Advances in monitoring technology, as presented elsewhere in this volume, have also occurred in monitoring to the brain and spinal cord. These techniques have created the opportunity to explore function and prognosis in patients who otherwise are unable to participate in a neurologic examination. This chapter overviews the anatomy, technology, and applications of several of these techniques.

Before starting, it is important to mention that, in general, these techniques are not a replacement for the neurologic examination. The complexity and breadth of examination possible with awake testing cannot be matched by these techniques. Furthermore, the clinical examination can be more sensitive than these tests. For example, clinical function becomes abnormal at reduced cerebral blood flow (approximately 25 mL/min per 100 g) above that which causes alteration in electrophysiological monitors.

Each of these monitors has a variety of uses depending on the specific method of monitoring and the specific neural tracts or tissue assessed. Although these methods can detect abnormalities, there are often indistinct thresholds for when changes correlate to clinical changes or prognostication of injury. Nevertheless, these techniques have found substantial application in the care of neurosurgical patients in whom the information gathered can enhance treatment decisions and evaluate the effectiveness of management approaches.

Electroencephalograph

The electroencephalogram (EEG) is produced by the spontaneous electrical activity of excitatory and inhibitory synapses in the superficial
(pyramidal) layers of the cerebral cortex. These potentials last only 20 to 30 ms and are small; the activity recorded at an individual scalp electrode represents the synaptic activity within 2 to 2.5 cm from the recording electrode. This local activity can be from intrinsic activity of the local cortex, or it could be the result of the influence of other neural regions (most notably the pacemaker-like influence of deeper structures on the background rhythm).

The EEG is recorded from scalp electrodes by amplifying the electrical activity in a pair of scalp electrodes amplified through a differential amplifier, and noise in a third, “ground” electrode is removed by common mode rejection. Filtering out low- and high-frequency activity which is not within the EEG range (0.5–30 Hz) allows further signal improvement. The resulting signal is then displayed visually on a screen or on paper as a plot of amplitude versus time.

Because each electrode assesses only a small region of cortex, a diagnostic EEG is usually conducted with a large number of electrodes so that recording pairs allow evaluation of the entire cerebral cortex. The exact location of the electrodes has been coded by the International 10–20 system. These locations reliably place electrodes over different anatomic regions of the brain. For intraoperative evaluation, the recording pairs could be limited to the specific regions of interest. For example, for mapping of a seizure focus before resection, a large number of closely spaced electrodes can be placed over the cortex where the seizure focus occurs. For intracranial aneurysm clipping, electrodes can be placed over the vascular territory placed at risk by the clipping. However, for extracranial vascular surgery, symmetrically spaced leads allow differentiation between ischemia and deep anesthesia by the evaluation of symmetry. Hence, carotid endarterectomy monitoring might use symmetrically placed electrode pairs over the distributions of the right and left anterior, middle and posterior cerebral arteries.

Traditional methods of EEG analysis involve visual inspection of the tracings. Frequency content, amplitude, patterns of activity, and relationship of activity between channels are a few of the factors in analysis. Several rhythms or patterns of activity have been identified, notably spike and wave activity that forms the basis of seizure detection during operative or intensive care monitoring. The basic frequency content and its symmetry about the midline forms an important assessment. Beta frequencies (13–30 Hz) are fast frequencies typical of a normal subject who is wake and alert. Here the EEG appears disorganized without any basic rhythm (as if each portion of the brain is “doing its own thing”). The alpha frequencies (8–12 Hz) are typical of a patient who is relaxed and has his or her eyes closed. Here the EEG shows an underlying rhythm as if a pacemaker in the thalamus is driving the cortex. A predominance of alpha rhythm has been used for biofeedback and is also typical of the sedated or lightly anesthetized patient. Slower EEG frequencies in the theta (4–7 Hz)
or delta range (0–3 Hz) are seen during sleep but are usually considered abnormal when awake. In the anesthetized subject, slow frequencies and low amplitude could be the result of drug effects (such as deep anesthesia) because synaptic function is chemically impaired.

Because of the basic role of frequency and amplitude, computerized EEG analysis has been used to follow the trends of important variables and (notably amplitude, topographic distribution, and frequency content). The most common method of analysis is based on the mathematical technique of Fourier series analysis. When this is used, a smoothed x-y plot can be drawn that shows the relative amplitude at each of the component frequencies (EEG power can also be plotted vs. frequency). A useful variation of this plot is the compressed spectral array (CSA), in which the effect of time is shown by stacking these x-y plots in a third dimension.

The effects of anesthesia on the EEG are well known and form the basis of a sequential change in amplitude, frequency, and distribution. Unfortunately, these changes are drug-dependent, so use of the EEG as a guide to the depth of anesthesia has been delayed until recent methods of computerized processing. These methods have focused on developing a dimensionless index between 0 and 100, which represents the depth of sedation.

In addition to anesthesia, the EEG is affected by a large number of physiological variables; a typical response is slowing of frequency when neuronal functioning is depressed by metabolic means. Hypoxia, hypotension, and ischemia cause slowing and flattening of the EEG. Hypothermia produces slowing below 35°C with electrical silence at 7 to 20°C. The response to ischemia is rapid, with a flat EEG occurring within 20 seconds when complete ischemia occurs. During partial ischemia, the EEG slows with blood flows below 18 to 20 mL/min per 100 g and becomes flat at 12 to 15 mL/min per 100 g. Because the time to infarction is related to the rate of residual blood flow, the more residual flow that is present, the longer the time to infarction. As much as 10 to 15 minutes could elapse before infarction after graded ischemia produces EEG changes. Hence, the EEG can serve to warn of impending stroke and allow attempts to correct the blood flow before irreversible injury. These effects, notably those of ischemia, have made the EEG a valuable tool in assessing patients at risk for several events leading to cerebral ischemia.

This warning function has made EEG monitoring a component of carotid endarterectomy (CEA) and intracranial vascular surgery in many centers. Several studies have shown that the EEG can be used to identify some patients who appear to benefit from shunting during CEA and who cannot tolerate temporary clipping of aneurysms. Some studies have demonstrated an improvement in outcome with reduction in neural morbidity. Other studies have not shown an improvement in outcome, and hence the EEG is not used at all centers. Similarly, EEG has been used to monitor patients undergoing cardiopulmonary bypass to determine if adequate
blood flow is present. However, hypothermia usually used with these procedures could reduce the effectiveness of the monitoring.

**Evoked Potentials**

Whereas the EEG is the measurement of the spontaneous electrical activity of the brain, evoked potentials are a measurement of the electrical potentials evoked by a stimulus. These stimuli can be physiological in nature (eg, light flashes to the eyes) or they can be nonphysiological (eg, electrical pulses to peripheral nerves like used for monitoring neuromuscular function). Because stimulation focuses testing on a specific neural tract, assessment is also specific. Depending on the stimulation site and recording locations, the recorded potentials can be from peripheral, subcortical, or cortical regions.

It has been nearly 50 years since the first somatosensory evoked potentials were recorded in humans and over 20 years since their use was reported in the operating room. In that timespan, evoked responses have earned a valuable place in intraoperative surgical decision making. In some cases, monitoring has become indispensable (eg, neuroma in situ), in others a standard of care (eg, facial nerve monitoring in acoustic neuroma and spinal monitoring during scoliosis correction), and in many cases a valuable adjunct that has been integrated into patient care.

Evoked potentials are measured using differential amplifiers and filtering, similar to the EEG. Because these evoked electrical potentials are very small (less than 10 µV compared with the EEG which is 10–1000 µV), a technique known as signal averaging is used to resolve them from the much larger EEG and electrocardiogram (ECG) activity. Signal averaging involves repeatedly stimulating the nervous system and measuring the response for a set window of time (the time containing the neural activity of interest). After averaging several hundred or thousand windows, the evoked response becomes apparent because the desired signal is related to the stimulation but the other activity is not and averages out. Because of this need for signal averaging, the equipment is complex and evoked potentials did not become widely available until the development of inexpensive digital computer averagers. The time required for signal averaging is determined by the number of averages needed to distinguish the signal from the noise (usually several hundred) and the speed of stimulation (usually limited by the ability of the nervous system to recover from the previous stimulus). This acquisition time (often 1–2 minutes) could be sufficient to delay rapid feedback to the surgeon. Criteria for when a change in an evoked response becomes significant are not well established. Fast losses (with minimal latency change) could be the result of mechanical injury or localized ischemia. As a general principle, amplitude reduction of 50% or latency increase of 10% is often considered significant.
A typical evoked response consists of a plot of voltage versus time as measured using 3 electrodes similar to the EEG but with peaks (and valleys) that are thought to arise from specific neural generators (often more than one neural structure) and therefore can be used to follow the response at various points along the stimulated tract. The information recorded is usually the amplitude (peak to adjacent trough) and the time from the stimulation to the peak (called latency).

Like the EEG, several factors that alter neuronal and synaptic function can alter the evoked responses. In addition to technical problems, anesthesia and physiological changes can alter the responses. Physiological effects can simulate neural dysfunction if they hamper the stimulated tracts. These effects include hypothermia, ischemia or hypoxia, raised intracranial pressure, or reduced ionic or metabolic substrates critical for neuronal functioning.

The most commonly used evoked potentials are those produced by stimulation of the sensory system, the sensory evoked potentials (SEP). The 3 commonly used types include visual evoked potentials (VEP), produced by stimulation of the eye by light; auditory brainstem response (ABR), produced by stimulation of the ear with brief sound bursts; and somatosensory evoked potentials (SSEP), in which peripheral nerves are stimulated using electric pulses sufficient to depolarize the nerve (similar to methods for testing of neuromuscular blockade).

**Visual Evoked Potentials**

Visual evoked potentials are produced by light stimulation of the eyes. The traditional VEP are recorded by electrodes over the occipital cortex and appear to be generated by the visual cortex. The neural response to visual stimulation can also be recorded by electrodes placed near the eye (electroretinogram [ERG]). Cortical VEPs have been used to monitor the anterior visual pathways during craniofacial procedures, during pituitary surgery, and to identify ischemia in the retrochiasmatic visual tracts and the occipital cortex. However, the bilateral nature of the response makes this monitoring less effective, and studies suggest that although it could help identify the structural integrity of the optic tracts, it might not correlate well with postoperative vision. One interesting application is to use the cortical response as an index of intracranial pressure (ICP).

**Auditory Brainstem Responses**

The Auditory Brainstem Response (ABR), also referred to as the brainstem auditory evoked response (BAER), is produced when sound activates the cochlea. The neural impulse travels through the brainstem
acoustic relay nuclei and lemniscal pathways until it reaches the cortical auditory cortex. In the first 10 ms after stimulation, 3 major peaks are usually seen. Wave I is generated by the extracranial portion of cranial nerve VIII, wave III is generated from the auditory pathway nuclei in the pons, and wave V comes from high in the pons or midbrain (lateral lemniscus and inferior colliculus). The neural pathway of the ABR appears to follow the normal hearing pathway, and the several peaks in the ABR allow identification of the anatomic location of a neural dysfunction. Responses to auditory stimulation can also be recorded over the auditory cortex (cortical AEP). These responses appear to be related to the auditory sensory cortex and have been used to assess the depth of anesthesia.

ABRs have been used extensively for monitoring during surgery involving the posterior fossa, perhaps because of its importance for hearing and the frequent involvement of the cochlear nerve with tumors in this region. Complete loss of wave I can be the result of loss of cochlear blood supply by vascular obstruction or vasospasm with subsequent loss of useful hearing. In general, if waves I and V are preserved, hearing is usually preserved, but if they are both lost, there is little chance of preservation of hearing postoperatively.

Somatosensory Evoked Responses

The electrophysiological technique with the greatest use is the SSEP. In this technique, a peripheral nerve is stimulated and the neural response is measured along the pathway. The large, mixed motor and sensory nerves (and their component spinal roots) usually used are median n. (C₆-T₁), ulnar n. (C₈-T₁), common peroneal n. (L₄-S₁), and posterior tibial n. (L₄-S₂). It is currently thought that the incoming volley of neural activity from the upper extremity represents primarily activity in the pathway of proprioception and vibration mediated in the dorsal column of the spinal cord ipsilateral to stimulation. It synapses at the cervicomedullary junction, crosses the midline, and ascends the brainstem through the contralateral medial lemniscus. It synapses in the ventroposterolateral nucleus of the thalamus and finally projects to the contralateral parietal sensory cortex. Recordings after stimulation of the lower extremity appear to include additional components that pass in the more anteriorly located spinocerebellar pathways.

The use of the SSEP in the operating room and intensive-care unit has been discussed in several reviews. The SSEP has been used extensively to monitor for ischemia in the cortical tissue generating the evoked response and for diagnostic and prognostic studies in spinal cord injury and head injury. Similar to the EEG, the SSEP is also sensitive to ischemia. The SSEP remains normal until cortical blood flow is reduced to approximately 20 mL/min per 100 g and are altered and then lost at
blood flows between 15 and 18 mL/min per 100 g. Subcortical regions appear to be less sensitive, explaining why the SSEP persists at blood pressures below which the EEG disappears.

Because of this sensitivity to cortical blood flow, the SSEP has been used to monitor during surgical procedures such as carotid endarterectomy (CEA) as indications for shunt placement and to predict postoperative morbidity. The SSEP has also been used during intracranial vascular procedures to determine the adequacy of collateral blood flow, tolerance to temporary vessel occlusion, or tolerance to deliberate hypotension.

Monitoring can also be used to identify ischemia from vasospasm with subarachnoid hemorrhage (eg, aneurysm rupture) or when a combination of factors produces unexpected ischemia (eg, retractor pressure, hypotension, temporary clipping, and hyperventilation). Other applications include ischemia monitoring during neuroradiologic procedures. Because the cortical SSEP is generated in the sulcus between the motor and sensory cortex, it has been used for localization of the sensory–motor cortex in the anesthetized patient.

The SSEP is probably best known for monitoring during spinal surgery, when mechanical or ischemic insults can result in alteration or loss of transmission through the surgical field are associated with SSEP latency and amplitude changes simultaneous to motor function deterioration. In addition, the SSEP can be used to identify physiological insults (eg, hypotension) or positioning problems, especially those related to the brachial plexus. Studies in humans undergoing spinal surgery indicate that the SSEP is predictive of neural outcome. Perhaps the best testament to the use of the SSEP in spinal surgery is the analysis conducted by the Scoliosis Research Society (SRS) and European Spinal Deformities Society. The overall injury incidence was 0.55% (1 in 182 cases), well below the 0.7% to 4% expected with the instrumentation used, suggesting a reduction in neural morbidity associated with monitoring.16

Because motor pathways are not assessed by the SEP, methods have been developed to assess the motor tracts. Furthermore, the presence of synapses in the motor tract could make it more susceptible to injury than the axonal tracts of the SSEP.

Spinal cord stimulation techniques have been developed; however, both sensory and motor tracts appear to be involved, so selective monitoring has not been possible. Even recording muscle responses has failed to selectively monitor motor tracts; sensory tract activation can result in a descending volley of activity that activates anterior horn cells and peripheral motor fibers through local spinal reflex pathways.

Attempts to develop an evoked response that is purely motor tract in nature have centered on stimulation of the motor cortex using electrical or magnetic stimulation techniques.6,17 The evoked response travels down the lateral corticospinal and ventral corticospinal tracts and is recorded as a peripheral motor nerve response or as peripheral muscle compound
action potential (CMAP). Responses to transcranial stimulation can be recorded in the epidural space or in the muscle. These CMAPs can differentiate unilateral changes as well as provide the ability to assess potential injury at several nerve root levels simultaneously. Recording methodology is similar for MEP and SEP, except that CMAP responses are much larger, requiring less signal averages to resolve the signal.

The use of MEP for assessing the spinal cord or motor cortex has increased despite the excellent track record of the SSEP. This is because of the use of MEP in the detection of vascular insult to specific neural regions. This is particularly true in the spinal cord where the motor pathways are supplied by the anterior spinal artery fed by the aorta through penetrating vessels (notably the artery of Adamkiewicz and radicular arteries), and the SSEP is nourished by the posterior spinal artery system. This problem is most important in the thoracic spinal cord, which is particularly vulnerable to ischemia because it is not well collateralized and could have only one anterior feeding vessel between T4 and L4. Thus, MEP has been used for a large majority of procedures (notable spinal surgery) in which the SSEP has also been used. Monitoring of motor tracts could be particularly important during spinal cord surgery for vascular malformations and spinal cord tumors, in which injury to the spinal cord could be highly localized and missed by other techniques. In addition, motor evoked potentials (MEP) could actually be an earlier predictor of impending damage to the cord than the SSEP, perhaps because of the sensitivity of the synapse in the pathway located in the anterior horn of the spinal cord.

The major drawback of the transcranial techniques has been the effects of anesthesia. Inhalational anesthetic agents (including nitrous oxide) could obliterate the responses at low anesthetic concentrations as a result of effects at the cerebral cortex and anterior horn cell. Fortunately, the effect of anesthetic depression appears to be partially overcome by newer multipulse techniques, in which magnetic or electrical impulses are delivered to the scalp at 200 to 500 Hz.

**Electromyography**

Electromyography is the recording of muscle electrical activity by placement of needles within the muscle. This procedure can detect muscle disorders, disorders of the nerves that supply the muscle, and spontaneous or evoked activity in the motor pathways. The traditional needle electrode examination is conducted by placing a recording electrode within a muscle and examining the electrical activity it produces using equipment similar to the EEG. The activity is displayed on an oscilloscope and played through a loudspeaker, as characteristic sounds assist in diagnosis. Normally, a resting muscle is electrically silent after mild
reactivity to the needle insertion. Abnormal neuromuscular states can increase this insertional reactivity.

Although diagnostic EMG studies have been done to characterize injury, the more common application is to monitor the integrity of the nerve supplying a monitored muscle. Current methods of EMG recordings in the operating room involve recording electrodes in the muscle of interest with visible display of the electrical activity and audible presentation of the electrical activity over a loudspeaker. This monitoring system usually focuses on 2 basic types of abnormal activity. First are brief (less than 1 second), phasic “bursts” of activity. These result from single discharges of multiple nerve axons and are usually caused by mechanical stimulation of the nerve (nearby dissection, ultrasonic aspiration or drilling, retraction), but can also be caused by thermal (irrigation, lasers, drilling, electrocautery) and chemical/metabolic insults. This serves to indicate to the surgeon that the nerve is in the immediate vicinity of the surgical field.

More injurious stimuli can cause longer tonic or “train” activity, which is an episode of continuous, synchronous motor unit discharges. These have audible sounds with a more musical quality and have been likened to the sound of an outboard motor boat engine, swarming bees, popping corn, or an aircraft engine. These trains are often associated with nerve compression, traction, or ischemia of the nerve, and are thought to be an indication of nerve injury. The proposed mechanism of the repetition of discharge is that the insult has raised the resting membrane potential to near or above threshold and represents an evolving injury pattern. Finally, using a handheld stimulator, the surgeon can stimulate the nerve at rates of 1 to 5 Hz. The repetitive bursts in synchrony with the stimulation (sounding like a machine gun) verify the nerve integrity or confirm that structures for removal are not the nerve. If an injury pattern should evolve, stimulation can be used to determine which segment of the nerve is injured. Finally, in complex cases, some surgeons use instruments that are always electrified, so that during tumor dissection, the nerve will automatically be stimulated to identify its presence.

Ideally, EMG recording could be used to monitor any nerve with a motor component such as numerous cranial nerves. However, the most common application is for facial nerve monitoring during posterior fossa neurosurgery, in which tumors commonly grow to involve the facial nerve. The frequent involvement of the facial nerve with tumors in the cerebellopontine angle and acoustic neuroma (currently known as vestibular schwannoma) has led to the application of facial nerve monitoring during these surgeries in an attempt to salvage function. Facial nerve monitoring increases the likelihood that anatomic integrity of the nerve will be maintained during surgery allowing improved functional outcome (over 60% of patients with intact nerves at the conclusion of surgery will regain at least partial function several months postoperatively).
Monitoring of facial nerve function for resection of acoustic neuroma is accomplished by placing closely spaced bipolar recording electrodes in the orbicularis oris and orbicularis oculi (with an indifferent or ground electrode elsewhere on the face). The value of identifying nerve integrity is that over 60% of patients with intact nerves will regain at least partial function several months postoperatively, whereas loss of response is associated with a poor outcome. The excellent outcome data when facial nerve monitoring is used during acoustic neuroma has prompted a National Institutes of Health consensus panel to identify facial nerve monitoring as a routine part of acoustic neuroma surgery. 18

In addition to using these indicators of inadvertent nerve irritation, the surgeon can intentionally stimulate the nerve to assess the integrity of the nerve or to locate the facial nerve in the operative field. A response could be possible with as few as 1% to 2% of the nerve fibers remaining intact. 19 Other motor cranial nerves in addition to c.n. VIII can also be monitored using similar methods (Table 1).

EMG monitoring has also been used during spine surgery. For example, during surgery on the cauda equina, the anal sphincter and various leg muscles can be monitored. Also of interest is monitoring for injury during spine fixation by screws placed in the pedicle of the vertebra (pedicle screws). A better technique involves monitoring the electrical activity of the muscles innervated by the component nerve roots, similar to facial nerve monitoring. In this type of monitoring, spontaneous muscle activity can be used to indicate inadvertent nerve irritation. Alternatively, evoked muscle activity can be used to test screw placement by stimulation of the screw or screw hole (to detect loss of integrity of the pedicle wall by the screw hole). 21

Transcranial Doppler Monitoring

Transcranial Doppler sonography (TCD) was introduced in 1982 by Aaslid 22 and has been used extensively for diagnostic and monitoring

| Table 1. Recording Locations for Cranial Nerve EMG Monitoring |
|-----------------|-----------------|
| III Oculomotor  | Inferior rectus |
| IV Trochlear    | Superior oblique|
| V Trigeminal    | Masseter, temporalis |
| VI Abducens     | Lateral rectus |
| VII Facial      | Orbicularis oculi, orbicularis oris |
| IX Glossopharyngeal | Posterior soft palate (stylopharyngeus) |
| X Vagus         | Vocal folds, special endotracheal tubes, cricothyroid muscle |
| XI Spinal accessory | Sternocleidomastoid, trapezius |
| XII Hypoglossal | Tongue, genioglossus |

EMG = electromyography.
applications for the intracranial vasculature because it is a surrogate for cerebral blood flow. TCD uses an ultrasonic beam to penetrate through thin areas of the skull and receive a signal that is bounced off of the blood flowing in the basal cerebral vasculature. Because the blood is moving, the frequency of the reflected signal (fr) will be different from the insonating beam (fo). This Doppler frequency shift (fr-fo) is related to the velocity of the blood (v) by the formula: fr = fo(1+v/c) where c is the speed of ultrasound in the medium and v is the speed of the blood toward the transceiver. If the actual flow is not exactly toward or away from the signal, the frequency shift will be reduced by the cosine of the angle. In actual use, angles of flow greater than 30° (cosine 0.87) are not effectively measured so the detected velocity in practical terms is always within 87% of the real velocity.

Hence, TCD allows an estimation of the blood velocity. If assumptions are made about the cross-sectional diameter of the blood vessel and the velocity profile of the blood across the blood vessel (ie, the velocity in the middle of the vessel could be different from that at the edge), the flow of blood can be estimated. Because these variables might not be exactly known, TCD is more useful for estimates of changes in cerebral blood flow (assuming no change in these variables).

During measurement or monitoring, the vessel diameter can change. Causes include vasospasm, vasoactive agents, and anesthetic agents. Of particular note is that the basal cerebral arteries are not affected by carbon dioxide or blood pressure, and the effect of vasoactive agents and inhalational anesthetic agents is variable. However, if these agents are held at steady-state, their contribution to change should be minimal and changes in velocity can be interpreted as changes in blood flow.

There are 3 major “windows” for TCD in which the skull is thin enough to allow sufficient ultrasound beam to enter and return to the transceiver. The transtemporal route just above the zygomatic arch allows insonating the anterior, middle, and posterior cerebral arteries. The transorbital approach through the eye socket allows insonation of the carotid siphon, but the possibility of risk to the eye limits its use. The suboccipital route through the foramen magnum allows insonating the basilar and vertebral arteries, but the lack of easy mounting of the transceiver limits its usefulness for monitoring.

Most frequently used for monitoring, the transtemporal approach allows monitoring the proximal (M1) segment of the middle cerebral artery in over 90% of patients in whom the window is usable. Because this segment carries 75% to 80% of the flow from the internal carotid artery on that side, monitoring this signal allows an excellent estimate of the hemispheric blood flow. However, the thickness of the skull varies with race, gender, and age, such that the transtemporal approach could fail in 20% to 30% of patients.

In addition to identifying different vessels, the TCD displays the ve-
locity profile of the vessel with a waveform similar to an arterial line. The most commonly acquired data is the velocity data. Both the maximal velocity and the mean velocity are usually determined. The mean velocity correlates closer to CBF, but the maximal velocity is usually easier to determine. The mean can be calculated from the systolic and diastolic values, similar to calculating the mean of the blood pressure. Superimposed on this waveform could also be transient signals from emboli that are very reflective of the beam referred to as high intensity transient signals (HITS; eg, air or particulate matter).

The shape of the velocity profile is dependent on the cerebral perfusion pressure, the viscoelastic properties of the blood vessels, and blood rheology. In the absence of vasospasm or venous stenosis, the shape is primarily a reflection of vascular resistance. Pulsatility index (PI), also known as the Gosling index, is used as a reflection of the vascular resistance. It is calculated as the difference between the systolic and diastolic flow velocity divided by the mean velocity. Alternatively, the resistance index (also known as the Pourcelot index) is calculated as the difference between the systolic and diastolic flow velocity divided by the systolic velocity. It is important to note that both indices are affected by vasoconstriction and intracranial pressure and the PI is affected by heart rate.

In addition to inferring changes in cerebral blood flow, TCD has been used to determine the “reserve” of the cerebral blood vessels. Here, the ability of the vasculature to undergo physiological changes from CO₂ and perfusion pressure (autoregulation) indicates their ability to change diameter as needed to maintain homeostasis (ie, compensatory dilatation to tolerate decreases in perfusion pressure, oxygen, or glucose). For example, velocity should change with the degree of vasoconstriction associated with changes in CO₂. The failure of velocity to rise suggests that the vessels are already at maximal dilation and have exhausted their reserve.

To detect whether autoregulation is intact, the blood pressure must be changed using means that do not alter cerebral vascular tone. Techniques include sudden deflation of large thigh tourniquets (dynamic hypotension), raising the blood pressure 20 mm Hg by an infusion of Norepinephrine (static hypertension) and transient compression and release of the carotid artery (transient hyperemia). These tests usually reveal 2 components of autoregulation, a rapid response sensitive to pulsations followed by a slow-acting response that follows mean pressure.

TCD has also been used to estimate cerebral perfusion pressure (CPP). This is qualitatively assessed by examining the diastolic flow velocity because diastolic velocity decreases as the intracranial pressure (ICP) increases. As CPP approaches 0, the flow actually oscillates in and out of the arteries signaling circulatory arrest. Quantitatively, CPP can be estimated using the pulsatility index, and this has become useful in patients in whom ICP is not directly monitored.

TCD has been used in the intensive-care area and for monitoring
during operative procedures. One common application is during carotid endarterectomy in which it has several uses. Preoperatively, it has been used to assess cerebrovascular reserve and CO₂ reactivity, and has been used to assess flow reversal with carotid occlusion that could help with assessing collateral circulation such as the competency of the anterior communicating artery.

Intraoperatively, its primary use is to infer critical reductions in cerebral blood flow during carotid crossclamping (thought to be responsible for 40% of perioperative strokes) and the need for an operative shunt. Reductions in TCD flow velocity below 40% have correlated with EEG changes during ischemia. No universally agreed criteria have been accepted, but TCD velocities less 15 cm/s or lower than 40% preclamping have been used. The converse is also true. Studies have revealed that shunting when the flow velocities are above 40% show an increased incidence of emboli, which has been associated with neuropsychiatric problems postoperatively and intraoperative infarcts. Hence, TCD has been used for decisions about selective shunting and identifying when a shunt is malfunctioning. Postoperatively, TCD has been used to identify the need for wound exploration for hematoma (declining velocity), or identifying those patients with hyperemia at risk for cerebral edema or hemorrhage (velocities in excess of 230% baseline) in whom postoperative blood pressure management is critical. Because embolic phenomena also contribute to neurologic injury, the ability of TCD to identify emboli has been used to examine operative technique as it has during cardiac surgical procedures, particularly procedures where the cardiac chambers are opened.

TCD has been used extensively in patients sustaining subarachnoid hemorrhage (SAH) after intracranial aneurysm rupture. The major application is to identify vasospasm, which is a leading cause of morbidity and mortality in these patients. With vasospasm, the diameter of the vessel changes resulting in an increase in blood flow velocity that can be detected by TCD. Vasospasm is generally considered in the specific vessel being insonated if the flow velocity in the middle cerebral artery exceeds 120 cm/s or if the ratio of the flow velocity is more than 3 times the flow velocity in the internal carotid artery.

TCD has also been used in the management of intracranial vascular problems such as arteriovenous malformations (AVM). Here, the feeding artery usually has high flow velocity, low pulsatility, low perfusion pressure, and decreased CO₂ reactivity allowing TCD to make a diagnosis and assess the normalization, which occurs with embolization or resection. Furthermore, after treatment, TCD might be able to assist in the diagnosis and treatment of a hyperperfusion syndrome. TCD has been used to identify patients with inadequate cerebral blood flow in which the internal carotid artery needs ligation for management of giant aneurysms or vascular masses. In these cases, if the TCD
flow velocity in the middle cerebral artery remains above 65% of baseline, the patients tolerate the occlusion well. If it falls below this level, a high level of neurologic deficit occurs (85%).

TCD has also been used in closed head injury to assess flow velocity, waveform pulsatility, and assessment of cerebral autoregulation, which help identify patients at high risk for a poor outcome. Similar to SAH, vasospasm can be identified. TCD can also be used to identify hyperemia in which the flow velocity of the middle cerebral artery is high, is less than twice the flow velocity of the internal carotid artery, and the mixed venous saturation in the jugular bulb is high.

Finally, TCD has been used in stroke to identify arterial occlusion, recanalization as well as identifying embolic phenomenon and possible sources (unilateral emboli usually arise from the carotid artery, whereas bilateral emboli usually arise from cardiac sites).

### Jugular Bulb Venous Oximetry Monitoring

Measurements of the jugular venous blood oxygen saturation (SjvO₂) allow estimation of the global balance between cerebral oxygen demand and supply. The method has been used for some time, but newer technologies have allowed a wider application of the technique and greater integration into patient care. The technique takes advantage of the fact that virtually all of the blood from the brain flow through the venous sinuses and terminates in the right and left sigmoid sinuses. From here it courses through the jugular foramina and jugular bulbs before flowing into the internal jugular vein. Only a small component of the drainage passes through the vertebral venous plexus, which is most prominent when standing.

Jugular venous oxygen saturation is monitored by intermittent blood sampling or continuous optometric techniques using a catheter placed in the jugular bulb. This catheter is placed using the Seldinger technique through vascular access similar to the placement of internal jugular central lines. However, the needle and catheter are threaded cephalad into the jugular bulb approximately 12 to 15 cm. The catheter tip must be above C1/C2 to minimize contamination from the facial vein.

Many individuals place the catheters preferentially on the right side because it is thought that this side preferentially drains the cerebral cortex (with the left internal jugular draining predominantly the subcortical veins). Some authors suggest that placement in the jugular vein whose occlusion causes the largest ICP rise will monitor the dominant venous structure. Controversy surrounds whether the monitor should be placed on the side of focal ischemia if the side is known.

The jugular venous oxygen saturation can be used to determine the cerebral arteriovenous oxygen content difference (CavDO₂), which re-
flects the oxygen uptake and metabolism in the tissues between the artery and venous structures sampled for the measurement. If we ignore the amount of oxygen dissolved in the blood, CavDO$_2$ can be calculated by measuring the arterial and venous oxygen content ($\text{HgB} \times 1.39 \times \text{SaO}_2$) where the arterial and jugular venous O$_2$ saturation ($\text{SaO}_2$, SjvO$_2$, respectively) are measured. Hence, if hemoglobin is constant, CavDO$_2$ = $\text{SaO}_2$ – SjvO$_2$.

The cerebral arteriovenous oxygen saturation is also related to cerebral blood flow and oxygen consumption. The metabolic consumption (cerebral metabolic rate of oxygen consumption [CMRO$_2$]) is equal to the cerebral blood flow (CBF) times the cerebral arteriovenous oxygen content difference (CavDO$_2$). Hence, CavDO$_2$ = CMRO$_2$/CBF.

Thus, SjvO$_2$ = $\text{SaO}_2$ – CMRO$_2$/CBF. Similar to mixed venous oxygen saturation, when oxygen delivery exceeds demand (as with hyperemia), SjvO$_2$ increases. This suggests hyperemia, particularly indicated by values over 90%. This could occur with severe metabolic depression such as brain death or coma or could occur with arteriovenous malformations (also carotid–cavernous fistulas).

Under normal conditions (CavDO$_2$ about 2.8 µmole/ml) SjvO$_2$ is between 50 and 54 and 75%. When supply exceeds demand (hyperemia), values rise, and when demand exceeds delivery, the numbers fall. Low values are of great concern, but no generally agreed on critical value has been determined. However, values below 50% are generally agreed as values to raise concern. Support for this comes from studies with carotid endarterectomy in which patients with values below 50% demonstrated transient neurologic dysfunction, whereas those above 60% did not. Furthermore, in patients with head injury, repeated values below 50% are associated with poor neurologic outcome; and in normal volunteers, mental dysfunction or EEG slowing occurs with values in the 40% to 50% range.

Jugular bulb saturation must always be interpreted as a result of the relationship of supply (cerebral blood flow) and demand (cerebral metabolism). The contribution of SjvO$_2$ to monitoring and treatment is to identify ischemia and help optimize the balance of supply and demand. Hence, depending on the other associated findings, treatment could involve correcting systemic oxygenation ($\text{SaO}_2$ <90%), increasing PaCO$_2$ (PaCO$_2$ <25 mm Hg), transfusion (Hct <30%), increasing blood pressure (MAP <80 mm Hg or CPP <70 mm Hg), treating elevated ICP with mannitol or Lasix, depressing metabolism or stopping seizures, or treating vasospasm.

During ischemia, when extraction of oxygen increases, SjvO$_2$ decreases. When SjvO$_2$ falls below 50%, ischemia is generally suggested with risk of ischemic injury or infarction. This could be indicative of inadequate delivery (such as with anemia), increased demand (such as seizures), or decreased blood flow. It is important to note that if infarction occurs, the regional hyperemia could result in falsely normal values.
A variety of physiological factors can affect the SjvO₂. Factors that increase CMRO₂ will decrease SjvO₂. Conceptually, metabolism can be divided approximately equally between the basal components and the metabolic activity that is related to neuronal activity. Hence, increases in temperature and seizures increase metabolism and decrease SjvO₂. Conversely, hypothermia, sedative hypnotics, and anesthetics decrease neuronal metabolism, thus increasing SjvO₂. It is important to note that some anesthetic drugs could increase EEG activity before they produce depression so that SjvO₂ could initially fall.

Factors that decrease CBF will decrease SjvO₂. Hence, hypotension below the lower limit of autoregulation, hyperventilation, increases in ICP and vasospasm will decrease SjvO₂. Conversely, increases in blood pressure, carbon dioxide, and lowering ICP will increase SjvO₂. Finally, factors that affect oxygen delivery will alter SjvO₂. For example, systemic hypoxemia will lower SjvO₂. Similarly, anemia will reduce deliver the total amount of oxygen delivered, thereby decreasing SjvO₂. Anemia will adversely affect SjvO₂ because SjvO₂ will remain relatively constant until CBF can no longer compensate for the lowered O₂-carrying capacity of blood. Below this level, SjvO₂ will fall as hemoglobin falls, despite CBF and CMRO₂ being normal.

The effectiveness of oxygen extraction will also impact on the interpretation of SjvO₂. If the increase in oxygen extraction can no longer compensate for reduction in oxygen delivery, then the CMRO₂ will fall without a predicted change in CBF. The failure of normal oxygen extraction (such as with “sick cell syndrome,” or cyanide or carbon dioxide poisoning) also alters the extraction of oxygen such that SjvO₂ will be inappropriately high. It could also be high if there is shunting of arterial blood as can happen in preterminal events associated with very high ICP and low CPP.

Perhaps the greatest limitation is that the process is a mixed value representing a global effect. Hence, regional ischemia or hyperemia can be masked by the global effects. Therefore, it is not sensitive to ischemia. For this reason, simultaneous lactate measurements have been suggested. A second problem is that approximately 2.7% of the jugular venous blood is extracranial (notably the facial vein) and will not reflect intracerebral events. Because this blood has a higher oxygen saturation, it could result in falsely high values. This will be particularly true if blood is withdrawn rapidly for analysis. Falsely high values can also occur as a result of the Bohr effect of a leftward shift in the oxyhemoglobin dissociation curve during alkaline conditions, but this effect is not significant on SjvO₂ until the pH exceeds 7.6.

Because jugular bulb oxygen saturation indicates the relationship of metabolism to supply, it is of greatest use in monitoring when global ischemia can occur. The application of jugular venous oxygen saturation monitoring has been suggested in traumatic brain injury in which poor
neurologic outcome is associated with repeated desaturation episodes.\textsuperscript{46} In head injury, the most common causes of desaturation are high ICP, hypocapnia, and systemic hypotension.\textsuperscript{47} It has also been found useful with subdural hematomas.

It is currently thought to be most useful in guiding hyperventilation such as in head injury in which hyperventilation can contribute to injury by reducing blood flow that is already reduced from injury. The management could also be of help in circumstances of relative hyperemia (high SjvO\textsubscript{2}) in which aggressive hyperventilation or metabolic suppression (eg, barbiturates) could be of value. Here, hyperventilation could lower ICP and produce vasoconstriction in areas of hyperemia, but could also cause vasoconstriction that could result in ischemia. Hence, SjvO\textsubscript{2} could help determine optimal hyperventilation. This is particularly true if hyperemia is present because hyperventilation could reduce the consequences of the hyperemia.\textsuperscript{48} This technique can also assist in determining the optimal blood pressure in which autoregulation is lost and CBF might need to be matched to metabolism.

Hence, in head injury, SjvO\textsubscript{2} has been suggested for use in early detection of ischemia and has been used to guide hyperventilation therapy, fluid and oxygenation management, optimizing perfusion pressure, and detecting arterial–venous fistulas. Furthermore, with simultaneous TCD and lactic acid levels, it can help differential vasospasm from hyperemia.\textsuperscript{49} A problem occurs in head-injured patients in whom CMRO\textsubscript{2} can be uncoupled from CBF to an unpredictable degree. Thus, SjvO\textsubscript{2} can increase or decrease in the presence of decreased CMRO\textsubscript{2} making SjvO\textsubscript{2} readings difficult to interpret. Despite this limitation, SjvO\textsubscript{2} between 45\% and 50\% is considered mild and <45\% considered severe cerebral hypoxia.\textsuperscript{50}

In the operating room, monitoring has also been found useful during elective or emergency craniotomy. In elective neurosurgery, the major cause of desaturation is hypocapnia and systemic hypotension.\textsuperscript{47} This has allowed investigators to adjust the ventilation (particularly with AVM, SAH, head trauma, or intracerebral hematomas) or blood pressure (especially with intracranial aneurysms) to more optimal levels. Also, in AVM patients, SjvO\textsubscript{2} has been found useful to observe the decrease in AVM flow during resection\textsuperscript{51} and to identify possible hyperperfusion after embolization.\textsuperscript{52} Furthermore, with cardiopulmonary bypass, SjvO\textsubscript{2} has identified periods of desaturation during rewarming when metabolism could have increased in excess of supply (17–23\% of patients).\textsuperscript{53}

\section*{Transcranial Cerebral Oxygen Saturation Monitoring}

The application of near-infrared spectroscopy (NIRS) for monitoring the brain was introduced by Jobsis in 1977.\textsuperscript{54} The most commonly used
device uses a concept similar to pulse oximetry in which the change in absorption at different wavelengths allows determination of the relative amounts of the absorbing species (ie, oxygenated vs. nonoxygenated). However, unlike pulse oximetry, the signal cannot be completely transmitted through the adult brain, so a reflected beam is used. In addition, NIRS can also detect the oxidation state of cytochrome aa3, the terminal cytochrome in the electron transport chain. NIRS takes advantage of the fact that near-infrared light (wavelengths 700–1000 nm) easily penetrates skin and bone with only a small amount being absorbed by skin pigments (melanin and bilirubin). Secondly, very few biologic substances absorb NIR so that hemoglobin and cytochrome aa3 become the major absorbers.

The monitor shines NIR into the tissues and records the reflected light. Two receiving sensors are usually used, one near the transmitter to predominantly sense the reflected light from the superficial tissues (extracranial—skin and bone) and a second farther away that will include intracranial reflected NIR. By subtracting the superficial response, the cerebral response can be determined, although the current monitors are not completely independent of changes in extracranial blood. NIRS measures the state of all hemoglobin and cytochrome aa3. Because hemoglobin is primarily in the venous blood (84%), and the absorbance of hemoglobin is 10 times the absorbance of cytochrome aa3, the signal is predominantly recording of venous oxygenation.

No gold standard is available to calibrate the current NIR devices. The actual tissue contributing to the signal is not known such that an absolute determination of saturation impossible. Relative shifts in the proportion of the blood in venous compartments can change the reading. Thus, a head-down position can shift the reading to a lower value with no real change in the oxygenation state. Hence, the monitors are really trend monitors with the patient as their own control. Perhaps the greatest limitation is that the boundaries of the brain monitored are not known. Because it involves reflectance, the superficial brain tissues likely make the greatest contribution.

Questions have been raised about the ability to detect ischemia in the brain surface because normal or near-normal values have been obtained in dead individuals. This could be the result of a balanced reduction in metabolism and blood flow. Similar problems can occur if the sensor is placed over infarcted brain or an existing subdural or epidural hematoma. This suggests a computed axial tomography scan could help identify suitable placement locations in head injury.

A variety of applications have been proposed. These include assessment in patients with microangiography, patients at risk for ischemia in the operating room (such as carotid endarterectomy or coronary bypass procedures), and patients with traumatic head injury, stroke, or at risk for intracranial hemorrhage. Of particular interest is its use for early detec-
tion of intracranial hematomas in the region of monitoring (eg, epidural, subdural, and intracerebral hematomas within 2–3 cm of the brain surface).

### Brain Tissue Oxygen Monitoring

Perhaps the newest form of monitoring involves invasive electrodes placed into the brain tissue for monitoring of local brain PO$_2$, PCO$_2$, pH, and temperature. These are offshoots of similar devices manufactured for measurements in the arterial blood. The sensor is a 0.5-mm diameter catheter (fits through a 20-gauge catheter). Fluorescent dyes that respond to oxygen, carbon dioxide, and hydrogen (pH) are used, as is a temperature sensor and a Clark electrode (for oxygen) placed near the tip. The entire catheter is placed 2 to 3 cm deep into the brain (usually the frontal cortex) through a small burr hole.

A variety of studies have been performed with this monitor. It clearly has the advantage (and disadvantage) of looking at a small region of the brain. As opposed to the monitor above, it can give the most insight into the local chemistry that ultimately leads to functional correlates or factors relating to morbidity or mortality of neural tissue.

Attempts using this device to determine a critical tissue O$_2$ level (below which infarction will occur) has led investigators to conclude tissue O$_2$ (TiO$_2$) levels below 19 to 23 are associated with conditions leading to infarction. Tissue O$_2$ monitoring has also been used to determine the effect of cerebral perfusion pressure. Studies suggested that tissue O$_2$ was best maintained at CPP of 60 mm Hg with the best method to achieve this with arterial hypertension (hyperventilation or mannitol caused decreased tissue O$_2$). Increases in CPP above this level did not improve tissue oxygenation.

Tissue oxygenation monitors have also been used to study the relationship of CMRO$_2$ with CBF (metabolic coupling). Not surprisingly, intravenous anesthetics producing EEG burst suppression lower TiO$_2$ as CBF is decreased. Similarly, TiO$_2$ increases with inhaled anesthesia and CBF increases. Patients in whom the coupling of CMRO$_2$ and CBF was lost had poor outcome, suggesting the state of coupling reflects the severity of injury.

Used in traumatic brain injury, significant differences in outcome have been associated with significant differences in TiO$_2$ (39 vs. 19 mm Hg), PCO$_2$ (50 vs. 64 mm Hg), and pH (7.14 vs. 6.85). Monitoring has identified changes in tissue chemistry associated with changes in inspired oxygenation that are thought to have improved outcome. Another proposed use is in acute stroke in which the assessment of hyperoxygenation could be made.

Several clinical studies were done in brain-injured patients to examine
the correlation of tissue hypoxia with outcome. One study found the likelihood of patient death correlated with the time duration of tissue O₂ levels. They concluded that the likelihood of death increased with increasing duration of TiO₂ <15 mm Hg or with any occurrence of TiO₂ <6 mm Hg. Another study noted that 56% of patients with TiO₂ <10 mm Hg for over 300 minutes died, 22% had unfavorable outcome, and 22% had a favorable outcome. A third study found TiO₂ <5 mm Hg were associated with poor outcome.

## Conclusion

Each of these monitors has clear advantages and disadvantages for the use in monitoring the brain and detecting circumstances that can alter patient management. In some cases, they have become routinely used in patient care; and in others, they have given insight into management strategies and better understanding of disease processes.

## References


