TRANSCRANIAL DOPPLER ULTRASONOGRAPHY

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BASIC PRINCIPLES OF TRANSCRANIAL DOPPLER ULTRASONOGRAPHY

Transcranial Doppler ultrasonography (TCD) is a method introduced by Aaslid et al[1, 5] to record blood flow velocity in the basal cerebral arteries in humans. Early investigators using ultrasound to measure blood flow concluded that recording from the intracranial arteries would be impossible due to the barriers imposed by the human skull. It was, however, possible to evaluate the cerebral circulation by recording from the carotid arteries in the neck, and this application has been refined extensively and widely used in clinical medicine. The groundwork for the development of transcranial applications was made possible by improvements in Doppler equipment along with the use of a relatively low frequency (2 MHz) and the introduction of spectral analysis and pulsed range-gated Doppler. Initial recordings were made of the middle cerebral artery through the transtemporal window. It was subsequently recognized that a more complete examination of the basal cerebral arteries could be obtained by recording through the orbit via the transorbital route and also through the foramen magnum via the transforaminal route. Utilizing these three windows, extensive examination of the basal cerebral arteries can be accomplished. Details of the examination techniques have been published elsewhere and describe the various methods for obtaining signals from different intracranial arteries.[15] Various techniques are available for identification of the individual intracranial arteries. The most common is the hand-held technique, which utilizes the examiner's knowledge of the vascular anatomy and vascular interrelationships as well as the characteristic signal generated by the various arteries examined.[1, 15] Additional techniques include vessel mapping as well as transcranial color-coded real-time ultrasonography (color-flow) techniques.[5, 10]

Transcranial Doppler study makes use of two important principles to measure pathological changes in the cerebral circulation. First, under conditions of constant flow, the velocity through a vessel will increase in proportion to the decrease in cross-sectional area produced by vessel narrowing. Second, in the absence of any significant changes in vessel diameter, changes in flow will be directly proportional to changes in the average cross-sectional velocity. Changes in the maximal flow velocity (V_{max} or spectral outline) will be proportional to changes in average velocity in the absence of any turbulence or altered flow patterns in the vessel.[6] It is also essential to maintain a fixed probe position in relation to the artery during any calculation of relative flow changes.

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The velocity signal in the basal cranial arteries, particularly in the middle cerebral artery, can therefore be monitored and used to indicate relative flow changes under a variety of circumstances.[57] This information can be used in the intensive care unit setting to assess cerebral reactivity in response to CO_2 changes, blood pressure changes, and changes in intracranial pressure (ICP), as well as during various spontaneous waves in the ICP and in response to certain medications. TCD monitoring can therefore be used to accomplish many of the objectives that previously required more cumbersome techniques for measurement of cerebral blood flow (CBF). Measurement of CBF following head injury has been a subject of intense investigation. After the collection of much data, Langfitt and Obrist[23] defined some of the potential clinical applications for CBF studies as follows:

1. To ensure sufficient CBF to meet metabolic demands of the brain.
2. To aid in predicting clinical outcome.
3. To assess vasoreactivity in the cerebral circulation by testing autoregulation and CO_2 reactivity.
4. To evaluate the effect of various therapies for management of ICP.

Transcranial Doppler monitoring cannot give quantitative blood flow data and, therefore, cannot be used for the first two applications mentioned. The ability to calculate relative blood flow changes in response to CO_2 as well as perfusion pressure changes and the ability to calculate relative blood flow changes to various therapeutic regimens enables TCD to be used for the third and fourth applications mentioned.[42] Advantages over the radioactive xenon CBF method include the fact that TCD provides continuous relative blood flow information, can be performed relatively easily using portable equipment in the intensive care unit, and does not involve the use of radioactive isotopes.

REQUIREMENT FOR EXAMINATIONS AND MONITORING

The development of TCD has been a natural extension of vascular ultrasound. The initial application of TCD to detect cerebral vasospasm following subarachnoid hemorrhage made it of much interest to neurologists and neurosurgeons.[2, 54, 55] The subsequent extended applications of TCD have made it of interest also to anesthesiologists, intensivists, and vascular surgeons. Vascular technology training programs are now including TCD methodology in their curricula. Many vascular laboratories in the United States now offer TCD as a clinical service. We established a transcranial Doppler laboratory in the Department of Neurological Surgery at the University of Washington in 1986 and have found it essential to have highly skilled personnel with a background in vascular ultrasound who are trained to perform the examinations. TCD is a difficult vascular examination and requires training and practice. Maintenance of a high-quality laboratory requires a high volume of examinations as well as constant feedback in the form of correlation with clinical condition and radiographic studies including angiography.

Some of the requirements for obtaining continuous monitoring tracings were incorporated into the first transcranial Doppler design by Aaslid.[5] These features included a monitoring headband to ensure probe stability as well as the ability to sample spectral information and the spectral outline as analog information. A variety of devices can be used to record

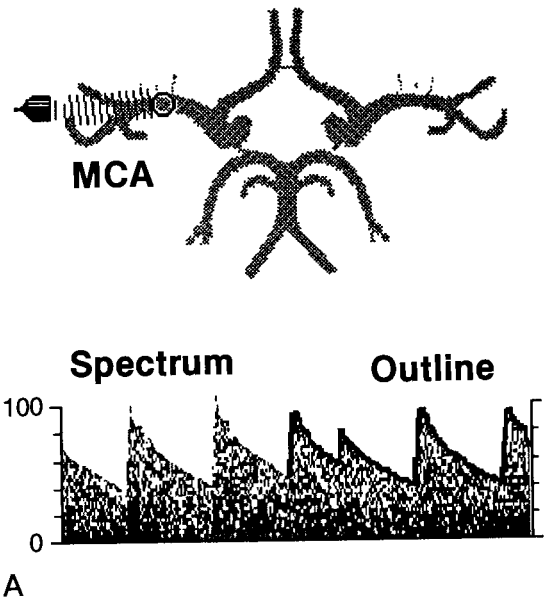

Figure 1A. Recording from the middle cerebral artery that yields a spectral tracing. The spectral tracing can then be assigned a spectral outline that can be used for monitoring relative changes in blood flow.

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continuously either the spectral signal or the analog signal from the spectral outline.[30, 42] Different recording devices are needed for various applications. For example, when performing monitoring of emboli, it is most useful to record the entire spectral signal as well as the audio portion using a video recorder. To record relative blood flow changes, the spectral outline which can be optionally assigned to the spectral signal can be recorded using a variety of devices including magnetic tape and strip charts or by converting it to a

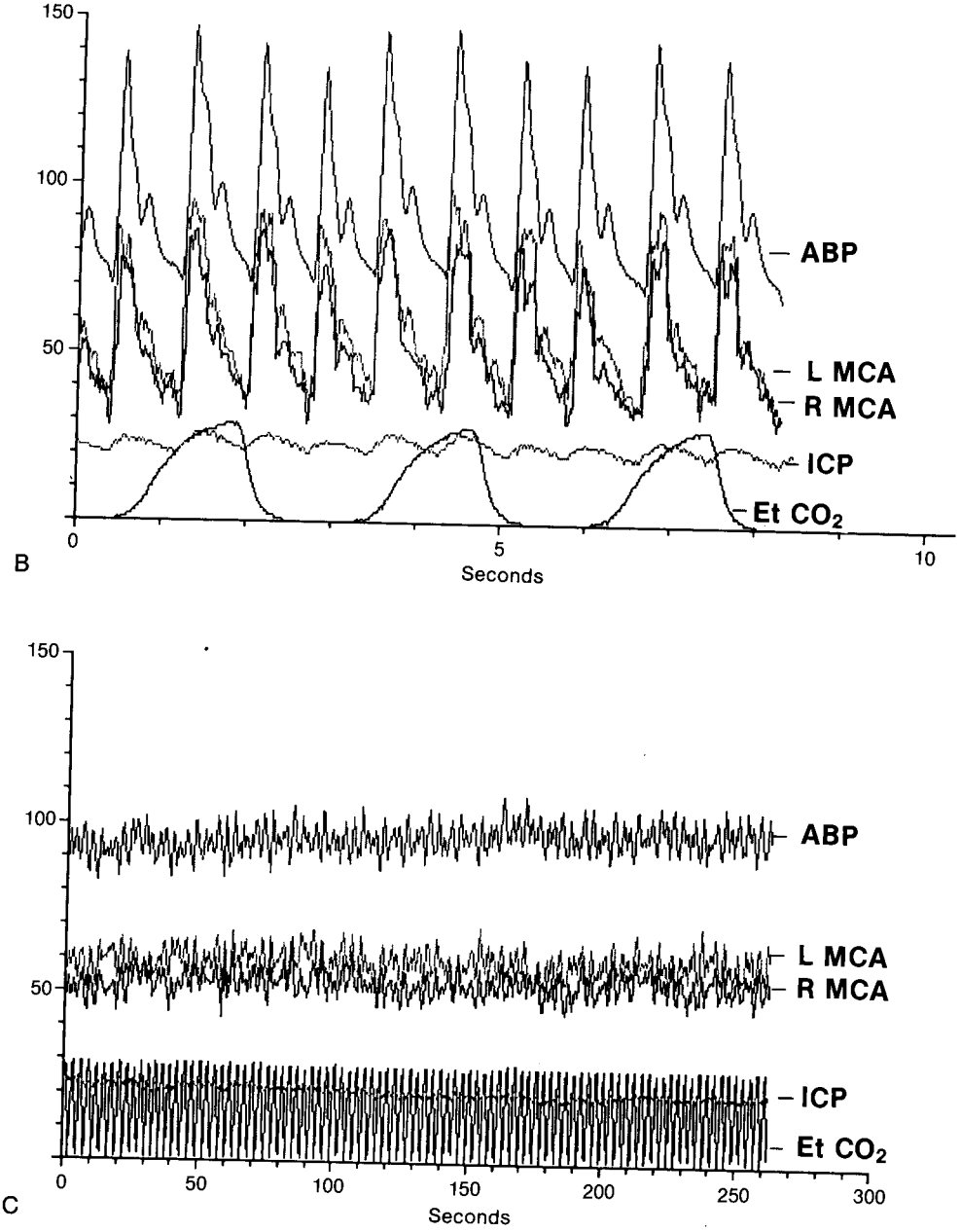

Figure 1*B*. Simultaneous recordings of arterial blood pressure, bilateral middle cerebral artery velocity, intracranial pressure, and end tidal CO_2 are illustrated. ***C.*** Recording of similar signals as in *B* as a longer trend. ABP = arterial blood pressure; MCA = middle cerebral artery; LMCA = left middle cerebral artery; RMCA = right middle cerebral artery; ICP = intracranial pressure; $ETCO_2$ = end tidal CO_2.

digital signal and using computerized storage devices. The last option has been refined and is now being incorporated into TCD equipment that offers software for continuous monitoring. Computerized storage of digitized signals offers trend analyses as well as software to analyze various short intervals that are commonly used for reactivity testing. The development of multi-channel Doppler ultrasonography has allowed continuous recording of multiple channels, most commonly, both middle cerebral arteries. This feature allows simultaneous testing of both hemispheres during reactivity testing (Fig. 1).

PHYSIOLOGIC FACTORS AFFECTING BLOOD FLOW VELOCITY

Normative data on blood flow velocities in the basal intracranial arteries of humans have been collected by various investigators and summarized by Adams et al.[7] Some of the variables affecting velocities have included age, gender, hematocrit, and metabolic factors such as CO_2 and oxygen concentration. Physiologic factors include physiologic blood flow fluctuations as well as ICP, blood pressure, and the state of cerebral autoregulation. Table 1 summarizes some of the factors that may have a role in the intensive care unit setting and that may have an impact on TCD velocity values.

Table 1. CONDITIONS IN NEUROINTENSIVE CARE INFLUENCING BLOOD FLOW VELOCITY

Condition	Effect on Flow Velocity
↑ Age	↓
↓ Hematocrit	↑
↓ Cerebral metabolism	↓
↓ PCO_2	↓
↓ O_2	↑
↑ Intracranial pressure	No change between CPP 50–150 with intact autoregulation
	↓ Below CPP of 50
	↓ With abolished autoregulation
Mannitol administration	↑ Greater increase with impaired autoregulation
Barbiturate administration	↓
Spontaneous fluctuations, B waves	Velocity fluctuates synchronously with ICP B waves
A waves	↓ At peak of wave

↑ = increase; ↓ = decrease; PCO_2 = partial pressure of carbon dioxide; O_2 = oxygen; CPP = cerebral perfusion pressure; ICP = intracranial pressure.

VASOREACTIVITY

The ability of the cerebral circulation to undergo vasoconstriction and vasodilatation in response to various stimuli has been termed *vasoreactivity*. Many of the currently used treatments for lowering ICP, such as hyperventilation, mannitol therapy, and barbiturate therapy, rely on intact vasoreactivity for their action.[11, 12, 32–35, 45] Conditions leading to hospitalization in the neurosurgical intensive care unit such as subarachnoid hemorrhage, intracranial hemorrhage, or head injury can impair vasoreactivity and therefore make it difficult to control ICP. By monitoring relative changes in CBF velocity, TCD can be used to evaluate CO_2 reactivity, autoregulation, and responses to various medications.[16, 18, 30, 37, 42–44]

Transcranial Doppler ultrasonography can be used to calculate CO_2 reactivity in the intensive care unit patient by monitoring the blood flow velocity in the middle cerebral arteries while inducing a brief period of hypocapnia (usually 2 to 3 minutes by manual hyperventilation with a ventilation bag). During changes in CO_2 concentration, major changes in cerebrovascular resistance are produced at the microcirculatory level, and there is little or no change in the diameter of the main trunk of the middle cerebral artery.[17, 21] This has been documented by several studies in humans,[17, 21] and CO_2 reactivity measured using TCD correlates well with CO_2 reactivity calculated with other blood flow methods.[9, 57] The relative change in velocity through the middle cerebral artery in response to CO_2 changes is calculated on a percentage basis, and this appears to correlate with relative changes in CBF.[9, 57] The reactivity is expressed as percent change in CBF per mm CO_2. Normal CO_2 reactivity in humans is approximately 3% change per mm CO_2.[35] There are three potential uses of calculating CO_2 reactivity in intensive care patients.

First, if hyperventilation is to be used for ICP control, knowledge of the CO_2 reactivity may be helpful. Hyperventilation for ICP control has been the subject of recent controversy. Hyperventilation in the acute setting with head injury as well as other conditions leading to high ICP has been standard therapy in most

emergency rooms and trauma centers. More prolonged hyperventilation for ICP control may be unsound on a theoretical basis, and, in addition, there is evidence to suggest that it is not of benefit in head-injured patients.[36] Muizelaar et al[34] have shown that the vasoconstriction induced by acute hypocapnia is usually reversed within 24 hours, and, therefore, the reduction in ICP by this mechanism is not sustained. A recent prospective study showed that treatment with hyperventilation for 5 days in head-injured patients was not found to be beneficial.[36] Shorter periods of hyperventilation in the intensive care unit setting may be appropriate for transport of patients or for lowering ICP on an acute basis. If hyperventilation is to be considered for these purposes, it may be beneficial to know the CO_2 reactivity in advance. In severe head injury, CO_2 reactivity can be abolished or severely impaired,[11, 12, 13] and it would not be useful to employ hyperventilation in this subset of patients.

Second, CO_2 reactivity may correlate with prognosis in head-injured patients as well as other patients with neurosurgical conditions.[13, 14, 51, 52] Previous studies using CBF methods have shown that CO_2 reactivity can become impaired or absent in patients with severe brain damage, and CO_2 reactivity has been correlated with outcome.[52] Recent studies using TCD for the same purpose have confirmed this relationship.[18, 43, 51]

Third, CO_2 reactivity may correlate with the response to barbiturate therapy and may be useful in predicting the effectiveness of this therapy.[45]

Cerebral autoregulation refers to the ability of the cerebral circulation to maintain a constant blood flow during changes in cerebral perfusion pressure (CPP).[24, 48] This mechanism appears to be different from CO_2 reactivity and is believed to operate by a separate control mechanism. Cerebral autoregulation can be evaluated in head-injured patients using several different CBF methods. Most of the data on impaired autoregulation following head injury has been obtained using the xenon CBF method, which employs radioactive xenon.[13, 33, 47] More recently, TCD has been utilized to evaluate cerebral autoregulation.[3, 16, 37, 44] Several methods to measure autoregulation have been described, including the observation of velocity changes in response to spontaneous blood pressure changes,[37, 42] induced blood pressure changes,[3, 4, 44] or transient reduction in local perfusion pressure by carotid compression.[16] All of these methods make use of the principle that relative velocity changes through the middle cerebral artery reflect relative flow changes through this vessel in response to changing CPP.[4, 26, 44] Aaslid et al[3] introduced a method to lower the blood pressure transiently by rapidly deflating bilateral thigh cuffs in observing the blood flow velocity response to rapid step change in arterial blood pressure (Fig. 2). Despite concerns to the contrary,[22] the validity of this method has been confirmed experimentally in several groups of human subjects.[4, 44] The evaluation of cerebral autoregulation following head injury may have several clinical applications.

1. Pressure autoregulation may have implications in the ability to control ICP adequately using various maneuvers. Muizelaar et al[33] have shown that mannitol is less effective in reducing ICP when cerebral autoregulation is impaired.
2. Increasing arterial blood pressure to improve CPP results in reduced ICP if the autoregulation is intact and may increase ICP if autoregulation is defective.[35]
3. It may be useful to identify patients with absent autoregulation to prevent elevated blood pressures, which may aggravate edema and cause secondary hemorrhages. This also may help the clinician be more vigilant in preventing hypotension, which may be induced by secondary surgical procedures or other preventable causes.[53]
4. The effectiveness of strategies to improve autoregulation, such as hyperventilation, can be assessed.[59]

EVALUATION OF VASOSPASM

One of the original applications of TCD was in the detection of cerebral vasospasm.[2] Subsequently, many studies have confirmed its validity and usefulness in detecting vasospasm following subarachnoid hemorrhage.[19, 27, 54, 55] In addition, vasospasm following head trauma has been recognized to be a clinical entity.[25, 31] Vasospasm can cause deterioration and infarction following closed head injury.[19, 42] Vasospasm following subarachnoid hemorrhage most commonly affects the

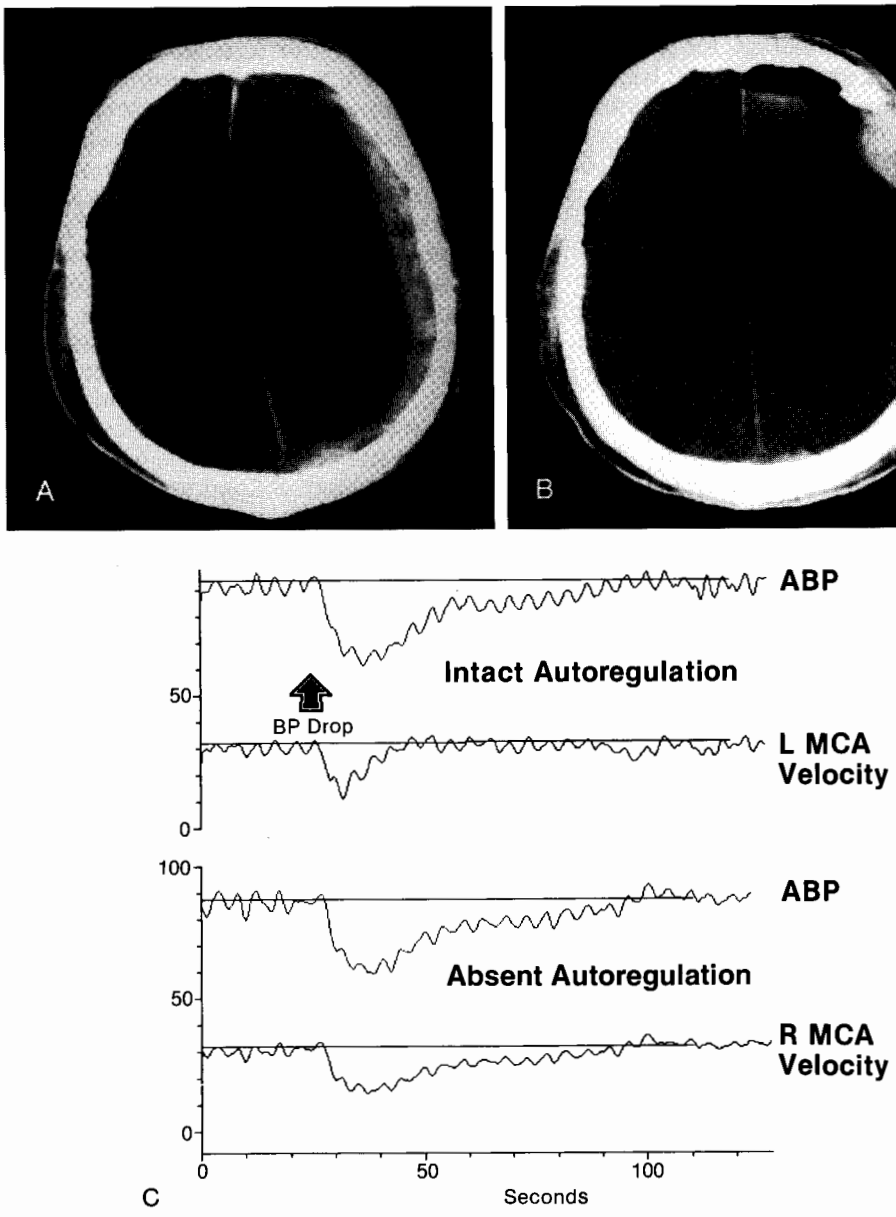

Figure 2A. CT scan of a patient with an acute subdural hematoma. Note early low density changes in the right hemisphere. *B*, Postoperative CT scan 1 day later showing decompression of the subdural hematoma with some residual low density changes in the right hemisphere. *C*, Demonstration of cerebral autoregulation on the left and right side assessed by using rapid induced blood pressure drops. Upper tracing illustrates intact autoregulation on the left side. Lower tracing illustrates completely abolished autoregulation on the right side despite an adequate cerebral perfusion pressure. ABP = arterial blood pressure; LMCA = left side middle cerebral artery; RMCA = right side middle cerebral artery.

basal cerebral vessels.[40] TCD is most useful in detecting vasospasm of the middle cerebral artery and distal internal carotid artery, but it is also useful in evaluating other intracranial arteries. Correlations between angiographic narrowing of cerebral vessels and elevation of TCD velocities have revealed close correlations.[4, 27, 39, 56] Sloan et al[56] revealed an 84% sensitivity and 89% specificity when comparing angiography with TCD in the middle cere-

bral artery. Lindegaard et al[27] have reported a close correlation between elevated velocities and angiographic vasospasm. Their study revealed that TCD had a sensitivity of 94% and a specificity of 90% for detecting angiographic spasm of the middle cerebral artery. Advantages of intermittent monitoring of vasospasm using TCD include the ability to follow the development and resolution of the spasm by repeated examinations. Knowledge of the time course of the vasospasm can be helpful in determining the risk of delayed ischemic neurologic deficit.[19] Vasospasm following subarachnoid hemorrhage may affect the distal cerebral vasculature selectively in certain isolated cases. Isolated distal vasospasm following subarachnoid hemorrhage causing neurologic deficit is uncommon, however,[40] and frequently is associated with distally located blood on the original CT scan.

When using TCD to evaluate head-injured patients for vasospasm, it is recommended that velocity recordings also be obtained from the distal internal carotid artery in the neck as described by Aaslid et al[4] and Lindegaard et al.[27] By constructing a ratio of the recordings in the middle cerebral artery versus the internal carotid artery, velocity correlations can be made for hyperemia, which is common in head-injured patients. Several studies have found this method useful in detecting vasospasm in head-injured patients.[31, 58]

INTRACRANIAL PRESSURE

Transcranial Doppler monitoring can be used to reflect various hemodynamic changes in the cerebral circulation that occur with changes in ICP. Lundberg[28] published an extensive review of his initial observations using ICP monitoring in humans. Characteristic fluctuations occurred in the ICP, and several waves were regularly observed in neurosurgical patients. Lundberg A waves or plateau waves are characterized by a sudden increase in ICP that may last from several minutes up to 20 minutes followed by an abrupt decline. Subsequent investigators have documented that during Lundberg A waves or plateau waves, there is a marked increase in cerebral blood volume as well as a decrease in CBF.[29, 49] It is believed that these waves result from an instability in the cerebral vascular control mechanism that leads to a positive feedback cycle under conditions of reduced intracranial compliance.[46, 50] Cerebral vasodilatation recorded during Lundberg A waves reveals a marked decrease in velocity and increase in pulsatility index (systolic

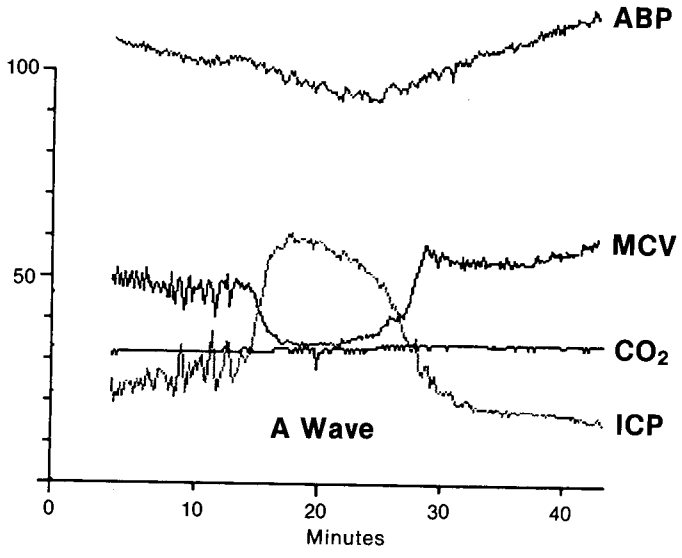

Figure 3. Illustration of multimodality recording of an intracranial pressure A wave showing marked increase in intracranial pressure and reduction in middle cerebral velocity during the A wave. ABP = arterial blood pressure; MCV = middle cerebral velocity; ICP = intracranial pressure.

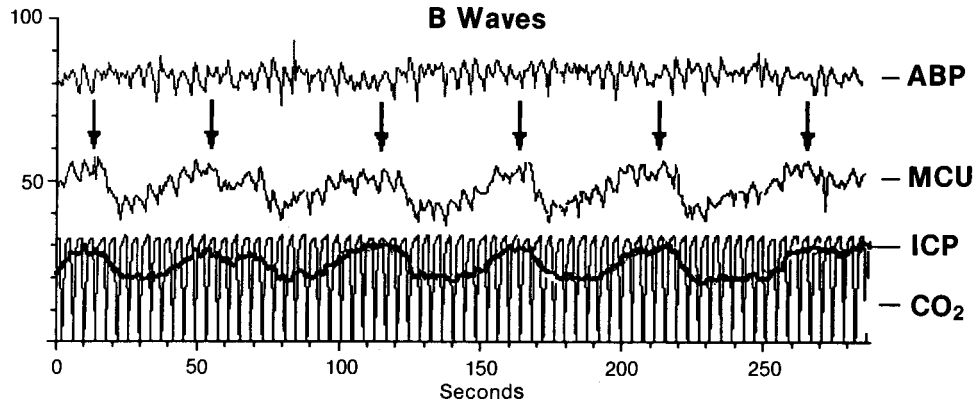

Figure 4. Illustration of multimodality recording during B waves indicating synchronous fluctuations of the middle cerebral velocity with intracranial pressure B waves. Note that there are no significant changes in end tidal CO_2 in this ventilated patient and no significant changes in arterial blood pressure. ABP = arterial blood pressure; MCV = middle cerebral velocity; ICP = intracranial pressure.

velocity − diastolic velocity/mean velocity) during the peak of the wave (Fig. 3). The most likely explanation is that the middle cerebral velocity is reflecting a decrease in CBF through the middle cerebral trunk. Following the cessation of the wave, a hyperemic phase can often be seen, characterized by an increase in velocity above the values recorded immediately preceding the wave. Lundberg also described smaller amplitude periodic fluctuations in the ICP that usually occurred at a frequency between 0.5 and 2 per minute, which he termed *B waves*.[28] B waves have been observed in conditions associated with reduced intracranial compliance and are believed to be the result of vasomotor waves of the small regulating vessels.[8, 41] We observed synchronous velocity fluctuations in the middle cerebral artery that were in phase with the ICP B waves in a series of head-injured patients[41] (Fig. 4). Velocity waves of similar frequency also were present in a cohort of

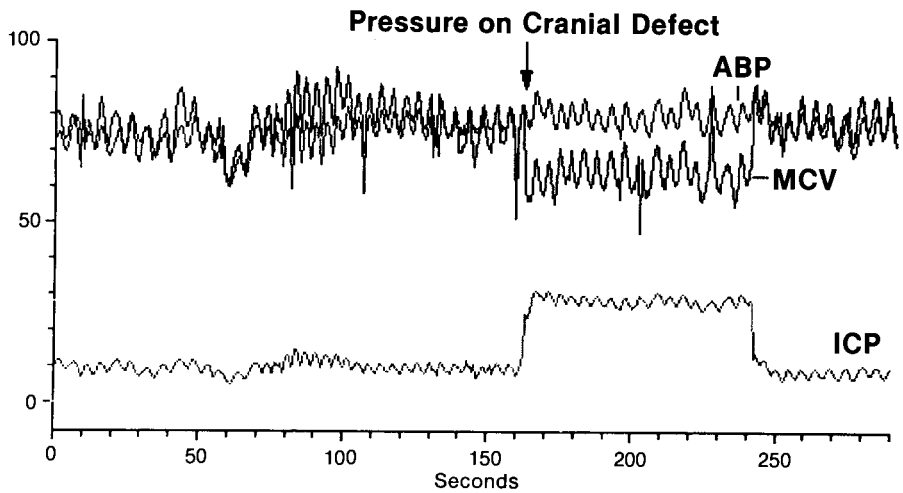

Figure 5. Illustration of the effect of increasing intracranial pressure (decreased cerebral perfusion pressure) on the middle cerebral artery velocity in a patient with impaired autoregulation. Note the concordance of the arterial blood pressure tracing and middle cerebral velocity tracing previous to the test. There is a marked decrease in middle cerebral velocity induced by the increase in intracranial pressure. ABP = arterial blood pressure; MCV = middle cerebral velocity; ICP = intracranial pressure.

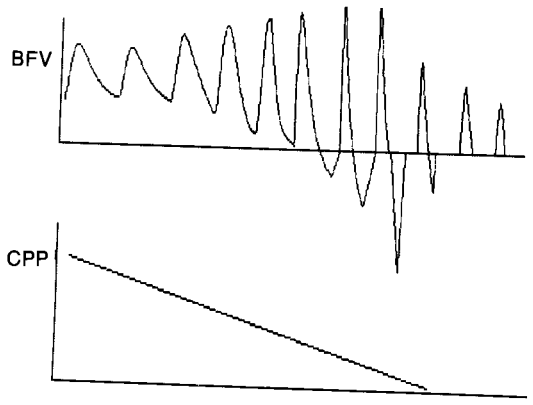

Figure 6. Illustration of the effect of decreasing cerebral perfusion pressure on the middle cerebral artery velocity waveform. Note that with progressive decreases in cerebral perfusion pressure, a marked decrease in diastolic velocity occurs, as does a slight increase in systolic velocity. With progressive decreases in cerebral perfusion pressure, the diastolic velocity becomes reversed and progresses to an oscillating pattern. With further compromise of the circulation, only small systolic peaks are eventually seen which indicate a very short burst of antegrade movement of blood in the vessel in systole. BFV = blood flow velocity; CPP = cerebral perfusion pressure.

normal volunteers, indicating that they may be a common phenomenon. It appears that the B waves in the ICP associated with velocity fluctuations usually become amplified in the ICP tracing in states of reduced intracranial compliance.[41]

ALTERATIONS IN VELOCITY WITH INCREASED INTRACRANIAL PRESSURE

Characteristic changes in the velocity in the middle cerebral artery have been recorded with increased ICP.[20] The changes seen will be dependent, in part, on the level of the CPP and also the state of the cerebral autoregulation. In patients with intact cerebral autoregulation, increases in ICP will cause an increase in the pulsatility index and no change in the mean flow velocity if the CPP remains in the autoregulatory range (50 to 150 mm Hg). Further increases in ICP which reduce the CPP below the range of autoregulation will cause a further increase in pulsatility index as well as a decrease in mean velocity. In patients with absent autoregulation, any decrease in

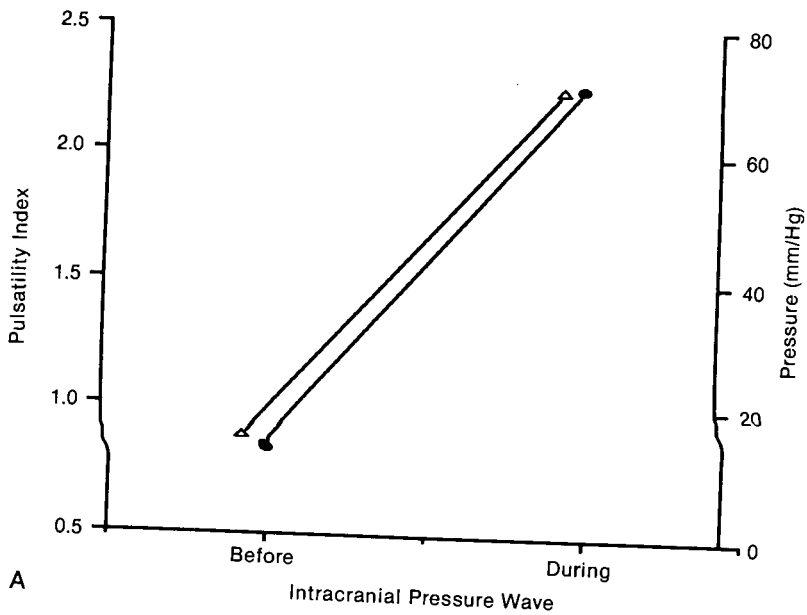

Figure 7A. This figure indicates the increase in pulsatility index seen with marked increases in intracranial pressure as seen during an intracranial pressure A wave. Note the marked increase in pulsatility index seen with increases in intracranial pressure.

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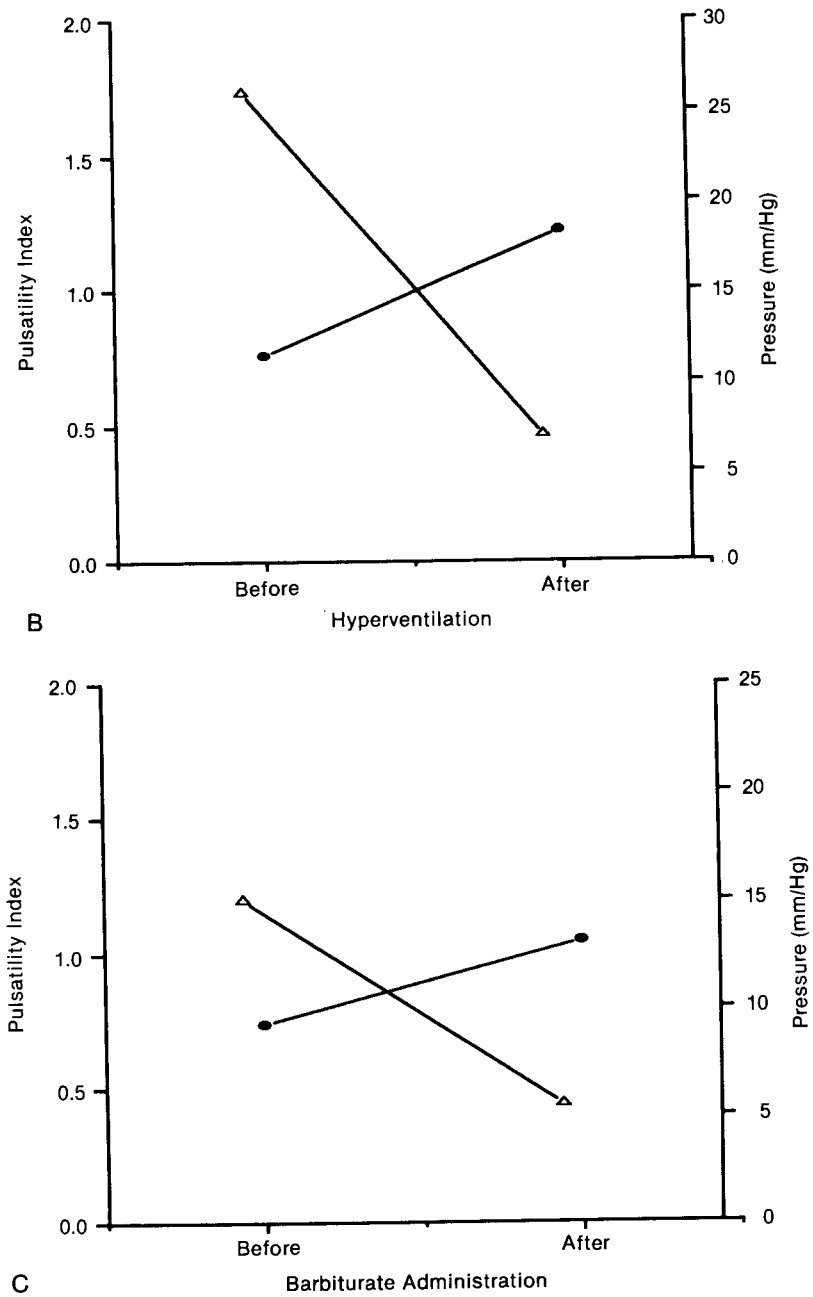

Figures 7*B* and 7*C*. Effect of hyperventilation in barbiturate administration on pulsatility index and intracranial pressure. *B*, After hyperventilation, there is a marked increase in pulsatility index; however, there is a decrease in intracranial pressure in contrast with the response seen in Figure 7*A*. *C*, Increase in pulsatility index seen after barbiturate administration and simultaneous decrease in intracranial pressure. B and C illustrate the effect of increased vascular tone induced by intrinsic vascular factors which increase the pulsatility index and decrease intracranial pressure. These figures demonstrate that pulsatility index alone is a nonspecific indicator of increased intracranial pressure and cannot be used to reliably predict ICP. Triangles = intracranial pressure; ovals = pulsatility index.

CPP will decrease the velocity in the middle cerebral artery (Fig. 5).

Characteristic changes in the velocity waveform have been described in patients who have progressed to brain death, usually from conditions which cause marked increases in ICP.[20] These initial changes are characterized by marked increases in the pulsatility index, with a decrease in diastolic velocity of the velocity waveform. The diastolic velocity then reaches zero, and, subsequently, the flow of velocity becomes reversed in diastole, eventually progressing to an oscillating waveform with a pendular flow and finally to a pattern characterized by small sharp systolic peaks. Finally, no velocity recording can be obtained when the blood fails to fill the basilar intracranial arteries (Fig. 6). These characteristic changes have been correlated with cerebral angiography as well as with radioisotope blood flow measurements.[20, 38] Recognition of these characteristic patterns can be useful in identifying patients who have progressed to brain death.

Changes in pulsatility alone, however, cannot be used to predict ICP. The pulsatility index is an attempt to evaluate the resistance in the distal cerebral vessels and increases with progressive obstruction to blood flow. The pulsatility index can be unreliable, however, due to the fact that it can be very heavily influenced by cardiac factors and can change dramatically due to changes in contractility with no change in the cerebrovascular resistance.[6] A more important confounding factor is that the pulsatility index can be increased by increased vascular resistance due to increased vascular tone of the cerebral vessels produced by vasoconstriction. It also can increase by increased vascular resistance due to extrinsic compression of the vessels as seen in high ICP. For this reason, increases in pulsatility index alone are nonspecific and are not necessarily indicative of high ICP. One of the causes of increased vascular resistance in head-injured patients is hyperventilation. Another cause of increased vascular resistance is low cerebral metabolism, which can occur in head-injured patients and also following the administration of barbiturates. Both hyperventilation and barbiturate administration increase the pulsatility index and decrease ICP. The pulsatility index is therefore nonspecific and cannot be used to predict ICP in head-injured patients unless the ICP is at extremely high levels. Figure 7 shows an example of the change in the pulsatility index that can be affected by an increase in ICP, hyperventilation, and barbiturate administration. Future work will concentrate on the relationship of the vascular tone and critical closing pressure of the cerebral vessels to ICP.[6] An index derived from these measurements may be much more specific in predicting levels of ICP.

SUMMARY

Transcranial Doppler ultrasonography is an extremely useful adjunct in neurosurgical intensive care. Continuous improvements in TCD equipment as well as computer software have improved examination success and also vessel identification. Recent expanding applications of TCD have also allowed the study of disorders of control of the cerebral circulation. TCD can be used to detect vessel narrowing from a variety of causes, including vasospasm, and also can be used to detect cerebral emboli and to evaluate CO_2 reactivity, autoregulation, and the response to certain medications, as well as to indicate progressive obstruction of the cerebral circulation as seen in conditions leading to brain death. In the future, TCD may offer the ability to estimate the ICP using noninvasive means by evaluating velocity in the middle cerebral artery and arterial blood pressure tracings. The noninvasive determination of cerebral autoregulation may be useful in evaluating strategies to improve cerebral autoregulation as well as aid in the optimal management of ICP control and preservation of optimal cerebral circulation.

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