37 Intracranial Pressure Monitoring

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This chapter includes an accompanying lecture presentation that has been prepared by the authors: Video 37.1.

KEY CONCEPTS

- Intracranial pressure monitoring is recommended for conditions that may lead to an increase in intracranial pressure, such as traumatic brain injury (TBI), subarachnoid hemorrhage (SAH), intracranial tumor, intracranial hemorrhage, stroke, hydrocephalus, CNS infection, and fulminant hepatic failure.
- The American College of Surgeons recommends intracranial pressure monitoring in TBI patients with a Glasgow Coma Scale score ≤8 and structural brain injury on CT.
- There are a variety of modalities available to monitor intracranial pressure, although use of the extraventricular drain and intraparenchymal bolt is preferred in current practice.
- Several noninvasive methods of intracranial pressure monitoring are currently under investigation.

HISTORICAL PERSPECTIVE

The importance of intracranial pressure (ICP) was first recognized by Alexander Monro more than 200 years ago and is now referred to as the *Monro-Kellie doctrine* or the *Monro-Kellie hypothesis*.[1] The Monro-Kellie doctrine states that (1) the brain is housed in the nonexpandable skull, (2) brain parenchyma is fairly noncompressible, and (3) the volume of blood is relatively constant, and outflow of venous blood is necessary for the inflow of arterial blood.[1] Later, CSF was recognized as a component of brain volume in addition to brain parenchyma and blood, and it was incorporated into the doctrine. If there is a new intracranial mass lesion such as a tumor or hematoma or an abnormal increase in the volume of any of the components, such as CSF (during hydrocephalus) or parenchyma (during brain edema), the volume of venous blood or CSF or both will decrease to accommodate. However, this compensatory reserve is limited, and any further increase in the volume of the pathologic lesion will lead to an increase in ICP because of the rigid, nonexpandable skull. An increase in ICP will then result in a decrease in perfusion pressure and cerebral blood flow and eventually cerebral herniation and death.[1]

For more than a century, there has been clinical interest in measuring ICP. Early efforts to measure ICP were based on the observation that because the cranial and spinal CSF compartments communicate with each other, their pressure should be equal. Measurement of spinal CSF pressure through lumbar puncture should therefore reflect cranial CSF pressure, or ICP.[1,2] However, it was soon recognized that measurement of opening pressure via lumbar puncture is associated with a risk for cerebral herniation in the presence of an intracranial mass lesion and that it may not reflect ICP if there is any obstruction to CSF flow between the cranial and spinal CSF compartments.

During the first half of the 20th century, several investigators measured ventricular fluid pressure in a small number of patients.[2] Its clinical use, however, was limited until the 1960s, at which time the pioneering neurosurgeon Nils Lundberg started to measure ICP with a ventricular catheter connected to an external strain-gauge pressure transducer and a standard ink-writing potentiometer recorder.[2] CSF drainage was also used to reduce ICP.[2] This method of ICP monitoring and CSF drainage was used in more than 400 patients, many of whom had traumatic brain injury (TBI), and this marked the beginning of the modern era in ICP monitoring.[3]

Today, ICP monitoring is an integral part of neurocritical care. ICP monitoring has been used in the management of patients with TBI, subarachnoid hemorrhage (SAH), intracranial tumor, intracranial hemorrhage, stroke, hydrocephalus, CNS infection, and fulminant hepatic failure.[4] However, despite the adoption of ICP monitoring in the modern critical care unit and the establishment of an association of intracranial hypertension with increased mortality, the benefits of ICP-directed management strategies have been equivocal.[5–10] Results from the first randomized controlled trial to evaluate ICP-directed therapy in severe TBI patients, the Benchmark Evidence from South American Trials: Treatment of Intracranial Pressure (BEST TRIP), have generated further controversy. This multicenter trial conducted in Bolivia and Ecuador compared ICP-directed management versus a novel CT imaging and clinical examination–guided management protocol and found no differences in morbidity or mortality measured at 6 months after injury.[11] Analyses of the trial have scrutinized its design and challenged its generalizability given the study's locale.[12–14] Ultimately, the BEST TRIP study was not a trial of whether or not one should monitor ICP, but rather a comparison of two different management strategies for severe TBI. It highlights the need for a deeper understanding of the pathophysiology of TBI and the interpretation of ICP in context of other clinical, radiographic, and monitoring information to individualize care.[15-17] While a consensus-based interpretation of the BEST TRIP data advises against changing practice if ICP is already routinely monitored,[1,18] results of the BEST TRIP study can also assist clinicians in developing an algorithm for treating suspected intracranial hypertension in the absence of ICP monitoring.[19]

The application of ICP monitoring is recommended in guidelines from several national and international societies. The Brain Trauma Foundation (BTF) published the first evidence-based guidelines for managing severe TBI in 1996. ICP monitoring and ICP-lowering therapy recommendations composed the mainstay of treatment options for severe TBI in the early versions of the guidelines.[20,21] The latest edition of the BTF guidelines continues to recommend using information from ICP monitoring to reduce postinjury mortality in severe TBI patients.[22] However, as a result of changes in methodologies for grading quality of supporting evidence, the recommendation for placement of an ICP monitor in all patients with GCS ≤8 and an abnormal CT scan was removed. Meanwhile, the American College of Surgeons Trauma Quality Improvement Project (ACS

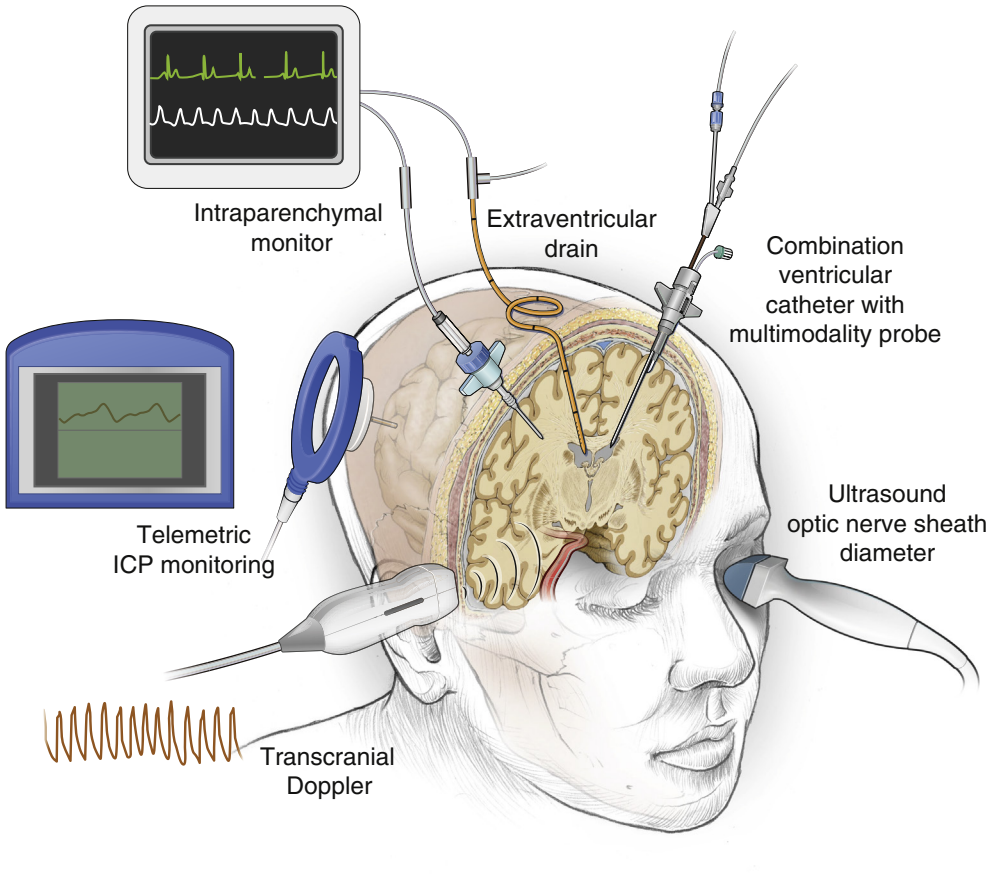

Figure 37.1. There are many invasive and noninvasive methods for intracranial pressure *(ICP)* monitoring, some of which are shown here. See the text for detailed descriptions of each method. (*Illustration by Noel Sirivansanti and Kenneth X. Probst.*)

TQIP) best practices guidelines, developed using a combination of best available evidence and expert census, still advocate for the use of ICP monitoring in patients with a Glasgow Coma Scale (GCS) score ≤8 and structural brain injury on CT. Furthermore, they suggest ICP monitoring for patients with a higher GCS score who have structural injury with a high risk for progression, such as those with large contusions or coagulopathy and for patients who require urgent surgery for extracranial injuries.[23] Consensus statements published by the Neurocritical Care Society and the European Society of Intensive Care Medicine also strongly recommend the use of ICP monitoring for other acute brain injuries such as SAH and encephalitis as part of structured management protocols.[15]

GENERAL PRINCIPLES AND STANDARD OF INTRACRANIAL PRESSURE MONITORING TECHNOLOGY

Since the 1960s, there has been a continuous effort to develop new technology for ICP monitoring. Nils Lundberg outlined the basic requirements for an ICP monitor, which still apply today: minimal trauma during placement, negligible risk for infection, no CSF leakage, easy to handle, reliable, and able to continue to function during various diagnostic and therapeutic procedures.[3] The Association for the Advancement of Medical Instrumentation developed the American National Standard for Intracranial Pressure Monitoring Devices, which specifies that an ICP monitoring device should have a pressure range of 0 to 100 mm Hg, accuracy of 2 mm Hg in the range of 0 to 20 mm Hg, and a maximal error of 10% in the range of 20 to 100 mm Hg.[24] Throughout the years, many different ICP monitors have been developed, but only very few are in active clinical use today.

CURRENT INTRACRANIAL PRESSURE MONITORING TECHNOLOGY (FIG. 37.1)

External Ventricular Drain

An external ventricular drain (EVD), or ventriculostomy drain, connected to an external strain gauge is currently the "gold standard" for measuring ICP.[24] It remains the preferred method for monitoring ICP among neurosurgeons in the United States[25] and is recommended by the ACS TQIP guidelines as the first monitor of choice.[23] An EVD can be placed at the bedside in the emergency department, ICU, or operating room, depending on local practice tradition. Most practitioners use anatomic landmarks (freehand technique) to insert the ventricular drain into the lateral ventricle with the tip in the foramen of Monro (Fig. 37.2).[25,26] The catheter can then be tunneled subcutaneously to minimize CSF leakage and infection.[27] Ventricular fluid pressure, which represents ICP, is transmitted to an external strain-gauge transducer via the fluid-filled EVD. The strain-gauge transducer can be recalibrated without manipulation of the EVD. It can be connected to many standard ICU monitoring systems and allows ICP measurements to be displayed along with other physiologic data such as pulse, blood pressure, or central venous pressure.

Advantages of the EVD as an ICP monitoring device include its extensive history, low cost, and reliability.[24,25] Most important, an EVD can also serve as a therapeutic device to remove CSF and lower ICP.[2,24] In patients with SAH or intraventricular hemorrhage, in which the elevated ICP is frequently a result of hydrocephalus, an EVD is the most appropriate ICP monitoring

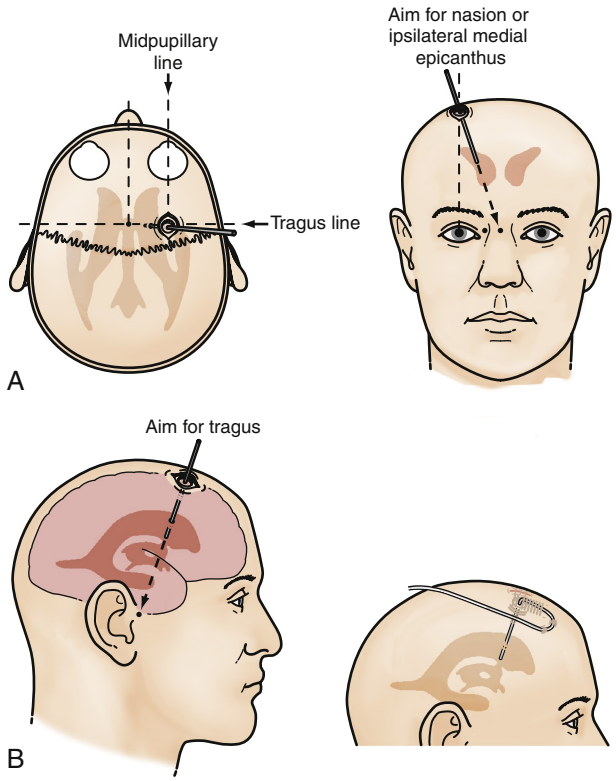

Figure 37.2. Schematic representation of landmarks used for ventriculostomy catheter placement. (A) In the mediolateral plane, one should aim for the ipsilateral medial epicanthus. (B) In the anteroposterior plane, one should aim for the ipsilateral tragus.

device, given its monitoring and therapeutic capabilities. However, an EVD has several weaknesses. Accurate placement of an EVD may be difficult with the freehand technique. In a recent survey of practicing neurosurgeons and residents, the success rate of cannulation of the ventricle was just 82%, even in the hands of practicing neurosurgeons.[25] Currently, there is an EVD placement guide available that may increase the accuracy of placement of EVDs, although it is not widely used in the neurosurgical community.[26] In some patients, it is simply not possible to place an EVD because of the small size of some ventricles or ventricular shift as a result of a mass lesion or severe edema.

Complications from EVD placement for ICP monitoring and CSF diversion include malposition, occlusion, hemorrhage, and infection. The malposition rate of EVDs ranges from 4% to 20%.[28–31] Most of the misplaced EVDs did not cause any significant clinical sequelae, but about 4% of these EVDs did require replacement.[28,29,31] Occlusion by brain matter or blood clot occurs frequently, especially in patients with intraventricular hemorrhage or SAH.[28] Most of the occlusions can be resolved by flushing the EVD catheter.[28] Hemorrhage secondary to EVD placement occurs infrequently. Hemorrhage rates ranging from 0% to 15% have been reported in the literature, with an average rate of 1.1%.[24,29,31–33] Fortunately, most patients are asymptomatic from EVD-associated hemorrhage.[29,33] Clinically significant hemorrhage requiring surgical evacuation occurs about 0.5% of the time and results in intracerebral, subdural, and epidural hematoma.[29,31,33] Coagulopathy is thought to be associated with an increase in hemorrhage rate, and therapeutic anticoagulants and antiplatelet agents are also known to be associated with an increased risk for hemorrhage.[34,35] In addition, laceration of a cortical artery can lead to traumatic pseudoaneurysm formation, and this complication has been reported with placement of ICP monitors.[36]

The most significant risk associated with an EVD is infection. Biofilms have been isolated on 73% of EVD catheters after a median length of use of just 4 days.[37] Lozier and coworkers performed an extensive review of all literature on infection associated with EVDs.[38] The range of infection in all of the series was 0% to 22%, with a cumulative incidence of 8.8%.[27] More recent studies have found a similar rate of infection.[39–41] Clinical characteristics that have been identified to be related to increased EVD-associated infection include intraventricular hemorrhage, SAH, craniotomy, CSF leakage, systemic infection, increased CSF output, a history of diabetes mellitus, and depressed skull fracture.[38,39,42,43] Technical factors that may contribute to CSF infection include the duration of catheterization and irrigation of the catheter.[38] In 17 studies reviewed by Lozier and colleagues, 10 studies found an association between the duration of catheterization and infection, whereas 7 did not find such an association.[38] Careful inspection of the raw data of the latter group showed that there was an increased risk for infection after day 10 in one study.[38] More recent studies also showed an increased risk for infection with longer duration of catheterization.[39,41,44] Most studies have reported that there are few infections during the first 5 days of drainage and monitoring with an EVD but that the infection rate increases significantly after 5 to 10 days of catheterization.[31,45,46]

Because of the relatively high rate of CSF infection in patients with EVDs, multiple interventions have been used in an attempt to minimize the infection rate. However, most studies are retrospective in nature and often do not have enough statistical power to detect small absolute differences in the incidence of infection.[38] Such interventions are discussed in the following sections.

Venue of External Ventricular Drain Placement

Lozier and coworkers analyzed five studies that looked at whether there is a difference in infection rates in EVDs placed in the operating room, ICU, or emergency department[38] All but one of the studies revealed no significant difference in infection rate whether the EVD was placed in the operating room, ICU, or emergency department.[38] Two more recent studies also did not find statistically significant differences in infection rate related to the venue of ventriculostomy drain insertion.[41,44]

Extended Tunneling

Subcutaneous tunneling of the EVD catheter was reported by Friedman and Vries in 1980 as a way to reduce the infection rate.[27] Other investigators then extended the distance of tunneling to the upper part of the chest or abdomen and had an infection rate of 4%.[47] Two studies reported conflicting results. Sandalcioglu and Stolke reported that there was a significant difference in infection rate (83% vs. 17%) for catheters that were tunneled less than 5 cm subcutaneously versus catheters that were tunneled more than 5 cm, respectively.[48] However, patient details were not available, and the infection rate of 83% in this study is significantly higher than most reported infection rates. Leung and coauthors, in contrast, did not find a significant difference in infection rate with long-tunneled EVDs.[49] Most EVD insertion kits today contain a trocar for subcutaneous tunneling in excess of 5 cm.

Prophylactic Catheter Exchange

The observation that the infection rate rises with increased duration of drainage from an EVD prompted several investigators to advocate prophylactic catheter exchange.[31,46] Several

retrospective studies, however, showed no benefit of prophylactic catheter exchange, and there was, in fact, a higher incidence of infection in the group in which catheters were routinely exchanged.[38] This was also observed in one prospective, randomized trial comparing the infection rate in a group that underwent prophylactic catheter exchange versus a control group that did not undergo prophylactic catheter exchange.[50]

Prophylactic Antibiotic Use

Many studies have analyzed the use of prophylactic antibiotics for reduction of the infection rate of EVDs. Prophylactic antibiotics can be given periprocedurally only or administered during the entire duration that the catheter is in place. Studies in the 1970s suggested that prophylactic antibiotics did reduce the infection rate when compared with no antibiotics, but two studies conducted in the 1980s and one study in 2000 did not find any reduction in the EVD infection rate in patients who received periprocedural antibiotics versus patients who did not.[38,51,52] Several other studies also compared prophylactic antibiotics given just periprocedurally versus during the entire duration when the EVD is in place. In a large retrospective study, Alleyne and colleagues did not find any significant difference in infection rates between the two groups.[53] In a prospective, randomized controlled study, however, Poon and associates did find a reduction in CSF and systemic infection in the group that received prolonged antibiotic prophylaxis.[54] It should be noted that infections that develop in patients who receive prolonged or broad-spectrum antibiotic prophylaxis, or both, for EVD placement are often caused by more virulent microorganisms such as *Candida* and gram-negative organisms.[53-64] Currently, the Guidelines for the Management of Severe Traumatic Brain Injury do not recommend antibiotic prophylaxis for EVD placement or catheterization.[56]

Antibiotic-Impregnated Catheter

A recent development in EVD catheter technology is the antibiotic-impregnated catheter. An EVD catheter impregnated with rifampin is capable of releasing rifampin in a controlled-release manner. These EVD catheters have been shown to significantly reduce bacterial adhesion versus controls in vitro and in animal models.[57] In one randomized controlled trial, Zabramski and coworkers showed that a catheter impregnated with minocycline and rifampin reduced the infection rate significantly from 9.4% to 1.3% when compared with the nonimpregnated catheter control group.[58] Although antibiotic-impregnated catheters cost significantly more than nonimpregnated catheters, one also must consider the overall expense and length of hospital stay for patients with EVD catheter–related infections.

Silver-Impregnated Catheters

Silver has known bactericidal properties. Recent studies have examined using silver-impregnated EVD catheters. These studies have some promising data, but the results are mixed. There have been no randomized trials. Two meta-analyses of observational studies have shown superiority of silver-impregnated catheters over plain catheters, but not over antibiotic-impregnated catheters.[65,66]

Fiberoptic Intracranial Pressure Monitor

Fiberoptic devices for ICP monitoring in which the catheter tip measures the amount of light reflected off a pressure-sensitive diaphragm were developed in 1980s.[59] The most widely studied fiberoptic device is the Camino fiberoptic ICP monitoring device (Integra Neuroscience, Plainsboro, NJ). The Camino fiberoptic ICP monitoring device can be placed in the subdural, intraparenchymal, and intraventricular space.

The intraparenchymal Camino ICP monitor has the most extensive clinical experience. The main strength of the intraparenchymal ICP monitor is ease of insertion. The most commonly used technique involves insertion of the monitor into the right frontal region, although it is possible to insert the probe into a region with pathology as well. However, it should be noted that compartmental pressure differentials have been observed in different regions of the brain, so the choice of where to insert the monitor is important.[60,61] Because there is no need to cannulate the ventricular system, it is possible to insert the ICP monitor even in patients with severely compressed ventricles or those with a significant midline shift. Although this device has led to more widespread use of ICP monitoring in critically injured and ill patients, there are reports of some technical issues that should be kept in mind when using these devices.

A number of early studies demonstrated that there is a high correlation between ICP measured by the intraparenchymal Camino ICP device and ICP measured by an EVD, with a correlation coefficient (r) greater than 0.9 in both studies.[62] However, Schickner and Young found that the Camino overestimated ICP by an average of 9 mm Hg when compared with an EVD in 10 patients.[63] Nevertheless, because of its ease of insertion and low complication rate, it has gained popularity since its introduction to the market. Many large clinical series involving the intraparenchymal Camino device have been published, and overall clinical experience with the Camino as an ICP monitoring device has been positive.[60–62,64,67] Several studies have retrospectively examined EVDs versus intraparenchymal monitors (IPMs) with mixed results.[68–71] A 2019 meta-analysis by Volovici et al. examined these studies and found that the quality of studies was poor. The pooled analysis showed a higher rate of complications with EVD but no difference in mortality or functional outcome between the groups.[72] This is an area that needs further investigation.

Complication rates associated with the Camino intraparenchymal device are comparatively low. In one large series of more than 1000 patients, the hemorrhage rate was just 2.5%, and the hemorrhages were all clinically silent.[64] In the same series, there was no clinical infection.[64] In other series, the hemorrhage rate ranged from 0% to 5.1%.[60–62,67,73] Surgical evacuation was required in one patient in all series.[73] The infection rate is also lower than that with an EVD. Although colonization of the catheter is frequent, meningitis occurred in just three patients in all series.[61,67,73]

The most significant problem of the Camino fiberoptic device is zero drift. The device is first zeroed to atmospheric pressure (usually at room temperature) and then inserted into the brain parenchyma. Recalibration cannot be performed unless the transducer is removed from the patient, zeroed, and then reinserted. Zero drift then occurs over time, which will lead to an erroneous ICP reading. According to the manufacturer, the drift for the first 24 hours should be only 2 mm Hg and then should be 1 mm Hg for the first 5 days. However, clinical studies have shown that the daily drift is significantly larger than the manufacturer's specification. Daily drift rates of 0.5 to 3.2 mm Hg have been reported, and the maximal drift reported in most studies is usually greater than 20 mm Hg (positive or negative).[62,64,67,73] In most clinical series, recalibration was often needed, and this was often discovered when the clinical picture did not match the ICP reading or a negative ICP reading appeared on the monitor.[64,73] However, there has been no report of erroneous ICP reading resulting in clinical mismanagement, such as missing an enlarging mass lesion.

The Camino intraparenchymal device may be associated with mechanical problems. This was especially the case during the early study period because health care personnel were not familiar with

the device, and proper precaution in handling and securing the device was not taken. The fiberoptic cables are delicate and can be broken easily during transport or with patient movement. As many as 10% to 23% of the fiberoptic devices had a mechanical malfunction because of breakage of the cable, dislocation of the probe, or other unknown factors.[62] More recently, the rate of mechanical complication has been lower at about 5%.[64]

Currently, the Camino fiberoptic probe can also be inserted intraventricularly or in the subdural space. The intraventricular Camino bolt allows concurrent CSF drainage and ICP monitoring through the fiberoptic Camino bolt. ICP measurement through the fiberoptic device placed intraventricularly correlates well with ICP measured through an external strain gauge, with 97% of the readings being within 5 mm Hg.[74]

The Camino fiberoptic device can also be inserted into the subdural space. The subdurally placed monitor is marketed as a postcraniotomy monitor, although there are no large-scale clinical studies to evaluate its accuracy. In addition, the Camino fiberoptic device can also be inserted with a temperature probe or brain tissue oxygen probe.

Miniature Strain Gauge

A miniature strain gauge transducer has also been developed to monitor ICP, with the Codman MicroSensor ICP Transducer (Codman, Raynham, MA) being the prototype. The Codman MicroSensor has a microchip pressure sensor at the tip of a flexible nylon cable that produces different electrical resistance based on pressure.[75] This MicroSensor can be placed in various compartments, including the ventricle, parenchyma, and subdural space. Gopinath and associates compared ICP measured by an intraventricularly placed MicroSensor with ICP measured by an EVD connected to an external strain gauge.[75] There was excellent correlation between the two measurements, with a correlation coefficient of 0.97, and 90% of the readings were within 4 mm Hg of each other.[75] Drift was minimal, with only 0.2 mm Hg of drift observed.[75] For intraparenchymal ICP measurement, the miniature strain gauge appears to be less accurate. When ICP readings measured by an intraparenchymally placed sensor were compared with ICP from a ventriculostomy drain, Signorini and colleagues found that there was a constant offset between the two ICP readings that led to erroneous ICP readings from the MicroSensor.[76] Similarly, Banister and coworkers found significant differences in ICP measurement from a parenchymal MicroSensor and a Camino ICP monitoring device.[77] Moreover, several episodes of raised ICP with clinical significance were captured by the Camino ICP monitoring device but not by the MicroSensor in this particular study.[77]

A more recent study analyzed clinical use of the miniature strain gauge in 128 patients.[78] The authors reported good clinical usefulness of the MicroSensor for ICP monitoring in neurocritical care patients, with no infection and no clinically significant hematomas noted ("several minor hematomas" were observed, however).[78] Drift was just 0.9 mm Hg in this study.[60] In 22 patients, a ventriculostomy was also performed, and ICP data from the two methods were compared.[79] The authors reported good correlation of ICP measured by the two methods (r = 0.79), and a Bland-Altman plot revealed good concordance.[78] Careful inspection of the raw data, however, revealed a mean difference of –1.2 mm Hg on the Bland-Altman plot, with a standard deviation of about 3 mm Hg. Inspection of the scatter plot data also revealed that a difference of more than 5 mm Hg was found frequently as well.

Two studies analyzed the MicroSensor placed in the subdural space. These studies found that ICP measured by the MicroSensor placed in the subdural space had good correlation with pressure measured by a fluid-coupled transducer placed in the subdural space as well as with pressure measured by a MicroSensor placed in the parenchyma.[80] However, this was not compared with ICP measured by either ventriculostomy or other devices. In one series from Taiwan, the MicroSensor was used to monitor ICP in 120 patients with TBI.[81] There were no complications from monitor placement.[81] Comparison of ICP measured by the subdurally placed MicroSensor with that measured by a ventriculostomy drain was done in 22 patients.[81] The observed difference in pressure was –1 to –4 mm Hg, although no statistical analysis was performed in this case.[81]

Spiegelberg Parenchymal Transducer

The Spiegelberg Brain Pressure Monitor (Spiegelberg, Hamburg, Germany) uses an air pouch situated at the tip that is maintained at a constant volume. The pressure transducer is located in the ICP monitor, and recalibration to ambient pressure can be performed easily. Two studies evaluated the accuracy of ICP measured with the Spiegelberg pressure sensor (intraparenchymal or subdural placement) versus ICP measured by ventriculostomy. Both studies revealed good correlation of ICP measured by the Spiegelberg pressure sensor with that measured by ventriculostomy.[79,82] The initial clinical experience in 87 patients was positive, with no infection, one small hemorrhage, and a 3.4% mechanical complication rate.[79]

Hummingbird Synergy

The Hummingbird Synergy (InnerSpace NeuroSolutions, Tustin, CA) is an access device with an integrated parenchymal ICP monitor, a ventricular drainage system, and probe ports for multimodality monitoring. The unit has a single port with a titanium bolt. Once it is secured into the cranium, the trajectory of the ventricular catheter is limited to 4 degrees of angular variation during advancement. Two additional side ports can be used to place two additional probes, such as a brain tissue oxygenation monitor, 30 mm below the dura and angled 30 degrees away from the axis of the bolt. In one series, placement of the ventricular catheter was successful 93% of the time within the first two attempts. This was associated with a 10% rate of hemorrhage as identified on immediate postprocedural CT scan.[83]

In addition to the ports for the ventricular catheter and multimodality monitoring probes, the Hummingbird also has an integrated parenchymal ICP monitor. An air bladder positioned along the ventricular catheter transmits pressure waves along an air column charged with a precise amount of air. Once zeroed during the insertion process, this system provides an ICP recording with minimal artifact and is immune from positional changes. A direct comparison of the Hummingbird parenchymal and EVD measurements showed congruence within ±3 mm Hg in 93% of over 2000 recordings.[84] The Hummingbird parenchymal monitor is a viable alternative for ICP monitoring when placement of an EVD catheter is unsuccessful because of distorted anatomy.

Telemetric Intracranial Pressure Monitoring

Bedside ICP monitoring with EVD or intraparenchymal devices offers continuous ICP recordings but has several limitations. Patients are hospitalized, usually in the ICU, and are tethered to the monitoring apparatus with limited mobility. These percutaneous devices are at risk for dislodgement during patient care and transport and in uncooperative patients. They provide only a short-term monitoring solution and may offer limited insight in certain clinical scenarios.

Telemetric ICP monitoring systems offer the possibility of long-term ICP monitoring, especially during everyday conditions outside the hospital. Early systems were used to monitor ICP in patients after posterior fossa tumor resection

and in hydrocephalus patients after shunt insertion.[85,86] In 2011, the PTel implantable telemetric ICP monitoring system produced by RAUMEDIC became commercially available (PTel; RAUMEDIC; Mills River, NC). The system consists of an implantable probe, a reading device, and a portable recording device. The telemetry ICP probe consists of an intraparenchymal pressure sensor at the tip and is connected to a subgaleal transducer at the other end. The probe is implanted through a bur hole into the frontal parenchyma. Once the probe has been implanted, the ICP is measured by placing the external reader unit over the unit. ICP data are transmitted through the scalp and are finally registered by the recording device with a frequency of 1 or 5 Hz. Long-term animal testing showed reliable recording for at least 12 months.[87]

Early clinical experiences with the RAUMEDIC telemetric intraparenchymal ICP monitoring system have shown that outpatient long-term ICP monitoring is safe and can direct management decisions.[88–91] In a series of 185 patients with suspected or known hydrocephalus, the RAUMEDIC telemetric system was implanted for diagnostic purposes.[90] The patients were monitored for 3 to 409 days (mean 60.7 days). In 81% of patients with suspected ICP disorders, telemetric ICP monitoring led to definitive CSF diversion procedures. In patients with suspected shunt obstruction or overdrainage, telemetric ICP monitoring confirmed the diagnosis in 77% and 96% of patients, respectively. There was a 5.9% overall complication rate associated with implantation of the telemetric probe. One case of intracranial abscess and two cases of superficial infection occurred. Postimplantation imaging was obtained in 160 patients. Of these, there was a 15.6% incidence of hemorrhage of any size. Only one case of postprocedural hemorrhage was associated with neurological deficits. There was a 46.9% incidence of postimplantation-associated cerebral edema as demonstrated by postprocedural imaging. Of these, eight cases were associated with implantation-related complications, including infection, abscess, and new-onset seizures.

The RAUMEDIC device has been used in the ICU setting for continuous ICP monitoring as well. In 17 patients, it showed good functioning throughout their ICU stay, for a median of nearly 8 days, with the signal quality and stability being sufficient for clinical decision making.[92] The RAUMEDIC device was compared with the Meithke Sensor Reservoir shunt system (Meithke, Aesculap, Germany), which found that the RAUMETIC system was better for continuous monitoring than the Meithke system.[93]

EMERGING TECHNOLOGY

Compliance Monitor

A physiologic variable related to ICP is intracranial compliance. *Compliance* is defined as the change in volume per unit change in pressure. A low-compliance state means that a small change in volume will lead to a large change in pressure. A low-compliance state may therefore identify patients at risk for increasing ICP. The Spiegelberg Compliance Monitor uses the Spiegelberg Brain-Pressure Monitor as the sensor. To measure compliance, the monitor injects a small amount of air into the air balloon pouch and measures the pressure response to this change in volume. Calculation of compliance is then based on the changes in pressure during 200 cycles. The usefulness of compliance monitoring in the clinical setting is still unknown. Limited data suggest a significant inverse relationship between compliance and ICP in patients with TBI and tumor.[94] A less clear relationship exists for patients with hydrocephalus or SAH[94] Abnormal compliance in TBI patients or those with thalamic hemorrhage has been shown to return to normal with surgical intervention based on a small number of patients.[95,96] Currently, compliance monitoring is still at an experimental stage; preliminary data, however, suggest potential usefulness in the clinical setting.

Noninvasive Intracranial Pressure Monitoring

Since the 1960s, there has been a continuous effort to develop less invasive or noninvasive ICP monitors. CT characteristics, clinical examination findings, and monitored pressure in the epidural space have all been shown to be unreliable surrogates for ICP measurement.[97,98] There have been numerous reports of promising technologies for measuring or deriving ICP noninvasively, although none is being used clinically on a large scale. Several techniques that have been studied more extensively are discussed in the following paragraphs.

Noninvasive ICP monitoring technology can be divided into several categories. In one category, the eye or the ear is used as a window into the cranium.[99] A number of structures in the eye and the ear communicate with the CSF space and should therefore be influenced by ICP as well. The optic nerve is surrounded by the subarachnoid space and a dural sheath, and the subarachnoid space will expand in the presence of increased ICP.[100] Therefore, optic nerve sheath diameter (ONSD), which can be measured by ultrasonography, correlates with ICP.[100] Multiple studies have demonstrated a strong linear relationship between ONSD and ICP, but the critical value of ONSD for detecting elevated ICP (ICP >20 mm Hg) is different in the various studies, thus limiting its potential use at this time.[100,101] Ultrasound ONSD measurement has been shown to have better diagnostic accuracy than MRI ONSD or CT ONSD measurement.[102] Ultrasound OSND measurement at admission has been shown to correlate with mortality, potentially allowing it to be useful as a screening or triage tool.[103]

A similar principle is used by venous ophthalmodynamometry, which measures venous opening pressure (VOP), to calculate ICP.[104] In one study of 21 patients, VOP correlated well with ICP.[104] In 10 of 18 patients with ICP lower than 40 mm Hg, the calculated ICP from VOP was within 4 mm Hg of the measured ICP.[104] The biggest drawback of venous ophthalmodynamometry is that it requires dilation of the pupil to perform the measurement and thus takes away one of the most critical neurological examination parameters in a comatose patient. In addition, both ONSD and VOP measurement can be performed only intermittently and therefore is used just as a screening tool for ICP elevation rather than as a continuous monitoring tool.

Cochlear fluid pressure is thought to be related to ICP and can be indirectly measured by tympanic membrane displacement.[99] A number of studies have been performed to evaluate its use as a surrogate for ICP, and the results have been mixed.[99] Although there is a correlation between the two parameters, tympanic membrane displacement does not reliably predict ICP because of a wide predictive limit on linear regression.[105]

In another category, ICP measurement is based on the principle that increased ICP leads to changes in patterns of blood flow velocity in the intracranial arteries, which can be assessed by transcranial Doppler (TCD) imaging.[106] The middle cerebral artery (MCA) is considered a biologic pressure transducer whose vessel wall deflects in response to transmural pressure, modulating according to the pulsatile waveform of the cerebral blood flow velocity.[107] ICP can then be derived with various mathematical models by using the blood flow velocity data and variations in TCD waveform morphologies.[106,108] Several models have demonstrated the potential of these methods and shown that the derived ICP is within 6 mm Hg most of the time.[106,108] A recent comparison of four TCD-based algorithms for noninvasive ICP measurements against intraparenchymal monitoring in TBI patients showed moderate but significant correlations in reporting average ICP values during a single

recording session. However, none of the noninvasive methods provided satisfactory accuracy for detecting ICP changes across time.[107] Limitations of the TCD-based noninvasive ICP methods include dependence on operator experience, quality of recordings, and noncontinuous recordings. Furthermore, certain fundamental characteristics of the MCA as a biologic transducer, such as its linearity, stability, and calibration coefficients, are unknown, thus limiting the accuracy of TCD-based ICP estimations. Despite these shortcomings, TCD may have potential clinical usefulness for detection of cerebrovascular derangements in the setting of intracranial hypertension. As ICP increases and cerebral perfusion pressure (CPP) decreases, characteristic changes in flow velocity patterns can be detected by TCD.[109] Some studies have suggested that TCD-derived values such as pressure reactivity index may be more accurate than those derived from traditional ICP monitoring.[110]

Delay in visual evoked potentials has also been observed in patients with increased ICP.[111] In the 1980s, the delay in visual evoked potentials was studied in pediatric patients with hydrocephalus and cerebral edema and found to have a significant correlation with ICP.[112] Currently, one commercial ICP monitor (NIP-200 noninvasive ICP monitoring system; Chongqing Haiweikang Medical Instrument Co., Chongqing, China) is available in China that derives ICP measurement from this principle. In one study, Zhao and colleagues found that ICP measurements with this monitor correlated well with ICP obtained by lumbar puncture opening pressure or ICP measured in the epidural space.[111] In another study, this monitor was used to monitor ICP and guide mannitol therapy in patients with intracerebral hemorrhage.[113] Per report, this monitor had been used in more than 2000 patients by 2005.[88,111]

PEDIATRIC INTRACRANIAL PRESSURE MONITORING

Only a few studies have been dedicated to the study of ICP monitoring in pediatric patients. In the *Guidelines for the Management of Pediatric Severe Traumatic Brain Injury*, third edition, ICP monitoring is suggested to improve overall outcomes in patients with TBI and has a level III recommendation.[114] One study from the United Kingdom has shown that ICP monitoring was used 60% of the time in pediatric patients with severe TBI, which is a very high rate compared with adults.[115] However, it has been noted by others that monitoring in infants younger than 1 year of age is very infrequent.[116]

Techniques of ICP monitoring vary from center to center and include EVDs, intraparenchymal ICP monitors, and subdural monitors.[115,117,118] The complication rate of ICP monitoring in pediatric patients is probably comparable to that in adults. In one study, malposition of the EVD was noted 8.8% of the time.[117] Hemorrhage was observed in 17.6% of patients, although clinically significant hemorrhage requiring intervention was observed in just one patient (1.6%).[117] Infection was observed in only one patient (1.6%).[117] Although the hemorrhage rate and malposition rate were higher in this study than the cumulative adult rate, only 62 patients were studied in this report.[117] For intraparenchymal monitors, the hemorrhage rate was 6.4% in one study and 10% in another study, and all of these hemorrhages were silent.[117,119] There is no report on the correlation of ICP measured by ventriculostomy versus other devices in these studies.

CONCLUSION

ICP monitoring and ICP-directed treatment remain the cornerstone of contemporary neurocritical care. Although it was developed more than 70 years ago, an EVD connected to an external strain gauge remains the most reliable, cost-effective, and accurate method for monitoring ICP. It is also the only ICP monitoring technique that allows CSF drainage as well. However, EVD placement is associated with a significant rate of infection and a small but significant rate of hemorrhage.

Intraparenchymal monitors have gained increased popularity in the past decade. These monitoring devices are easy to insert and have a low complication rate. Although these monitors have significant problems related to zero drift and mechanical failure, clinical experience with these monitors is positive regarding their use in ICP monitoring and management. Moreover, some of these intraparenchymal monitors can be inserted along with other monitoring devices such as brain temperature or brain tissue oxygenation monitoring devices for advanced neurophysiologic monitoring.

The field of ICU monitoring technology is changing at a rapid pace. Newer technologies such as wireless data transfer and noninvasive monitoring are coming to the ICU in the near future. Although it is easy to generate an enormous amount of data in the ICU, how to interpret, integrate, and use these data for managing a critically ill patient remains an art that must be mastered by every ICU physician.

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