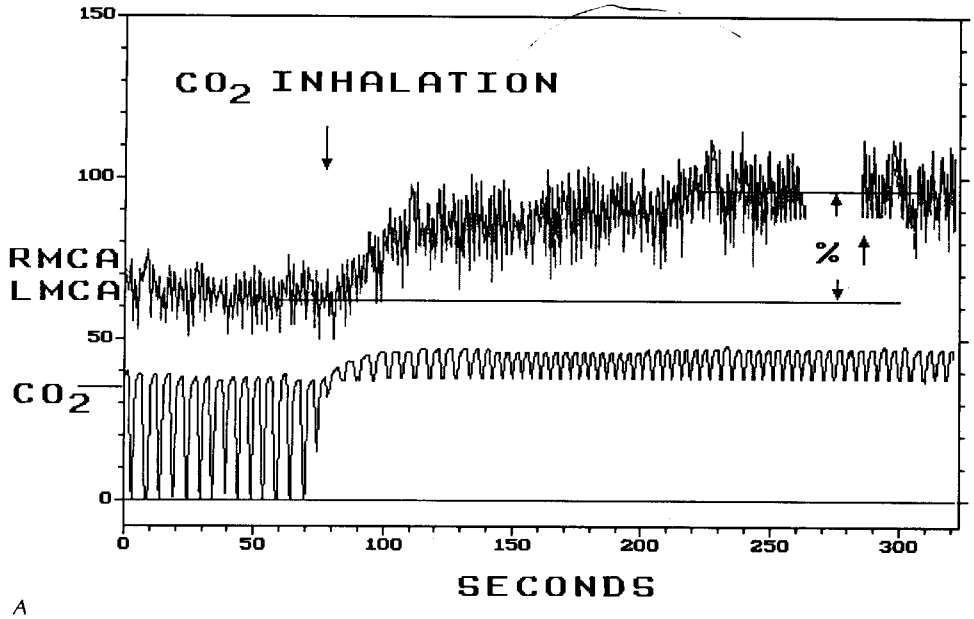
## TESTING OF VASOMOTOR RESERVE

The evaluation of vasomotor reserve in the cerebral circulation has served as an indirect method to evaluate the compensatory state of cerebral autoregulation. Normally, cerebral autoregulation preserves cerebral blood flow at a constant level between a mean arterial pressure of 50 to 150 mmHg.[33,34] This is accomplished by varying the resistance of the distal cerebral vasculature by vasoconstriction and vasodilation. As the blood pressure or cerebral perfusion pressure (CPP = systemic blood pressure − intracranial pressure) decreases, vasodilation of the distal regulating vessels lowers cerebrovascular resistance, maintaining constant CBF.

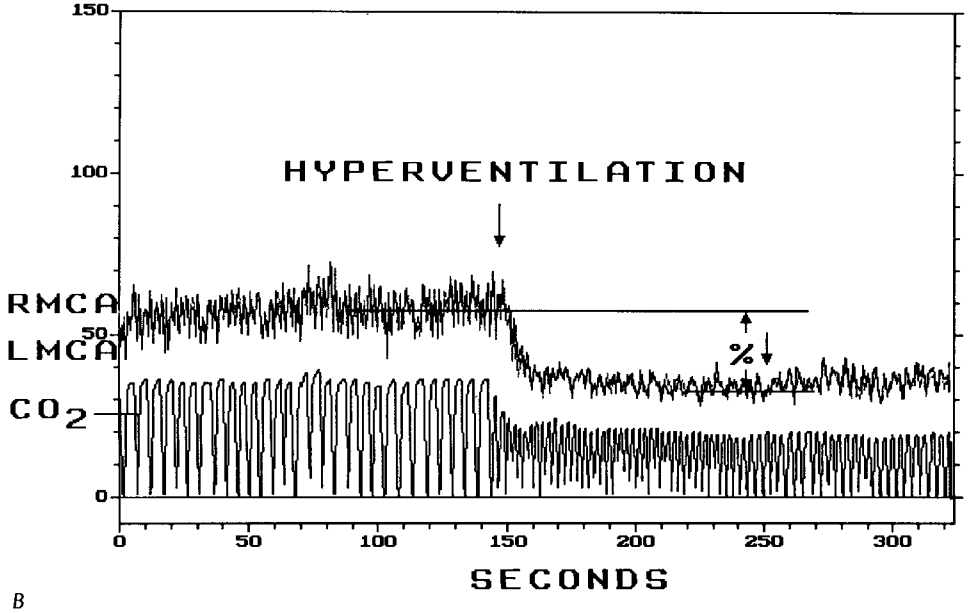
The distal cerebral vessels normally are very sensitive to the blood $CO_2$ concentration. They constrict in response to decreased $CO_2$ concentration (hyperventilation) and dilate in response to increased $CO_2$ concentration ($CO_2$ inhalation). When CPP decreases as a result of proximal arterial stenosis or occlusion, and the distal regulatory vessels become maximally dilated, they lose their responsiveness to $CO_2$. Diamox has also been used to effect distal cerebral vasodilation and probably works by a similar pH-dependent mechanism.[35] Lack of responsiveness to $CO_2$ or to Diamox can be used to indicate reduced CPP in the middle cerebral arteries due to the effects of proximal occlusive disease.

Several methods have been used to evaluate $CO_2$ reactivity.[133] Xenon has been used to measure CBF changes directly in response to $CO_2$ changes. Single photon emission tomography (SPECT) has been used for measuring regional differences in increased CBF induced by $CO_2$.[35] The use of TCD to measure vasoreactivity is based on its ability to measure relative changes in blood flow through the inflow vessels (MCAs) in response to changes in $CO_2$ concentration or to Diamox. The diameter of the MCA remains relatively constant during changes in $CO_2$ concentration.[36,37] Therefore, changes in velocity from baseline level correlate closely to relative changes in blood flow through that artery.[35,38] An important distinction between TCD and indicator methods is that TCD measures these responses in the MCA perfusion territory. This territory may become smaller in occlusive disease if the leptomeningeal collateral vessels provide increased perfusion to the cerebral hemisphere from the ACA and PCA.

The total percentage change in velocity between baseline and $CO_2$ inhalation and baseline and hyperventilation has been termed "vasomotor reactivity."[8] Ringelstein and coworkers,[8,31] have established normal values in a group of volunteers (age 20 to 75 years) for vasomotor reactivity in the MCA distribution. An average maximum increase in velocity of 52.5 percent with $CO_2$ inhalation and a decrease of 35.3 percent with hyperventilation was found, yielding an average vasomotor reactivity (VMR) of 87.8 percent. Figure 12-6 illustrates $CO_2$ reactivity testing using simultaneous bilateral monitoring of both MCAs. In a group of patients with carotid occlusions, VMR was significantly reduced in the ipsilateral MCA in 40 cases of unilateral occlusion. In 15 cases with bilateral occlusions, VMR was severely reduced on both sides. All patients with low-flow infarctions on CT ($n=5$), chronic ischemic ophthalmopathy ($n=2$), or repeated hypostatic TIAs ($n=2$) had VMR measurements of less than 38 percent.[8] The VMR present in patients with carotid occlusions is highly dependent on the configuration of the circle of Willis. In a group of 64 patients with carotid occlusions, Ringelstein

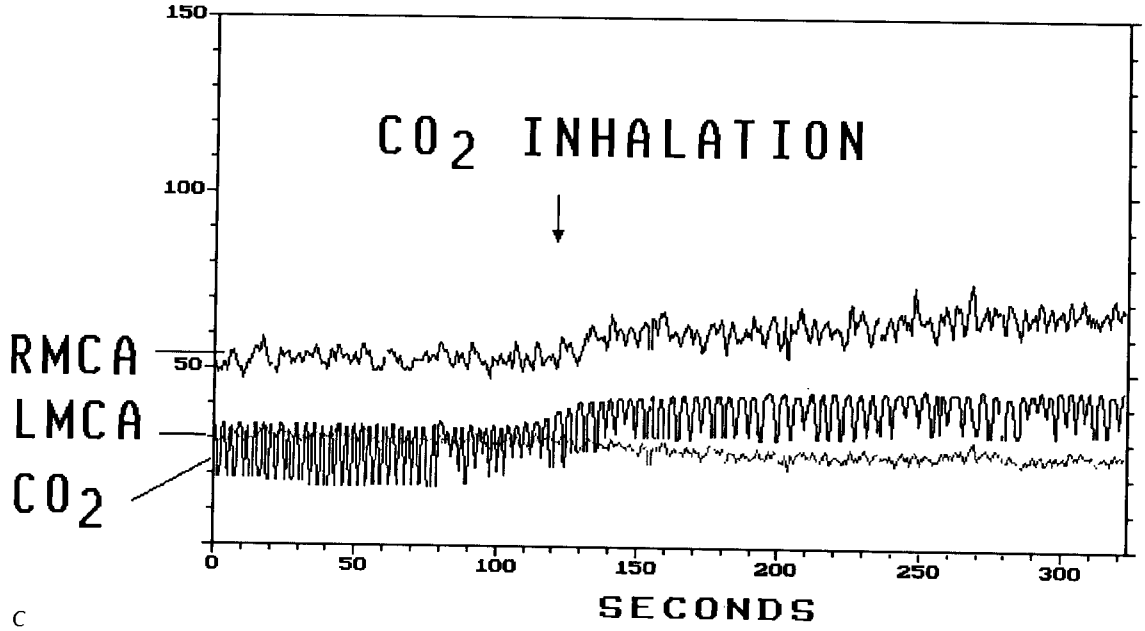



A




B

**Figure 12-6.** Blood flow velocity tracings illustrating normal and abnormal $CO_2$ reactivity. Continuous recordings are made from the middle cerebral arteries bilaterally and the patient is instructed to inhale 6 percent $CO_2$. Following this, the patient is instructed to hyperventilate. The percentage increase of flow velocity with $CO_2$ inhalation (*A*) and percentage decrease with hyperventilation (*B*) are used to indicate the cerebrovascular vasomotor reactivity. As the perfusion pressure to the cerebral circulation is decreased by extracranial or intracranial occlusive disease, the cerebral vasomotor reactivity becomes reduced. *C* and *D* indicate exhausted vasomotor reactivity on the left side with intact vasomotor reactivity on the right in a patient with an intracranial carotid occlusion. *LMCA* = left middle cerebral artery; *RMCA* = right middle cerebral artery.

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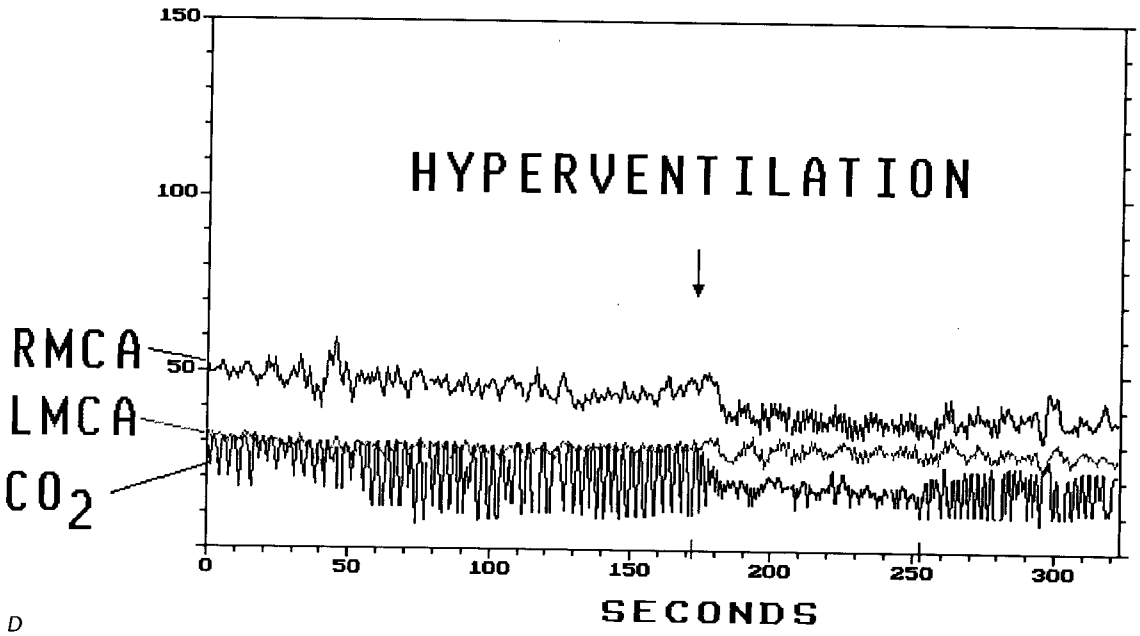



D

Figure 12-6. (*Continued*)

and coworkers[8] found a significantly reduced VMR in those with inadequate collateral vessels in the circle of Willis as compared to the subgroup with a normal circle.

Testing of VMR using TCD can provide valuable physiologic information about individual patients with extracranial occlusive disease or combinations of intracranial and extracranial occlusive disease. This information may be very helpful in establishing effective therapy, especially in patients who have recurrent transient ischemic events or repeated strokes. A carotid occlusion may have a benign natural history in patients who can maintain an adequate hemodynamic reserve through an intact circle of Willis. Other patients with the same lesion may have no hemodynamic reserve owing to inadequate collaterals and may be prone to repeated TIAs or strokes on a hemodynamic basis.

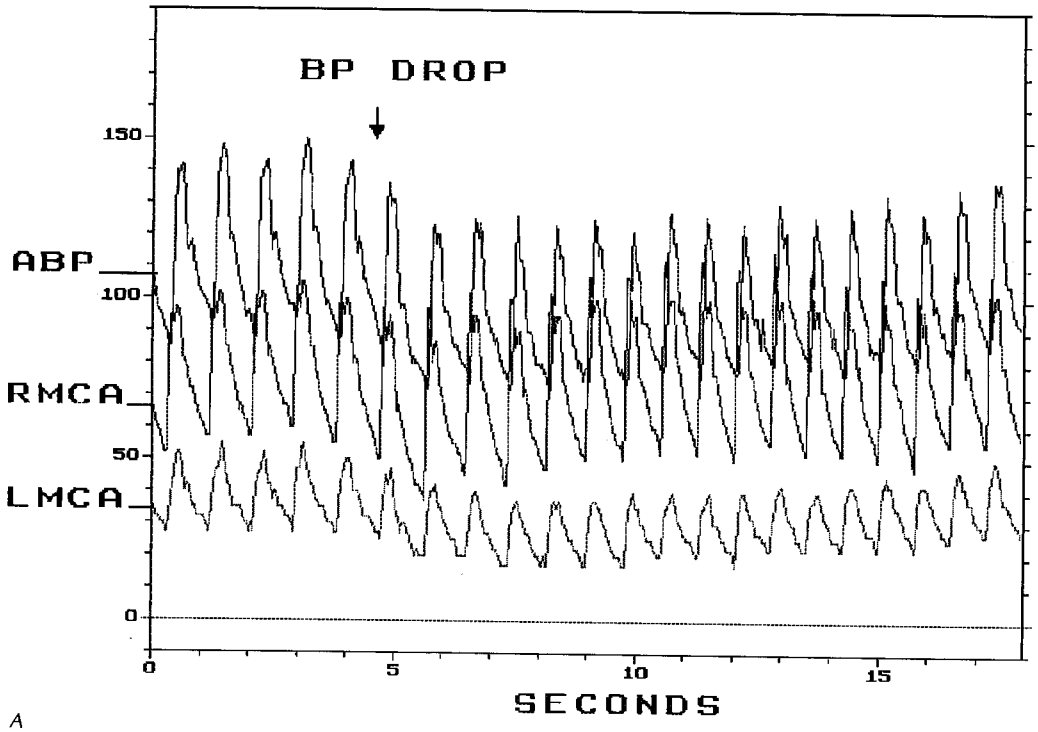
Kleiser and Widder[39] recently reported the results of a study of the natural history of patients with unilateral carotid occlusions who had VMR testing. In a group of 86 patients with unilateral carotid occlusion, 11 patients had exhausted VMR. This subgroup had a high ipsilateral stroke rate (17 percent per year over three years) compared with an ipsilateral stroke rate of 3 percent per year for the entire group (which is comparable to previously published series). Therefore, it appears possible by VMR testing to identify patients with poor hemodynamic reserve who have a high stroke risk and who may benefit from medical or surgical therapy to improve cerebral perfusion.

## CEREBRAL AUTOREGULATION

Cerebral autoregulation refers to the ability of the brain to maintain constant cerebral blood flow despite changes in cerebral perfusion pressure. Lassen documented this phenomenon in humans by measuring CBF at different blood pressures and established that CBF was relatively constant in the normal physiologic range of blood pressures.[33] Below a mean arterial pressure of 50 mmHg CBF begins to fall with further reductions in pressure. The methodology for determining cerebral autoregulation in the past was cumbersome and invasive, requiring radioisotopes for CBF measurement and vasoactive medication to change the blood pressure. It is primarily because of the impracticality of autoregulation measurements and the ease of $CO_2$ reactivity measurements that $CO_2$ reactivity has been more thoroughly investigated in cerebrovascular disease.

Transcranial Doppler can now be used to noninvasively determine autoregulation in the MCA perfusion territories. Aaslid and coworkers[4] have introduced a method in which blood pressure and MCA velocity are monitored noninvasively and the relative change in flow through the MCA in response to a rapid step change in arterial blood pressure is observed.[9] Large thigh cuffs are inflated to suprasystolic pressures and rapidly released to produce a transient drop in blood pressure. Initial reluctance to accept this methodology was based on criticisms[40] subsequently shown to be completely incorrect.[41,42] Recent com-

Figure 12-7. Autoregulation can be assessed with TCD by using the middle cerebral artery velocity as an index of relative change in blood flow in response to a transient drop in blood pressure. *A.* Unfiltered tracing of the arterial blood pressure and right and left middle cerebral artery velocity spectral outline tracings in a patient with no vasomotor reserve on the left side and normal vasomotor reserve on the right assessed by $CO_2$ reactivity. The results of the autoregulation testing indicate impairment in autoregulation on the left and intact autoregulation on the right. *B.* Filtered tracings of the same recording showing the rapid return of the right middle cerebral velocity to the baseline level 10 seconds after the blood pressure drop and no similar return of the middle cerebral velocity on the left side where the blood flow is pressure passive. *LMCA* = left middle cerebral artery; *RMCA* = right middle cerebral artery; *ABP* = arterial blood pressure.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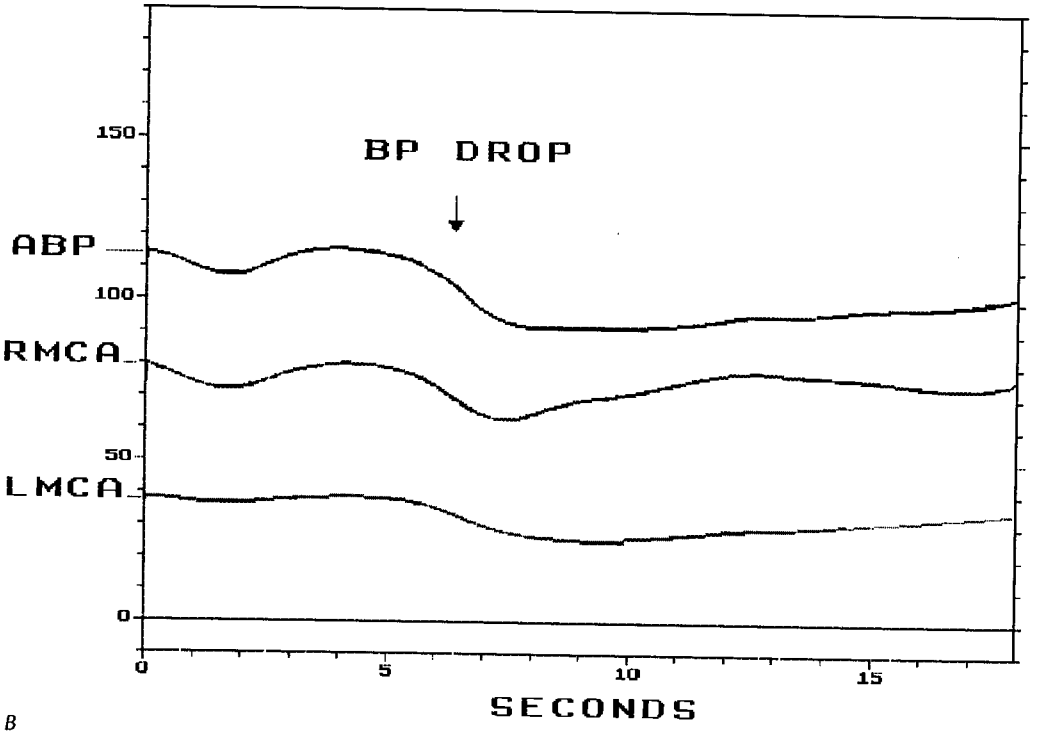
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B

parisons between MCA velocity and internal carotid artery flow have confirmed the validity of this method.[42]

Preliminary clinical testing in patients with cerebrovascular occlusive disease indicates that cerebral autoregulation is absent in patients with severely impaired $CO_2$ reactivity (Fig. 12-7). Noninvasive testing of cerebral autoregulation using TCD may prove useful in the complete hemodynamic evaluation of patients with cerebrovascular occlusive disease.

## INTRACRANIAL EMBOLI

Considerable interest has developed in the ability of TCD to detect intracranial microemboli passing through the basal cerebral vessels. Doppler ultrasound was first used to detect intravascular microemboli in the large vessels of animals exposed to decompression from hyperbaric air.[43] The first examination was performed using 5 MHz continuous wave ultrasound to produce audible, and later visual display signals. Ultrasound was utilized clinically to detect audible intravascular air microemboli during cardiac surgery[44] and during neurosurgical procedures.[45] Subsequent development of spectral analysis has allowed identification of embolic signatures in the spectral tracings (Fig. 12-8).

The ability of TCD to detect intra-arterial microemboli was first recognized by monitoring the MCA velocity during carotid endarterectomy (CEA) and open heart surgery.[46–49] Microemboli composed of air were identified following crossclamp release during CEA and heart operations. However, similar embolic signals were recognized during arterial dissection for CEA before the artery was entered. These microemboli also have been seen in patients with atrial fibrillation and prosthetic heart valves and are now recognized to be composed of formed elements.[11] In vivo animal experiments have confirmed the ability of Doppler ultrasound to detect microparticles

Figure 12-8. Spectral analysis tracing of intracranial arterial microembolus. The intermittent high frequency sound heard on the audio monitor is reflected in the spectral tracing as a discrete high-density signal (*arrow*).

composed of fat, platelet-rich thrombi, clotted blood, atheromatous materials, and air.[50,51]

Clinical evaluations of intracranial as well as extracranial microemboli detection have recently been described. Intracranial microemboli have been detected in patients with atrial fibrillation,[52] prosthetic heart valves,[53] carotid stenosis,[13] fibromuscular dysplasia, arterial dissection, intracranial stenosis,[54] and during such invasive procedures as angiography,[55,56] cerebrovascular and heart surgery.[46,49] Monitoring for intracranial air microemboli after venous injection also has been useful in identifying patients with cardiac and pulmonary defects causing right-to-left circulation shunts.[57]

Most microemboli do not cause overt symptoms. However, multiple microemboli have been associated with impaired neuropsychologic function following open heart surgery.[58] The clinical utility of intracranial emboli monitoring has not yet been fully established. It may serve a useful role in identifying patients at high risk for a poor outcome following stroke,[59] identifying the site of active embolization in the

arterial system in patients with TIAs,[54] and distinguishing embolic versus hemodynamic causes of stroke and TIAs.[13]

## CLINICAL UTILITY OF TCD IN OCCLUSIVE DISEASE

As with any new diagnostic tool that provides information about a particular disease process not previously obtainable, the clinical utility of TCD needs to be established. Part of this process involves the collection of data on new elements of pathophysiology revealed by this technique. It also requires categorizing patients, based on pathophysiology, into new subgroups that may have a different natural history. Studies using this approach are beginning to emerge.[8,39,59] The ability of TCD to disclose new information about patients with occlusive cerebrovascular disease can enable rational treatments and strategies for management. Several cases illustrating these principles follow.

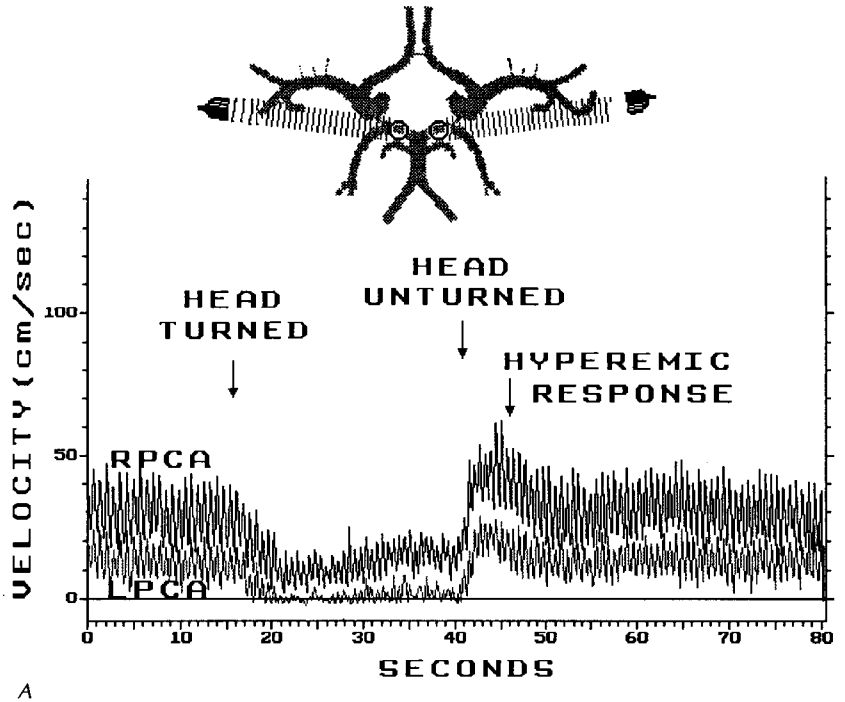
*Case 1* A 65-year-old male with a history of cerebrovascular disease complained of feeling faint upon turning his head to the right. TCD examination of the proximal PCAs revealed normal velocities in a neutral position; however, upon head turning, symptoms were elicited and a marked diminution in the velocity tracings was seen. Upon return to a neutral position, the velocity in both PCAs was increased above the baseline (hyperemia), indicating the occurrence of ischemia (Fig. 12-9). Cerebral angiography revealed an inadequate anterior-to-posterior communication through the circle of Willis (Fig. 12-5*E*) and an occluded left vertebral artery. The right vertebral artery became compressed on head turning owing to cervical spondylosis.

*Case 2* A 35-year-old female presented to the hospital in status epilepticus. Work-up revealed an acute right frontal infarction on MRI. Carotid duplex examination was normal. TCD examination revealed normal velocities in the intracranial vessels; however, frequent emboli were seen in the right MCA. Cerebral angiography demonstrated fibromuscular dysplasia in the high right cervical ICA beyond the range of carotid duplex. The patient was placed on aspirin and had no further symptoms. Emboli monitoring two weeks later, showed no emboli.

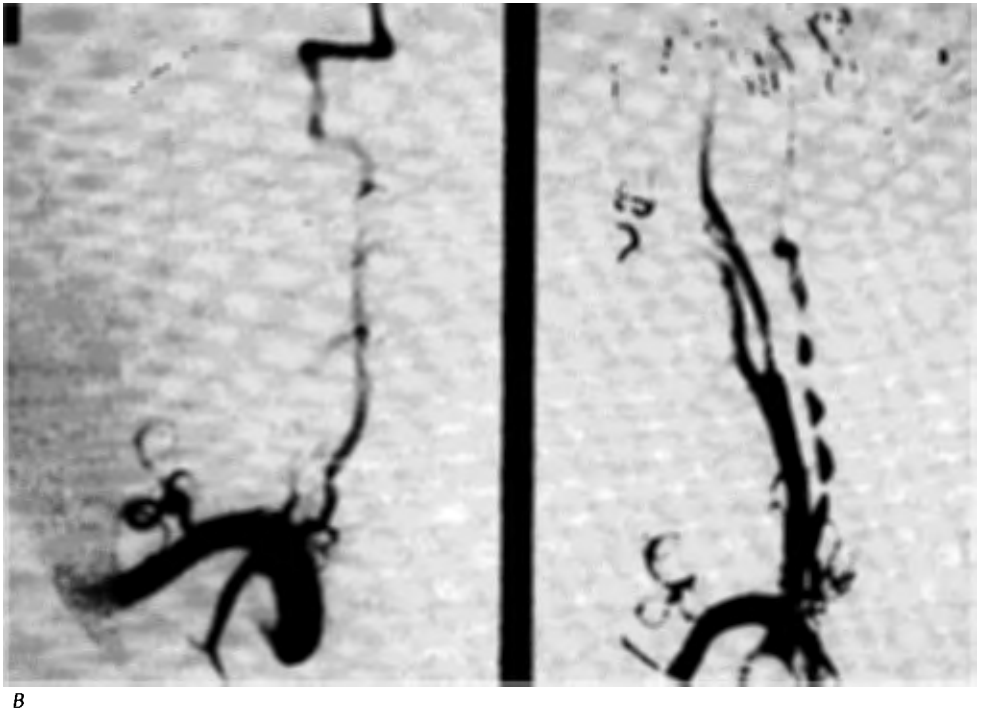
*Case 3* A middle-aged male presented with persistent TIAs following carotid endarterectomy. A CEA had been performed at another institution for TIAs in the hemisphere ipsilateral to a carotid stenosis identified by duplex scanning alone. Postoperatively, the patient continued to have TIAs, and TCD examination revealed emboli in the MCA ipsilateral to the surgery. No emboli were found in the ICA distal to the endarterectomy site. Cerebral angiography revealed resolution of the carotid stenosis and demonstrated an ipsilateral carotid siphon stenosis, presumed to be the source of the emboli. The patient was placed on anticoagulation therapy and the symptoms resolved.

*Case 4* A 53-year-old male was referred with TIAs related to the right hemisphere that were unresponsive to aspirin therapy. A 90 percent stenosis of the right supraclinoid ICA was found, and he was considered for angioplasty. TCD studies revealed normal vasomotor reactivity in both hemispheres with good left-to-right collateral crossover. Emboli were detected in the right MCA. The patient was placed on anticoagulation and had one more TIA, followed by resolution of his symptoms. He was able to avoid angioplasty since he was well compensated hemodynamically above the lesion.

*Case 5* A 30-year-old female had a stroke with onset of aphasia; then her symptoms resolved over one month. She then began having TIAs consisting of right hand numbness and clumsiness four to five times per week for several months, despite aspirin, Persantin, and Ticlopidine therapy. TCD examination revealed a low velocity in the left MCA with no emboli detected. Testing of VMR and autoregulation revealed absent VMR in the left MCA and normal VMR in the right MCA. Autoregulation was similarly absent in the left MCA and normal on the right. MRI showed a small infarct in a watershed zone between the left MCA and ACA distributions. The patient went on to have an extra-


VELOCITY (cm/sec)
100
50
0
HEAD TURNED
HEAD UNTURNED
HYPEREMIC RESPONSE
RPCA
LPCA
0
10
20
30
40
50
60
70
80
SECONDS

*A*



*B*

cranial to intracranial bypass procedure for presumed hemodynamic TIAs.

*Case 6* A 69-year-old male was well until he had a stroke manifesting as a left hemiparesis and dysarthria. He recovered completely but had a subsequent TIA. An angiogram revealed a right internal carotid artery occlusion with retrograde flow through the ophthalmic artery and minimal forward flow through a small right posterior communicating artery. There was no filling of the right MCA from the left carotid system. His circle of Willis resembled that seen in Fig. 12-5*D*. VMR testing revealed severely reduced VMR on the right. He subsequently had a gastrointestinal bleed with hypotension and developed a new stroke manifested as a severe left hemiparesis. He has made a partial recovery. His CT scan is illustrated in Fig. 12-10. He is now being considered for a revascularization procedure.

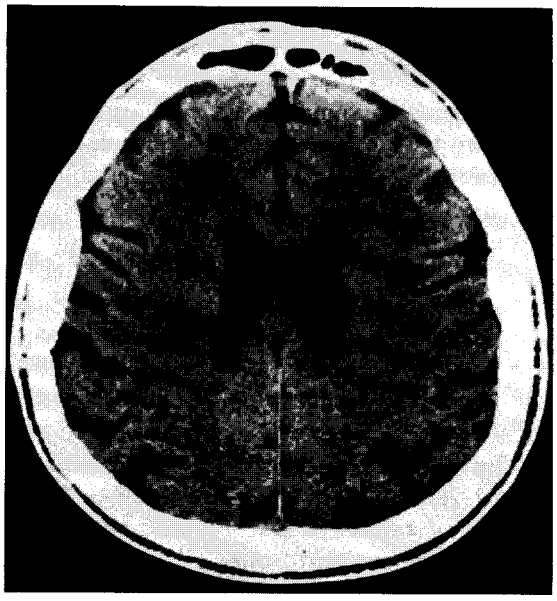


Figure 12-10. This is a typical low flow infarct (*arrow*) seen in the right hemisphere of a patient with severely impaired hemodynamic reserve on VMR testing (Case 6) and inadequate collateral pathways through the circle of Willis.

## MONITORING DURING CAROTID ENDARTERECTOMY

Transcranial Doppler has been used to continuously monitor the blood flow velocity in the MCA trunk during carotid endarterectomy.[59-63] This can be accomplished using a head band or other probe fixation device to attach the probe to the temporal window ipsilateral to the endarterectomy site. Important technical considerations are to be sure that the MCA is the artery being monitored and to devise a system of probe fixation that will not be disturbed during the operative procedure. One drawback of this type of monitoring is that it cannot be used in a small percentage of patients because of temporal hyperostosis. In one recent series, temporal hyperostosis prevented adequate monitoring in 13 percent of 150 carotid endarterectomies.[60]

Intraoperative TCD monitoring can provide information that may be used to avoid surgical complications. Four aspects of TCD monitoring can be of value during carotid endarterectomy: (1) the ability to detect emboli; (2) detection of hypoperfusion during cross-clamping; (3) detection of postoperative thrombosis; and (4) detection of postoperative hyperperfusion. The detection of emboli during endarterectomy was first recognized when loud high frequency signals were heard on the audio output and high density spectral signals were seen

Figure 12-9. *A.* This tracing demonstrates monitoring of both posterior cerebral arteries in a patient with symptoms of cerebrovascular insufficiency on head turning. The velocity tracings diminished markedly with head turning and increased upon return to a neutral position, indicating proximal obstruction. Subsequent cerebral angiography revealed occlusion of the left vertebral artery, compression of the right vertebral artery due to cervical spondylosis, and absent anterior to posterior collateral pathways as seen in Fig. 12-5E. *B.* Angiogram showing vertebral artery in neutral position (left) and with head turned (right). LPCA = left posterior cerebral artery; RPCA = right posterior cerebral artery.

on TCD during cross clamp release. It was assumed that most of these signals represented air entrained in the arterial circulation and had no particular clinical significance. It has subsequently been recognized that formed element emboli were passing into the MCA during dissection of the carotid artery before the circulation was entered. Sporadic emboli are commonly seen after closure of the arteriotomy. However, large numbers of emboli increasing in frequency after the completion of the endarterectomy may alert the surgeon to the possibility of an intimal flap or other technical problems.

The assessment of adequate cerebral perfusion during carotid cross clamping has been a subject of extensive investigation and debate among surgeons performing CEA. Past investigations have led to a more complete understanding of cerebral physiology during carotid cross clamping, and several facts have become clear. The threshold for cerebral infarction depends on both the severity and the duration of cerebral ischemia. Therefore, if the cross clamp time is brief enough, even those patients with severe hypoperfusion may not sustain infarction, whereas patients with prolonged moderate hypoperfusion may sustain permanent infarction. Most patients do not sustain severe hypoperfusion during carotid cross clamping because they are protected by intact collateral pathways from the posterior circulation and from the contralateral carotid circulation. Schneider et al. evaluated these collateral pathways in 50 patients prior to undergoing CEA.[61] During cross-clamping, significantly higher MCA velocities and stump pressures were maintained in those patients who had intact collateral pathways, compared with patients with impaired or absent collateral pathways. There were also fewer ischemic changes on electroencephalography (EEG) in the group with intact collateral pathways.

The goal of the surgeon performing CEA is to avoid cerebral hypoperfusion during cross clamping and also to avoid other complications that can occur during shunt placement. A reasonable strategy utilized by many surgeons is to shunt selectively by only shunting those patients who have hypoperfusion during cross clamping. TCD can be used to monitor the changes in MCA velocity that occur during carotid cross clamping to identify those patients with hypoperfusion. The most useful method for doing this has been to calculate the percentage drop in MCA velocity from a stable baseline preceding the cross clamp maneuver.

Halsey et al. compared regional CBF, TCD, and EEG during CEA.[62] There was a high degree of variability between the changes in blood flow velocity on TCD and changes in CBF. It was concluded that TCD may be a better indicator of flow in the basal vessels supplying the deeper areas of the brain while CBF may be a better indicator of cortical perfusion. Spencer et al. compared MCA velocity changes to carotid stump pressures in response to cross clamping.[63] An exponential curve was established between the two measurements, with the velocity reaching zero at a stump pressure of 15 mmHg. After allowing 10 to 15 seconds following clamping for an autoregulatory adjustment, the percentage decrease in MCA velocity from the baseline was calculated. It was found that an MCA velocity value of 40 percent of the baseline corresponded to a stump pressure of approximately 25 mmHg. In this study, all hypoperfusion-related complications occurred when the MCA velocity fell below 40 percent of the baseline figure.

Halsey has reported the results of a multicenter study using TCD monitoring during CEA.[64] In this large group of patients, shunts were used routinely in some and selectively in others. If the MCA velocity during cross-clamping fell below 15 percent of the baseline value, there was a significantly higher stroke rate in patients who were not shunted. If the

velocity in the MCA remained above 40 percent of the baseline, there was a higher stroke rate in patients who were shunted. The difference in stroke rate between shunted and nonshunted patients was not significantly different if the MCA velocity dropped between 16 and 40 percent of baseline. Each individual surgeon must determine how they will use the information gained from monitoring for hypoperfusion using TCD. However, intraoperative monitoring with TCD may give useful information regarding the level of residual perfusion through the MCA, which can aid the surgeon in the decision making process.

Monitoring of the MCA velocity during CEA may allow the early detection of two other potential complications: postoperative carotid thrombosis and postoperative hyperperfusion. To gain the maximum information from TCD monitoring, the monitoring should continue during the early postoperative period or longer if these complications are suspected. A sudden decrease in MCA velocity in the postoperative period to those levels seen during cross clamping can provide an early warning of postoperative carotid occlusion. Postoperative hyperperfusion is a dangerous complication which is associated with headaches and cerebral edema ipsilateral to the endarterectomy, and may result in intracerebral hemorrhage (Chap. 26).[60,65,66] Steiger detected a more than 100 percent increase in MCA flow velocity compared to preoperative values in eight out of a series of 150 cases.[60] These findings were associated with severe headaches in these eight patients. Ackerstaff et al. reported an average increase in MCA velocity of greater than 150 percent over baseline in four patients who had postoperative intracerebral hemorrhages from a group of 250 carotid endarterectomies.[65] This velocity value was significantly higher than the value in patients who did not sustain intracerebral hemorrhages.

The success of carotid endarterectomy in preventing strokes and TIAs in large populations is highly dependent on maintaining a low complication rate. Monitoring of MCA velocities using TCD may provide additional information that can be used to achieve the lowest complication rate possible.

## CONCLUSIONS

Transcranial Doppler can provide the clinician with information about the pathophysiology of individual patients with cerebrovascular disease not previously obtainable with noninvasive techniques. When properly used, TCD can reliably detect intracranial arterial stenosis as well as evaluate the distal effects of proximal arterial lesions. Hemodynamic effects of extracranial and intracranial vascular disease can be assessed using VMR testing, and autoregulation testing may provide additional information. Natural history studies are emerging which indicate a poor prognosis in untreated patients with absent hemodynamic reserve.[39] The importance of understanding the collateral capacity of each individual patient rather than classifying patients strictly according to arterial lesions is now being recognized. TCD should not be considered as an indirect test to evaluate the pressure drop across a carotid stenosis,[67] but rather as a direct test to evaluate the hemodynamic consequences of all the arterial lesions and the individual collateral capacity on the cerebral arteries distal to the circle of Willis. The use of TCD for detection of cerebral microemboli in patients with TIA and stroke holds promise to provide a better understanding of the pathophysiology of these conditions that may lead to more rational, physiologically based treatments.

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