Advances in ICP monitoring techniques

Jun Zhong, Manuel Dujovny, Hun K. Park, Eimir Perez, Alfred R. Perlin and Fernando G. Diaz

Biomechanics Laboratory, Department of Neurological Surgery
Wayne State University School of Medicine, Detroit, MI, USA

With the advent of newer devices for measuring intracranial pressure (ICP) and cerebral metabolism, more alternatives continue to rise aiming to control ICP. This manuscript presents a proposed analysis of different ICP monitoring devices in order to make appropriate selection of them in our clinical setting including general and pediatric applications. A systematic review of the literature was made analyzing the technical advances in ICP monitoring. The recent invitro and invivo tests as well as mathematical/computer models were reviewed. Practical applications of principles were discussed and compared based on the mode of pressure transformation. A ventricular catheter connected to an external strain gauge transducer or catheter tip pressure transducer device is considered to be the most accurate method of monitoring ICP and enables therapeutic CSF drainage. The significant infections or hemorrhage associated with ICP devices causing patient morbidity are clinically rare and should not deter the decision to monitor ICP. Parenchymal catheter tip pressure transducer devices are advantageous when ventricular ICP cannot be obtained or if there is an obstruction in the fluid couple, though they have the potential for significant measurement differences and drift due to the inability to recalibrate. Subarachnoid or subdural fluid-coupled devices and epidural ICP devices are currently less accurate. With an increasing miniaturization of the transducers, fiberoptic systems have been developed, however, there is a problem of measurement accuracy during the period of patient monitoring and external calibration should be performed frequently to ensure constant accuracy. Ventriculostomies continue to have a pivotal role in ICP control. With a rational understanding of the applications and limitations of the different ICP monitoring devices, the outcome for critically ill neurological patients is optimized. [Neurol Res 2003; 25: 339–350]

Keywords: Intracranial pressure; monitoring; sensor; fiberoptic; strain gauge; pneumatic

INTRODUCTION
During the middle of the 1990s, the measurement of intracranial pressure (ICP) was done indirectly by means of lumbar cerebrospinal fluid (CSF) pressure monitoring1,2, which was pioneered by Guillaume and Janny in 19513. The advent of routine direct monitoring of ICP began in 19604 and is credited to Lundberg5, who described the method of directly monitoring the fluid pressure in the ventricle. The next milestone in ICP monitoring came in 1973 with the introduction of the subarachnoid screw (bolt)6, which led to the development of other methods of monitoring ICP, including the subdural cup catheter7, extradural monitors8, and the fiberoptic catheter. Since then, due to the development of catheter-tip pressure transducers, parenchymal monitoring has also been utilized9. Each type of device, depending on the intracranial location and method of pressure transduction, has its advantages and disadvantages. An optimal device would meet various specific requirements: accuracy of absolute measurements (tolerance), constant values over timely measurements (drift), low dependency from previous or consecutive measurements (hysteresis), accuracy of repeated measurements (validity), and accuracy of the absolute value dependent on the magnitude of the value (linearity).

INTRACRANIAL LOCATION OF THE ICP SENSOR
Current ICP devices can be placed in either epidural, subdural, subarachnoid, parenchyma, or ventricular locations.

Intraventricular
These are essentially open-ended conduits placed directly into the ventricular CSF5. This method, consisting of a fluid-coupled device, is considered the gold standard for measuring ICP, and to which all new methods must be compared for reference. Using a three-way stopcock, one of the extracranial ends can be used to intermittently drain CSF, and the other can be attached to a pressure transducer via saline-filled tubing for continuous ICP recording. The catheter may also be used to instill selected medications into the CSF such as thrombolytic agents in cases of intraventricular hemorrhages or clotting at the proximal catheter, or the use of antibiotics in cases of ventriculitis. However, a ventriculostomy has the disadvantage that it penetrates the meninges and brain, which gives the risk of bacterial transmission through the fluid coupling. The ventriculostomy catheter can be difficult to place when there is compression or shift of the ventricles. In such cases, the ICP waveform may be dampened and the values
recorded by the catheter may be low due to artifact effect. Fluid leaks may be located at the port of entry of the catheter in the skin, through a stopcock, or due to a chink in the catheter resulting in erroneous and low ICP values. Air bubbles, blood clots, and brain or other debris can all interfere with the pressure wave conduction from the ventricles to the external transducer resulting in incorrect ICP readings. The transducer position needs to be readjusted each time the level of the patient’s head is changed in order to ensure reliable pressure values. Draining CSF and measuring ICP at the same time has inaccurately shown low ICP measurements not reflecting the actual ICP. This function requires the two measurements to be performed separately. The potential risks of misplacement, infection, hemorrhage, and obstruction have led to finding alternative intracranial sites and devices for ICP monitoring. We need to highlight that ventriculostomy continues to be the gold standard modality and the initial consideration in most circumstances. However, other ICP measurement modalities such as intraparenchymal transducers are gaining relative priority in selected cases. They are especially helpful in those situations where ventricles are small or slit with significant brain swelling.

Subarachnoid

These fluid-coupled systems connect the intracranial compartment to an external transducer via tubing. The subarachnoid bolt is a hollow screw that goes into the skull abutting the dura. The dural membrane is perforated allowing CSF to fill the bolt, and their pressures to become equal. Then the closed fluid tubing transmits the pressure in this space. Even though infection and hemorrhage risks are low, these devices are quite prone to errors including ICP underestimation, misplacement of the screw, and occlusion by debris.

Epidural

ICP monitoring from the epidural space is an attractive concept, as the dura does not have to be opened, the placement of the monitoring device is easy, and there may be a low incidence of serious infection and hemorrhages. However, these devices are prone to malfunction, misplacement, and baseline drift after a few days of continuous usage. The inaccuracy obtained is the result of the relatively inelastic dura that transmits the pressure from the CSF to the sensor rather than inaccuracy of the equipment.

Intraparenchymal

There are currently two types: fiber-optic and wire. The first one is made of thin fiber optic cables with a pressure transducer at the tip that requires a dedicated microprocessor to interpret the signal, which is also expensive, nonflexible, and liable to breakage. The wire system contains a micro-transducer at the tip of a flexible wire. This system is interfaced to be used with standard bedside monitors. In both types, the tip is introduced into the parenchyma through a 4 mm hollow screw inserted into the skull. Infection and hemorrhage rates are quite low, but these devices do not allow for CSF drainage. Accuracy is reliable and optimal, second only after intraventricular catheterization, and the device needs to be calibrated only once before insertion regardless of the head height level used.

Table 1: Features of monitoring devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Advantages</th>
<th>Pitfalls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraventricular catheter</td>
<td>Gold standard of accuracy&lt;br&gt;Allows drainage and sampling of CSF&lt;br&gt;Allows ICP control&lt;br&gt;Inexpensive</td>
<td>Most invasive&lt;br&gt;Sometimes difficult to cannulate ventricle&lt;br&gt;Catheter can be occluded by blood or tissue&lt;br&gt;Needs reposition of transducer level with change in head position&lt;br&gt;Potential infection</td>
</tr>
<tr>
<td>Subarachnoid bolt/screw</td>
<td>Quickly and easily placed&lt;br&gt;Does not invade brain&lt;br&gt;Allows sampling of CSF&lt;br&gt;May have lower infection rate</td>
<td>Blocked by swollen brain&lt;br&gt;Catheter can be occluded by tissue or blood&lt;br&gt;Must be balanced and recalibrated frequently</td>
</tr>
<tr>
<td>Subdural, epidural catheter/sensor</td>
<td>Least invasive&lt;br&gt;Easily and quickly placed</td>
<td>Increasing baseline drift over time, accuracy and reliability are questionable&lt;br&gt;Does not provide CSF sampling</td>
</tr>
<tr>
<td>Fiberoptic probe/Catheter tip strain gauge</td>
<td>Can be placed in the subdural, subarachnoid, intraventricular or intraparenchymal spaces&lt;br&gt;Easily transported&lt;br&gt;Minimal artifact and drift&lt;br&gt;High resolution of waveform&lt;br&gt;No irrigation less risk of infection&lt;br&gt;No need to adjust for patient position</td>
<td>Cannot be recalibrated after it is placed, unless a ventriculostomy is used simultaneously for reference&lt;br&gt;Breakage of the fiberoptic cable&lt;br&gt;High Cost</td>
</tr>
</tbody>
</table>

CSF, cerebrospinal fluid; ICP, intracranial pressure.
ICP monitored by means of parenchymal catheter-tip strain gauge or subdural catheter fluid-coupled device has been reported to be similar to ventricular ICP. While parenchymal or subdural monitoring locations have been supported in the literature to have accurate monitoring features; fluid-coupled epidural devices, subarachnoid bolts, and pneumatic epidural devices have been reported to have significantly different ICP readings as compared to ventricular ICP. However, other investigators have found that subdural and parenchymal fiberoptic catheter-tip pressure value does not always correlate well with ventricular ICP.

SENSORS
The first ICP microtransducers were introduced in the 1980s. Other than early laboratory prototypes, the first commercial design was the Honeywell Microtransducer Catheter MTC-P5F. It was initially designed for intra-parenchymal pressure measurement. The first microtransducer to be widely used was the fiberoptic Camino OLM ICP Monitor (Camino Laboratories, San Diego, CA, USA). It required a dedicated microprocessor-driven amplifier to provide a numerical value and/or continuous waveform display. However, the high price of the system and its disposable features prevented many neurosurgical centers from using this microtransducer-based ICP monitor.

Strain gauge catheter tip
This transducer tip contains a silicon microchip with diffuse resistant strain gauges. The diaphragm is coated with a thin layer of silicone rubber to insulate the transducer from the environment into which it is placed. The strain gauges are connected via tiny wires that extend through the length of the flexible nylon tube to complete a wheatstone bridge type circuit located in the connector housing.

Studies have found the Codman MicroSensor to be accurate, with an average difference of -0.5 to + 2.6 mmHg between the MicroSensor reading and an intraventricular fluid coupled external strain gauge transducer. It is stable, with a daily drift that varies between -0.13 to + 0.11 mmHg per day. The average zero drift of the MicroSensor measured at air pressure was 0.2 ± 0.5 mmHg for the average duration of 3.8 ± 1.6 days. It has a high fidelity with a frequency response greater than 10,000 Hz, which is achieved by the elastic properties of silicon, small overall size of the diaphragm and tiny volumetric displacement under pressure. When this is incorporated into a ventricular catheter, the system allows simultaneous drainage of CSF and ICP recording. It is flexible, and can be tunneled beneath the scalp, preventing it from being easily broken. Its small size (a nominal outer diameter of 0.7 mm for the nylon vent tube and 1.2 mm for the transducer case) is an additional advantage, particularly for pediatric patients. The absence of a fluid column precludes dampening by blood clots, debris, or air bubbles. Since irrigation is not needed, there is a low risk of infection.

Fiberoptic catheter tip
Fiberoptic transducers can be easily placed through the working channel of the endoscope and have interposed assembly. It is characterized as having very low zero drift over long periods of time, very good frequency response, and stable linearity. Crutchfield et al. reported that the device had an accuracy of ± 3 mmHg over a 0 to 30 mmHg range in vitro. The maximum daily drift was ± 2.5 mmHg, with an average daily drift of ± 0.6 mmHg and the drift rate over a 5-day period was ± 2.1 mmHg. In vivo, the pressures and waveform characteristics were very similar between the fiberoptic device and a strain-gauge transducer connected to a ventriculostomy. A very important advantage is that a pressure-sensitive element is placed in the head, so the risk of infection is minimized. This gives it an advantage over prolonged ICP monitoring, which uses a fluid-filled catheter and external transducer. They allow for continuous recording and monitoring of ICP in different brain compartments and give accurate pressure readings, making possible the analysis of waveforms in the compartment where the probe is placed.

Disadvantages commonly associated with external transducers, such as the influence of transducer displacement relative to the patient’s head, measurement artifacts, and damping of the high frequency components of the pressure waveform caused by the limited dynamic response of fluid-filled tubing, are also improved by the microtransducers.

At present, a new in vivo pressure sensor (FISO Technologies Inc, Québec, Canada) is available. This transducer combines its well-recognized white light interferometric interrogation technique with proven silicon micromachined technology. It delivers the advantages of both tip catheter and external invasive pressure transducers. Due to the optical nature of the transducer and transmission line, the system delivers high fidelity pressure measurements even in the presence of strong EM or RF fields or interference associated with those generated by electric scalpel, MRI systems. (http://www.fiso.com/page_fopmem.htm)

Implantable devices
For long-term usage, an ICP monitoring-implantable system with no external connections has obvious advantages. These devices would still act as foreign bodies, but the elimination of skin penetration would minimize the risk of infection. The principal problems associated with these types of systems are: difficult to be recalibrated after implantation, increased drift, requires complicated and expensive hardware, and shows slow dynamic responses. The Codman ICP Tele-Sensor is an implantable capacitance detector that is designed to be placed inline with chronically implanted ventricular shunt systems. Chapman et al. used a method of...
Figure 1A: Spiegelberg (Aesculap, GmbH & Co. Center Valley, PA, USA) KG Pneumatic ICP monitor. B: The sensor of Aesculap-Spiegelberg ICP monitor. The Air-Pouch is an air-filled bag mounted at the tip of a catheter. ICP is transmitted through the air in the pouch and the tube to the Brain-Pressure Monitor.
pressure monitoring in association with a ventricular catheter and subcutaneous reservoir. This has been found useful in eight patients without the disadvantages inherent in other methods of management.

Table 1 shows the advantages and disadvantage of different ICP monitors. Figures 1–3 demonstrate three kinds of ICP monitors and their sensors.

CEREBRAL PERFUSION PRESSURE: CONCEPTS AND MANAGEMENT
Studies made by Rosner et al.29, about cerebral perfusion pressure (CPP), ICP, and systolic arterial blood pressure (SABP) analyzed in response to different variables, have shown that these parameters are controlled by autoregulatory mechanisms and positional changes. Patients in whom CPP is greater or equal to 70 torr respond relatively poorly to mannitol with small ICP decline, and those with CPP less than 70 torr respond with adequate or more significant decline in ICP. The rationale for these results are based on the hypothesis based on the association of low CPP with autoregulatory vasodilation, whereas high CPP is associated with vasoconstriction. If mannitol should work by a vasoconstriction mechanism, the ICP effects should be most apparent under conditions of low CPP. Head elevation has mainly beneficial effects over ICP with a gross reduction of 1 mmHg in ICP and a decrease of 2–3 mmHg in CPP, for every 10 degrees of head elevation. Thus, demonstrating that the CPP was not beneficially affected by elevation of the head off the bed.

HARMONIC ANALYSIS OF INTRACRANIAL PRESSURE WAVEFORMS
The techniques of Fourier analysis have been utilized to characterize the wave components of the complex time-

Figure 2 A: Ventrix Fiberoptic ICP monitor (Model NL950-100. Camino, NeuroCare Group, San Diego, CA, USA).
B: The sensor of Ventrix ICP monitor
<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Description of Study</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Salmon</td>
<td>The applanation transducer was used to measure intracranial pressure (ICP) through the intact fontanel</td>
<td>The correlation coefficient with direct measurements of ICP was 0.98</td>
</tr>
<tr>
<td>1979</td>
<td>Dietrich K.</td>
<td>The transducer was implanted automatically coplanar to the dura via a burr hole of 4 mm diameter in the conscious patient without special surgical equipment</td>
<td>At a full scale range of 100 mm Hg the zero-point drift is less than 1 mm of Hg/24 h</td>
</tr>
<tr>
<td>1982</td>
<td>Weaver</td>
<td>Comparison of ICP measurements between two subarachnoid fluid-coupled pressure transducers in the same patients of 20</td>
<td>More than 50% of patients demonstrated significant differences in ICP. Patients harboring intracranial mass lesions showing clear differences</td>
</tr>
<tr>
<td>1983</td>
<td>Mendelow</td>
<td>Simultaneous recordings of ICP using two types of subdural fluid-coupled bolt devices and a ventricular catheter fluid-coupled system in 31 patients</td>
<td>ICP recordings were within 10 mmHg of ventricular ICO in 41% of the recordings using one type of bolt and 58% using the other kind</td>
</tr>
<tr>
<td>1984</td>
<td>Dearden</td>
<td>Assessment of ICP measurement accuracy in a subarachnoid/subdural fluid-coupled bolt device using an infusion test in 18 patients</td>
<td>Device read ICP accurately according to infusion test 48% of the time</td>
</tr>
<tr>
<td>1985</td>
<td>Barlow</td>
<td>Simultaneous recording of ventricular fluid-coupled ICP compared to a subdural fluid-coupled catheter in 10 patients and a subdural catheter tip pressure transducer device in another 10 patients</td>
<td>Compared to ventricular ICP, 44% of the subdural fluid coupled device measurements and 72% of the subdural catheter tip pressure transducer devices were within a 10 mmHg range</td>
</tr>
<tr>
<td>1985</td>
<td>Powell</td>
<td>Simultaneous recording of ICP using an epidural pneumatic pressure transducer and ventricular fluid-coupled catheter in 17 patients</td>
<td>Marked differences in pressure up to 30 mmHg were recorded</td>
</tr>
<tr>
<td>1987</td>
<td>Ostrup</td>
<td>Comparison of ICP readings between a parenchymal fiberoptic catheter tip pressure transducer device and ventricular fluid-coupled catheter of subarachnoid bolt in 15 adults and five children</td>
<td>Measure drift up to 1 mmHg per day. Parenchymal ICP readings were generally within 2–5 mmHg of ventricular or subarachnoid ICP measurements</td>
</tr>
<tr>
<td>1987</td>
<td>Pek</td>
<td>Comparison of ICP recordings between an epidural fluid-coupled catheter in another 10 patients</td>
<td>Parenchymal ICP was 4–12 mmHg lower than ventricular ICP but parallel changes in pressure were noted</td>
</tr>
<tr>
<td>1988</td>
<td>Mollman</td>
<td>Simultaneous recordings of ICP with a subdural/subarachnoid fluid-coupled and a ventricular fluid-coupled catheter in 31 patients</td>
<td>The difference between the ICP readings was 0.12 mmHg with a standard deviation of 5.29 mmHg</td>
</tr>
<tr>
<td>1990</td>
<td>Chambers</td>
<td>ICP recordings between a ventricular fluid-coupled system in 10 patients compared to a subdural fiberoptic catheter tip pressure transducer and the same device situated in the ventricular catheter in another 10 patients</td>
<td>54% and 74% of the fiberoptic subdural and fiberoptic ventricular ICP readings, respectively, were within 5 mmHg of the ventricular fluid-coupled ICP measurements</td>
</tr>
<tr>
<td>1990</td>
<td>Pek</td>
<td>Simultaneous recordings from a parenchymal strain gauge catheter tip pressure transducer device and a ventricular fluid-coupled catheter</td>
<td>An initial drift up to 4 mmHg in the first day. Parenchymal ICP measurements were generally 4–8 mmHg below ventricular ICP</td>
</tr>
<tr>
<td>1992</td>
<td>Artru</td>
<td>A prospective study of parenchymal fiberoptic catheter tip ICP monitors in 100 patients</td>
<td>Daily baseline drift of 0.3 mmHg</td>
</tr>
<tr>
<td>1992</td>
<td>Gambardella</td>
<td>Comparison of a parenchymal fiberoptic catheter tip pressure device to ventricular fluid-coupled ICP reading in 18 adult patients</td>
<td>55% of parenchymal fiberoptic ICP readings were 5 mmHg higher or lower than ventricular ICP measurements</td>
</tr>
<tr>
<td>1992</td>
<td>Schickner</td>
<td>Comparison of ICP readings between a parenchymal fiberoptic catheter tip pressure transducer and ventricular fluid-coupled catheter in 10 patients</td>
<td>66% of fiberoptic measurements exceeded ventricular ICP and 21% were lower. Absolute pressure differences of up to 40 mmHg were recorded</td>
</tr>
<tr>
<td>1992</td>
<td>Schwartz</td>
<td>Comparison of ICP readings between an epidural pneumatic pressure device and a subdural strain gauge, subdural fiberoptic or ventricular fluid-coupled catheter in six patients</td>
<td>ICP readings from the epidural device correlated with the other device readings in only one case</td>
</tr>
<tr>
<td>1993</td>
<td>Chambers</td>
<td>Simultaneous recording of ventricular fluid-coupled ICP compared to a fiberoptic catheter tip pressure at the tip of the ventricular catheter in 10 patients</td>
<td>60% of the ICP readings with the fiberoptic device were within 2 mmHg of the ventricular fluid-coupled ICP readings</td>
</tr>
<tr>
<td>1993</td>
<td>Czech</td>
<td>Comparison of simultaneous ICP recordings in 15 patients using a ventricular fluid-coupled ICP monitoring system and an epidural pneumatic ICP monitoring device</td>
<td>In the majority of comparisons the epidural device ICP measurements were different from ventricular ICP recordings with deviations between 20 and +12 mmHg</td>
</tr>
<tr>
<td>1993</td>
<td>Gambardella</td>
<td>Comparison of parenchymal fiberoptic catheter tip pressure transduction device to ventricular fluid-coupled readings in 12 pediatric patients</td>
<td>ICP values obtained by the parenchymal fiberoptic device were 3 ± 2 mmHg lower than ventricular ICP readings</td>
</tr>
<tr>
<td>1993</td>
<td>Gopinath</td>
<td>Six microsensor transducers, were monitored for drift at pressures of 10 mmHg and 20 mmHg</td>
<td>The maximal drift of any of the transducers was 1 mmHg over nine days</td>
</tr>
<tr>
<td>1995</td>
<td>Gopinath</td>
<td>Evaluation of the measurement accuracy and drift of a new catheter tip strain gauge ICP device. The device was placed in the lumen of a ventricular catheter in 25 patients</td>
<td>No significant measurement drift was noted over an average of four days. The device was 63% accurate (within 2 mmHg) compared to ventricular ICP recordings</td>
</tr>
<tr>
<td>1999</td>
<td>Morgalla</td>
<td>Tests were performed at six different pressure levels between 0 mmHg and 50 mmHg with temperature varied between 20° and 45°C</td>
<td>Very low drifts of less than 0.15 mmHg/°C for Codman, Epidyn and Neurovent. Gaeltec and Camino exhibited higher drifts of 0.18 mmHg and 0.2 mmHg/°C respectively</td>
</tr>
<tr>
<td>2000</td>
<td>Yau</td>
<td>Comparison of Spiegelberg intraventricular ICP/intracranial compliance monitoring device in five sheep</td>
<td>The Spiegelberg air-pouch ICP/compliance monitor provides ICP and compliance data that are very similar to those obtained using both gold-standard methods and an intraparenchymal ICP monitor</td>
</tr>
<tr>
<td>2001</td>
<td>Morgalla</td>
<td>Over a period of two years, 40 ICP transducers were implanted in 35 patients by one surgeon</td>
<td>From this study, a malfunction was detected in two devices by testing them in a water bath just before insertion. Readings for the probe by means of measurement in an open water bath just before insertion are strongly recommended</td>
</tr>
<tr>
<td>2002</td>
<td>Vassiliadis</td>
<td>Monitoring patients’ ICP during endoscopic surgery</td>
<td>The small size of the Microsensor ICP monitor enabled easy placement through the working channel of the endoscope and interposed assembly</td>
</tr>
</tbody>
</table>

Modified and updated from Guidelines for the Managements of Severe Head Injury, brain Trauma Foundation, 1995).
varying periodic waveforms of the human body. The periodicity and linearity parameters from the signal can propose the quality of the frequency response among the transducers in the current clinical market. The harmonic analysis can dissect a complex waveform into an infinite summation of sine and cosine functions of proper frequency units.

Neurophysiologists have employed Fourier analysis in order to quantify the pressure and frequency response of the transducers used in ICP measurement. The advantage of the technique lies in the quantitative representation of pressure wave from the intracranial space and the easiness to compare the frequency component of the waveform.

Czosnyka et al. measured frequency response from the ICP monitoring devices that are currently used in the clinical setting. The relative changes in the readings of time versus frequency domain of sine waves were reported. The range of frequency bandwidth varies from 20 to 30 Hz. It indicated that there is a difference in amplitude measurement by the different transducers. The report pointed out that there is a damping effect by the inlet tubing and it made a frequency difference of above 7 Hz. During the measurement, the pressure chamber has two different static pressure levels, 10 and 50 mmHg. The study compared the ratio of the fundamental harmonic amplitude among the transducers and defined good frequency properties within the range of 0 to 50 Hz. The dynamic property of test transducer showed dampening of the pressure waveform started at a frequency above 10 Hz and continued up to 50 Hz. However, there was no statistical difference in the frequency characteristics of transducers at the two static pressures (10 and 50 mmHg).

Figure 3 A: Strain Gauge Monitor (ICP express TM, Codman, Johnson & Johnson Professional, Raynham, MA, USA). This kit consists of a 38 cm catheter with an integrated stylet and ICP sensor, a catheter anchoring clip, and a 7-gauge tunneling trocar. B: The sensor of Codman ICP monitor.
COMPLICATIONS

Complications of ICP devices include infection, hemorrhage, malfunction and obstruction.

Factors associated with ICP monitoring related complications include: age (>44 years old), prolonged monitoring time (mean of 14 days or more), use of steroids, prolonged hospitalization time, and use in patients with moribund conditions. Colonization of ICP devices increases significantly after five days of implantation. Irrigation of fluid-coupled ICP devices significantly increases bacterial colonization. Excluding the higher rate in summarizing the range of infection for fluid-coupled devices, the average rate of bacterial colonization in different intracranial locations is 5% for ventricular, 5% for subarachnoid, and 14% in parenchymally placed catheter-tip strain gauge or fiberoptic devices. Even though these studies documented increasing bacterial colonization of all ICP devices over time, clinically significant intracranial infections are uncommon. Holloway et al. studied 584 retrospectively examined patients with head injuries that required ventriculostomy. The incidence of ventriculitis was 10.4%, and a steadily increasing daily incidence of infection was observed over the first 10 days of monitoring. The authors also found that prophylactic replacement of catheters at 5-day intervals did not reduce the frequency of infection. Commonly, incidences of ventricular catheter infections lie in the 10%–17% range. Randomized prospective studies are needed to definitively conclude that routine catheter replacement does not reduce the risk of infection. In most centers where ventriculostomies are frequently used, important factors for controlling CSF contamination appears to be related to periodical CSF sampling (usually every 2–3 days) through the catheter port using an aseptic technique, as well as making a tunnel under the scalp to exit the catheter away from the burr hole. Recommendations of where to perform a ventriculostomy in the intensive care unit and emergency room versus the operating room aiming to decrease contamination rates are based upon individual hospital conditions of infectious disease control. Those centers with acceptable low rates of nosocomial infections would be benefited placing ventriculostomies at the bedside.

The incidence of hematomas with all ICP devices is 1.4%. Significant hematomas requiring surgical evacuation occur in 0.5% of patients in published reports of more than 200 patients requiring ICP monitoring. The incidence of fatal hemorrhage depends on the sensor type. A 5% incidence of fatal hemorrhage in subdural devices, 4% in intraparenchymal, and 1.1% in ventriculostomies have been reported.

Malfunction or obstruction has been reported as 6.3%, 16% and 10.5% in fluid-coupled ventricular catheters, subarachnoid bolts, or subdural catheters, respectively. With ICP measurements higher than 50 mmHg, rates of obstruction and loss of signal are noted.

In a series of 536 indwelling cerebral monitoring devices from Detroit Receiving Hospital, ventriculostomies were associated with a 7.29% infection rate and 3.28% hemorrhage, whereas the use of fiberoptic devices was associated with 0.87% hemorrhage rate and no apparent infections.

IN VITRO TESTS

Morgalla and co-workers tested seven types of ICP transducers (HanniSet, Camino, Codman, Spiegelberg, Medex, Epidyn and Gaeltec) by increasing pressure levels up to 80 mmHg. Measurement accuracy was best with HanniSet probes. The maximum errors with this transducer were 3 mmHg. Camino and Codman showed similar results. Spiegelberg had slightly larger deviations. With Epidyn and Gaeltec, the highest error was noted, up to 10 mmHg in the high-pressure range. The 24-h drift was lowest with HanniSet (0.2 mmHg) and Camino (0.8 mmHg). The largest drifts were seen with Medex, Spiegelberg and Gaeltec (1.8 mmHg). Ten-day drift was lowest with HanniSet (0.11 mmHg day$^{-1}$) and Codman (0.2 mmHg day$^{-1}$). The highest long-term drifts were found with Epidyn and Gaeltec (1.5 mmHg day$^{-1}$). Drift did not exhibit a linear pattern.

The authors also found very low drifts of less than 0.15 mmHg/C for Codman, Epidyn and Neurovent. Gaeltec and Camino exhibited higher drifts of 0.18 mmHg and 0.2 mmHg/C, respectively. Within the temperature range of 35°C to 42°C, all probes tested showed insignificant drift by the temperature.

ANIMAL STUDIES

Yau et al. compared the Spiegelberg intraventricular catheter, a standard intraventricular catheter, and Codman intraparenchymal ICP microsensor in five sheep. ICP measured using the Spiegelberg intraventricular air-pouch balloon catheter displayed a linear correlation with ICP measured using the standard intraventricular fluid-filled catheter ($r^2=0.9846$), and the Codman intraparenchymal strain-gauge sensor ($r^2=0.9778$), respectively. Automated measurements of intraventricular compliance obtained using the Spiegelberg compliance device were compared with compliance measurements that were made using the gold-standard manual cerebrospinal fluid bolus injection technique at ICP's range from 5 to 50 mmHg. A linear correlation was demonstrated between the two methods ($r^2=0.7752$, $p<0.001$; average bias $-0.019$ ml mmHg$^{-1}$).

Kroin et al. implanted intracranial pressure sensors in the frontal white matter and placed a fluid-filled catheter in the cisterna magna (CM) of four dogs to measure CSF pressure. This was done in order to verify whether the ICP sensors matched CSF pressure changes. The animals were tested using standard physiological maneuvers such as jugular vein compression, head elevation, and CSF withdrawal from and saline injection into the CM. The mean ICP pressure and CM pressure were compared for months to demonstrate that the transducer system produced minimal drift over time. The results showed that the change in the ICP sensor closely duplicated that of the CSF waveform in the CM in response to the well-known physiological stimuli. More
important, mean ICP pressure remained within 3 mmHg of CM pressure for months, with a mean difference less than 0.3 mmHg.

**PEDIATRIC RESEARCH**

Although a variety of monitoring techniques and devices are available nowadays, there have been few studies made in the pediatric population. We present here some recent reports.

Jensen *et al.*[^1] studied 98 consecutive head injury children requiring fiberoptic–ICP monitoring. The monitoring devices were placed in the frontal parenchyma and no prophylactic antibiotics were used. All catheter tips were cultured upon removal. The usual duration of ICP monitoring was 3–15 days, with the exception of one patient who underwent monitoring for 40 days. No complications occurred during insertion of the ICP monitors. Catheter tip cultures were positive for *Staphylococcus epidermidis* in 7% of the children, but none developed clinical features of CNS infection. The location of placement or duration of ICP monitoring did not affect the rate of catheter tips with positive cultures. There was a 13% mechanical failure rate associated with the fiberoptic device.

Pople *et al.*[^2] studied 303 children requiring ICP monitoring. He found an infection rate of 0.3%, intracranial hemorrhage in 0.3% (result of low platelet counts), displacement of monitor in 1%, and malfunction of the system in 2.6%.

According to Gambardella and co-worker’s study[^3], the fiberoptic device and the ventricular catheter have the same accuracy and reliability when used in children. The fiberoptic method correlates very closely with the ventriculostomy method, but the pressure values were always 3 ± 2 mmHg lower than those obtained with the conventional pressure transducer system, especially in critically ill patients.

**MATHEMATICAL/COMPUTER MODEL**

Although invasive methods to measure ICP are the most accurate, attempts have been made for a noninvasive assessment of the ICP. Here are some recent studies.

Schmidt *et al.*[^4] introduced a method to continuously simulate ICP waveform. In a system analysis approach, the intracranial compartment was viewed as a black box with arterial blood pressure (ABP) as an input signal and ICP as an output. A weight function was used to transform the ABP curve into the ICP curve. The output ICP waveform was generated using a weight function derived from the transcranial Doppler blood flow velocity (V) and ABP curves. In order to establish the relationship between TCD characteristics and weight functions, the velocity, ABP, and ICP curves of a defined group of patients were simultaneously recorded. A linear function between the TCD characteristics and the weight functions was obtained by calculating a series of multiple regression analyses. Given examples demonstrate the procedure’s capabilities in predicting the mean ICP, the pulse and respiratory waveform modulations, and the trends of ICP changes.

According to Schmidt *et al.*[^5], the noninvasive ICP was calculated from the ABP waveform by using a linear signal transformation, which was dynamically modified by the relationship between ABP and cerebral blood flow velocity. In all simulations, parallel increases in real ICP and noninvasive ICP were evident. The simulated resistance to outflow of cerebrospinal fluid (Rcsf) was computed using nICP and then compared with Rcsf computed from real ICP. The mean absolute error between real and simulated Rcsf was 4.1 ± 2.2 mmHg min/ml. By the construction of simulations specific to different subtypes of hydrocephalus arising from various causes, the mean error decreased to 2.7 ± 1.7 mmHg min/ml, whereas the correlation between real and simulated Rcsf increased from $R = 0.73$ to $R = 0.89$ ($p < 0.001$).

Ursino and Lodi[^6] presented a simple mathematical model of ICP dynamics oriented to clinical practice. It included the hemodynamics of the arterial–arteriolar cerebrovascular bed, CSF production and reabsorption processes, the nonlinear pressure–volume relationship of the craniospinal compartment, and a Starling resistor mechanism for the cerebral veins. Moreover, arterioles are controlled by cerebral autoregulation mechanisms, which are simulated by means of a time constant and a sigmoidal static characteristic. The model is used to simulate interactions between ICP, cerebral blood volume, and autoregulation. Three different related phenomena are analyzed: the generation of plateau waves, the effect of acute arterial hypotension on ICP, and the role of cerebral hemodynamics during pressure-volume index (PVI) tests. Simulation results suggest the following:

1. ICP dynamics may become unstable in patients with elevated CSF outflow resistance and decreased intracranial compliance, provided cerebral autoregulation is efficient. Instability manifests itself with the occurrence of self-sustained plateau waves.

2. Moderate acute arterial hypotension may have completely different effects on ICP, depending on the value of model parameters. If physiological compensatory mechanisms (CSF circulation and intracranial storage capacity) are efficient, acute hypotension has only negligible effects on ICP and CBF. If these compensatory mechanisms are poor, even modest hypotension may induce a large transient increase in ICP and a significant transient reduction in CBF, with risks of secondary brain damage.

3. The ICP response to a bolus injection (PVI test) is sharply affected, via cerebral blood volume changes, by cerebral hemodynamics and autoregulation.

**ACCURACY AND STABILITY (TABLE 2)**

The American National Standard for Intracranial Pressure Monitoring Devices has been developed by the Association for the Advancement of Medical Instrumentation in association with the Neurosurgery Commit-
According to their standards, an ICP device should have the following specifications:

1. Pressure range from 0 to 20 mmHg;
2. Accuracy of ±2 mmHg within the range of 0 to 20 mmHg.
3. Maximum error of 10% in the range of 20 to 100 mmHg.

External strain gauge transducers are coupled to the patient's intracranial space via fluid-filled lines, which are accurate and can be recalibrated, but obstruction of the fluid couple can cause inaccuracy. Moreover, the external transducer must be consistently maintained at a fixed reference point relative to the patient's head to avoid measurement error, whereas catheter-tip transducers are placed intracranially. Catheter-tip strain gauge or fiberoptic devices are calibrated before intracranial insertion and cannot be recalibrated once inserted. Consequently, if the device measurement drifts and is not recalibrated, there is potential for an inaccurate measurement, especially if the ICP transducer is used for several days.

Although nonfluid-coupled systems are easier to use, as the ICP measurement is independent of head elevation, there are reports about significant ICP measurement drift with fiberoptic pressure transduction and strain gauge pressure transduction in the parenchymal space. Fiberoptic cables are subject to breakage if the cable is bent excessively. The accuracy of a pressure transduction device can be assessed by placing the device within the lumen of a ventricular catheter and comparing the fluid-coupled pressure reading to the device being tested. Some authors reported that, fiberoptic and strain gauge catheter-tip devices tested in this manner have shown differences compared to the ventricular ICP readings.

According to the literature, a premature cessation of ICP recording occurred in 5.5% of cases using a subdural catheter, 20.3% of cases involving a screw, and 7.1% of cases with a ventriculostomy. This premature cessation was usually due to a blocked catheter in the screw that could not be cleared by irrigation with saline. A significantly dampened trace occurred in 16% of cases with a Richmond screw, in 2.7% of cases using a subdural catheter, and in 2.5% of cases using the intravenricular catheter. Comparing these three methods, catheter dislodgement was not statistically significant.

The use of a balloon to measure ICP in the epidural space was found to be unreliable, as the measured pressure varied with the volume used to fill the balloon, and whether the balloon was filled or emptied.

According to Martinez-Manas et al., ventriculostomy catheters need to be calibrated every 8 h because they have a mean drift of 5 mmHg every 8 h with a maximum of 11 mmHg. Fiberoptic devices have a mean daily drift of 0.6–2 mmHg so that a significant cumulative error in ICP after 3–4 days monitoring can be recorded. Some authors stated that their tendency is to drift towards positive values, so when the results of monitoring are wrong, these errors tend to overestimate ICP. On the other hand, Bavetta et al. found a median value for zero drift of −3 mmHg in their study. Such a clear negative bias in zero drift had not previously been noted.

**INDIRECT MEASUREMENTS**

**Tympanic membrane displacement**

Another method that may be used to indirectly measure ICP is based on the measurement of the tympanic membrane displacement. Since the CSF and perilymph may communicate through the cochlear aqueduct, an increase in ICP will cause an increase in pressure on the oval window. This pressure will then be transmitted to the tympanic membrane via the (contracted) ossicles of the middle ear. An impedance audiometer placed in the external auditory canal emitted and detected sound waves bounced off the tympanic membrane to calculate the membrane’s displacement. If ICP were to affect the displacement in a consistent way, the ICP could be inferred. A reliable system has yet to be proven.

**Transcranial Doppler**

Transcranial Doppler (TCD) ultrasonography measures the velocity of blood flow in the basal intracranial arteries, and is most often used to detect vessel narrowing. Investigators have noted that characteristic changes in the blood flow waveforms occur with rising ICP. TCD may be helpful as an adjuvant diagnostic tool to indirectly determine elevations in ICP; as it has been demonstrated that diastolic flow velocity decreases, systolic peaks become sharper, and pulsatility index increases as ICP rises. Detecting changes in these TCD-variables may help to more closely monitor patients with subarachnoid hemorrhage (SAH) and stroke, among others.

**Transcranial ultrasound propagation**

By using bitemporal acoustic probes, an ultrasonic wave is transmitted through the head. It is assumed that elevated ICP and changes in intracranial tissue elastance will alter the velocity of a sound wave. In a pilot study of 10 healthy subjects and 11 patients with various types of neurological pathology, it was demonstrated that changes in wave velocity did appear simultaneously with changes in ICP (four patients had intraventricular catheters). The correlation of these changes with ICP was not made, and needs to be worked out in the future.

**Jugular bulb monitoring**

Jugular venous oxygen saturation (SjvO$_2$) monitoring may be of value in patients with elevated ICP. This measurement requires the retrograde insertion of an oximeter-tipped catheter into the jugular bulb, although some preliminary work shows that noninvasive measurement may be possible using near-infrared spectroscopy. As cerebral blood flow (CBF) decreases, SjvO$_2$ will also decrease in a non-linear fashion.
will fall if elevation of ICP results in a critical reduction of cerebral perfusion pressure (CPP) and CBF, because cerebral oxygen extraction is increased. Similarly, if the cerebral metabolic rate of oxygen (CMRO₂) increases and CBF remains constant, SjvO₂ will fall. Conversely, an increase in SjvO₂ may occur with ICP elevations related to cerebral hyperemia.

Visual evoked response

Vork et al.⁷⁰ have demonstrated a good relationship between ICP elevation and a shift in latency of the N₂ wave of the visual evoked response (VER). The N₂ wave is normally found at 70 msec and is thought to be a cortical phenomenon. It is therefore likely to be sensitive to potentially reversible cerebral cortical insults such as ischemia or increased intracranial pressure.

CONCLUSION

A ventricular catheter connected to an external strain gauge transducer or catheter tip pressure transducer device is considered as the most accurate method of monitoring ICP and enables therapeutic CSF drainage. The significant infections or hemorrhage associated with ICP devices causing patient morbidity are clinically rare and should not deter the decision to monitor ICP. Parenchymal catheter tip pressure transducer devices are advantageous when ventricular ICP cannot be obtained or if there is an obstruction in the fluid couple, though they have the potential for significant measurement differences and drift due to the inability to recalibrate. Subarachnoid or subdural fluid-coupled devices and epidural ICP devices are currently less accurate. With an increasing miniaturization of the transducers, fiberoptic systems have been developed. However, there is a problem of measurement accuracy during the period of patient monitoring. External calibration of the measurement accuracy should be performed frequently to ensure constant quality.

ACKNOWLEDGEMENTS

We are grateful for the contribution from the Great Omentum Foundation, LA; the critical editorial review by Joonsoo Park; the help of the Linn McDonald, Codman Co., Judith Ross, Aesculap Co., Integra Co.

REFERENCES

34. Bekar A, Goren S, Korfali E, Aksoy K, Boyaci S. Complications of
62 Dennis LJ, Mayer SA. Diagnosis and management of increased intracranial pressure. Neurol India 2001; 49 (Suppl. 1): S37–50