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The Roles of Ventricular and Parenchymal Intracranial Pressure Monitoring.

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Introduction

Intracranial pressure (ICP) is highly predictive of outcome in traumatic brain injured (TBI) patients with the proportion of hourly ICP greater than 20mmHg being a significant independent determinant of outcome [1-4]. The objective of such monitoring is to maintain adequate cerebral perfusion and oxygenation so as to avoid secondary insult to the traumatically injured brain. Furthermore, prophylactic treatment of ICP without ICP monitoring carries risk such as prolonged hyperventilation which worsens outcome [5]. For this reason, the Brain Trauma Foundation Guidelines make a Level II recommendation for intracranial pressure (ICP) monitoring in all salvageable patients with a severe traumatic brain injury (TBI) that have Glasgow Coma Scale (GCS) score of 3-8 post-resuscitation and an abnormal computed tomography (CT) scan [6].

Ventricular fluid coupled ICP monitoring remains the gold standard of ICP measurements and the reference standard for studying other ICP monitoring systems [6]. The main advantage of an intraventricular catheter for ICP monitoring is the ability to drain CSF as an ICP lowering therapy. Another advantage of a ventricular fluid coupled system is the ability to recalibrate in situ, allowing for prolonged accuracy during the duration of usage [7]. Conversely, there are a number of disadvantages to using an external ventricular drain for ICP measurements.

In many trauma patients the ventricles can be compressed by mass lesion such as contusions and/or can be slit due to generalized edema. Placing a catheter within the ventricles that are altered from normal anatomy can become challenging, often requiring multiple attempts and resulting in misplaced catheters. In a review of 346 ventriculostomies, Kakarla et al describes an overall functional accuracy rate of 87% in ventriculostomies, leaving more than 1 out of 10 EVDs placed as nonfunctional. There was a tendency for a higher percentage of non-functional EVDs found in TBI patients where ventricles were more likely to be effaced in some nature [8].

Placement of an external ventricular drain also has an expected rate of post-insertional hemorrhage and infection. A meta-analysis of 2428 ventriculostomies found a hemorrhage rate of 7.0% with clinically significant hemorrhages comprising less than 1% [9]. There is considerable variability with post-insertion hemorrhage rates in individual studies with some reporting as high as 41% [10]. In some cases, clinically significant hemorrhages include extra-axial hemorrhage requiring surgical evacuation [8].

Infectious complication is the most frequent reported post-ventriculostomy complication with rates ranging from 0 – 27%, although there is great variability on the definition of infection [11,12]. There are factors that predispose towards higher infection rates such as frequent CSF sampling, duration of usage, catheter irrigation, site leaks [13]. Catheter tunneling has been found to help reduce infection rates [14]. Other issues with ventricular fluid coupled ICP monitoring includes infiltration of the tubing with air and even clotting of the catheter resulting in a non-functional monitoring system and loss of the ability to drain CSF as a therapeutic measure [15].

Because of the invasive nature of ventriculostomies and subsequent complication rates of hemorrhage and infection as well as the inability to consistently place a catheter within the ventricle, additional monitoring systems play an important role in monitoring ICP in the neurologically critically ill patient. A popular alternative to ventricular ICP measurements is monitoring ICP intraparenchymally, typically within the frontal lobe at a depth of 2cm [16]. While parenchymal monitoring technologies have technical issues with recalibration causing an accepted error in recording, the main disadvantage with parenchymal monitoring is the inability to drain CSF as a treatment strategy as afforded by the ventricular monitoring systems. At our institution, we have used a dual monitoring system which incorporates both ventricular ICP monitoring which provides the gold standard in ICP monitoring and allows for therapeutic drainage as well as parenchymal monitoring which plays a pivotal role in providing ICP values especially when ventricular ICP cannot be obtained secondary to any of the above situations. Below we review the current parenchymal monitoring systems to assess the extent of drift, accuracy in correlation to ventricular monitoring, and complication rates as compared to our dual monitoring system.

Parenchymal ICP Monitoring Devices

The main advantage of parenchymal monitoring is the ease of placement as compared to ventricular monitoring especially in the case of compressed or shifted anatomy. Historically, the main disadvantage of parenchymal monitors in comparison to ventricular monitoring has been the inability to recalibrate the device following insertion with the resulting problem of zero drift [17]. Currently, there are three main types of parenchymal ICP monitoring devices, which are divided into fiber optic devices, strain gauge devices, and pneumatic sensors.

Fiber optic

Fiber optic intracranial pressure monitoring utilizes light, which is transmitted via a fiber optic cable towards a displaceable mirror. Changes in ICP will move the mirror causing varying intensities of reflected light, which are then used to calculate varying ICP values. The Camino ICP monitoring system (Camino Laboratories, San Diego, CA) is an example of this technology. The manufacturer's specifications for zero drift of the Camino device is +/- 2mmHg for the first day and +/1mmHg/day thereafter. A large study of 1000 patients with Camino intracranial pressure device found in 624 devices zero drift ranged from -17 to 21mmHg with a mean of 7.3 +/- 5.1mmHg. Drift did not exceed +/-4mmHg for less than 100hrs of usage but for longer periods could reach as high as +/- 20mmHg [17]. Another study of 50 Camino catheters found a drift ranging from -13 to 22mmHg with a mean drift of -0.67 +/- 5.9 [18].

In a study of 18 patients who underwent both parenchymal monitoring via Camino ICP monitoring and ventricular pressure monitoring via a fluid filled coupled system, a correlation coefficient of 0.946 was measured with the brain tissue pressure approx. 1-2mmHg lower than ventricular pressure [19]. And while this difference in pressure reading was potential prescribed to the device itself, another study found that with placement of the Camino probe within the ventricle, the Camino catheter read an average 1.5mmHg higher than ventricular pressure values obtained by an external transducer [20].

Complications include infection ranging from 0.7 - 9.5%; hemorrhage ranging from 1.9 - 5.1%; technical complications of the probe including dislocation of the probe, dislocation of the bolt mechanism, breakage of the optic fiber, and defective probe for unknown reasons ranged from 3.1 - 4.5% [17,21-23].

Strain Gauge

Strain gauge devices utilizes a transducer which is bent secondary to changes in ICP causing changes in resistance from which ICP is calculated. Examples of strain gauge devices include the Codman Microsensor (Codman and Shurtleff Inc, Raynham, MA), Raumedic Neurovent-P ICP sensor (Raumedic AG, Munchberg, Germany), and Pressio sensor (Sophysa, Orsay, France). Similarly to the fiberoptic system, the strain gauge devices must be calibrated before insertion and cannot be recalibrated in situ, leading to a recognized zero drift. The Codman microsensor, which is by the far the most popular model of this group of parenchymal monitors, is estimated by the manufacturer to have a drift of no greater than 3mmHg per 24 hour period. A study of 128 patients with placement of a Codman Microsensor reported a mean drift of 0.9 +/- 0.2mmHg after removal [24]. In another study of 88 patients with a Codman microsensor, 20% patients were found to have a drift that was 5mmHg or greater and 2% with a drift 10mmHg or greater which was significantly correlated with duration of monitor usage [25].

In regards to correlation between parenchymal and ventricular ICP values, Koskinen et al in 22 patients with Codman microsensor and ventriculostomy showed that mean ICP with the ventriculostomy was 18.3 +/- 0.3 and with the Codman microsensor was 19.0 +/- 0.2mmHg with a slightly higher bias towards parenchymal readings [24]. Similar findings were reported by Lescot et al where 15 patients had a Codman microsensor and ventriculostomy which showed a mean difference of 0.3mmHg between ventricular and parenchymal ICPs and a range 0f -6.7 to 7.1mmHg [26]. However this was not demonstrated in other studies where there was no consistent bias in parenchymal and ventricular pressures as measured by a Codman microsensor and ventriculostomy, respectively [27].

In the largest study reviewing complications of the Codman microsensor consisting of 549 patients and 650 implanted monitors, infectious complications were found in 3 of 529 patients (0.6%) which is extremely low; however, infection in that study was defined as wound infection or deep infection requiring antibiotic treatment. Hemorrhagic complications were reported in 4.6% of Codman microsensor implants, none of which were clinically significant [28].

The Raumedic Neurovent-P sensors are amongst the strain gauge devices and was advertised as having newer technology consisting of an improved catheter tip which would translate to superior zero drift characteristics. Citerio et al reviewed their experience with 99 Neurovent-P catheters. Zero drift was recorded as 0.8 +/- 2.2 with 13% of devices having drift > 3mmHg [29]. In one study with 98 Neurovent-P sensors placed, 1% sustained an intraparenchymal hemorrhage secondary to prove placement and 5% of the systems failed secondary to technical errors including kinking of the cable [30].

Pneumatic Sensor

The pneumatic sensors consist of a small balloon in the distal end of the catheter, which is inflated and registers changes in pressure secondary to ICP changes allowing for ICP calculations. The Spiegelberg system (Spiegelberg GmbH & Co. KG, Hamburg, Germany) is a pneumatic sensor created partially to deal with issues of recalibration

in vivo. The air pouch surrounding the catheter is automatically re-zeroed every hour which in theory should address drift issues. Lang et al describes their experience with 87 spiegelberg catheters with a maximum drift less than +/- 2mmHg. In 5 patients simultaneous fluid couple ventricular pressure measurements were recorded (around 15,104 paired readings) with the spiegelberg catheter showing an absolute difference of less than +/- 3mmHg in 99.6% and less than +/-2mmHg in 91.3% of readings. Further analysis showed a trend toward 10% lower spiegelberg readings with increasing ICP and became significant when ICP exceeded 25mmHg. In that study no complications of hemorrhage were noted as well as no clinical signs of infection requiring treatment. In 3 of the 87 patients (3.4%), erroneous pressure readings were observed secondary to technical complications of the device caused by air leakage from the balloon causing a pattern of decreasing pressure readings after each automated re-zeroing [31].

Dual Ventricular and Parenchymal ICP monitors

The Hummingbird Synergy Duo (Innerspace, Tustin, California) is a single-port system that consists of a titanium bolt (0.7-cm diameter) with polycarbonate wings and manifold which allows for placement of an external ventricular drain. The ventricular catheter is designed with an air bladder pouch encapsulating the parenchymal portion of the catheter which provides parenchymal ICP values similar to previously discuss pneumatic sensors. This system allows for simultaneous ventricular and parenchymal ICP monitoring. The single bolt also has two side channels for other monitoring probes such as brain tissue oxygenation, cerebral blood flow, or depth electrode for EEG monitoring (Figure 1). At the University Of New Mexico Hospital, Chohan et al published their institution's fiver year experience with 275 Hummingbird Synergy Duo devices reporting a 92% success rate in placement that yielded CSF drainage and a complication rate of 10% for hemorrhage and 4% for infection [32]. Analysis of over 1.5 million paired data points obtained from 20 patients showed that 95% of parenchymal ICP values were within +/- 12mmHg of the simultaneous recording ventricular ICP values. In general, the ventricular ICP values read 2.5mmHg higher than the parenchymal monitor [33].

Currently two other devices on the market that measure ventricular and parenchymal ICP values are the Camino Flex Ventricular Catheter (Camino Laboratories, San Diego, CA) as well as the Raumedic NEUROVENT-Sleeve Housing (Raumedic AG, Munchberg, Germany); however, there is no published literature on these devices at this time.

Discussion

Fluid filled coupled ventricular pressure readings remain the gold standard of intracranial pressure monitoring. A majority of practicing neurosurgeons prefer ventriculostomies to parenchymal monitoring, and the benefits of CSF drainage can be seen by a higher percentage of refractory intracranial hypertension in patients where intraparenchymal monitoring is used as compared to external ventricular drain [34,35]. Situations may occur especially in traumatic brain injured patients

Table 1: Comparison of Parenchymal ICP monitoring devices.

	Technology	Rate of Infection	Rate of Hemorrhage	Technical Errors	Comparison of parenchymal & ventricular ICP recordings	Zero Drift
Camino ICP Monitor	Fiber optic	8.5%[17] 4.75%[23]	2.50% (0.66% clinical significant)[17] 1.1%[23]	4.5%[17] 10%[18] 3.14%[23]	0.946* (180 paired data points)[19] 59.3% within ±2 mm Hg and 97% within ±5 mmHg[20]	Mean 7.3 ± 5.1 mmHg (range −17 to 21 mmHg)[17] Mean −0.67 mmHg (range −13 to 22 mmHg)[18] Mean 0.4 ± 0.57 mmHg (maximum 12 mmHg)[30]
Codman MicroSensor	Strain gauge	0%[23] 0%[44] 0%[24]	~0.3% (0% clinical significant)[24]	n/a	Mean difference 0.7mmHg[24] Mean difference 0.3mmHg (range -6.7 to 7.1mmHg) (1,527 paired data points)[26]	Mean 0.9 ± 0.2 mmHg (range −5 to 4 mmHg)[24] Mean 0.1 ± 1.6 mmHg/100 hours of monitoring[26] Mean 2.0 mmHg (range −6 to 15 mmHg)[25]
Raumedic Neurovent-P ICP sensor	Strain gauge	0%[29]	2.02% (0% clinical significant)[29] 1%[30]	5%[30]	n/a	Mean 0.8 ± 2.2 mmHg (range −4 to +8 mmHg)[29] Mean 0.2 ± 0.41 mmHg (maximum 3mmHg)[30]
Pressio	Strain gauge	n/a	n/a	n/a	Mean difference -0.6mmHg (range -8.1 to 6.9mmHg) (1,562 paired data points)[26]	Mean −0.7 ± 1.6 mmHg/100 hours of monitoring[26]
Spiegelberg	Pneumatic	0%[31]	0%[31]	3.45%[31]	99.6% within +/13mmHg and 91.3% within +/12mmHg (15104 paired data points)[31]	Mean< ±2mmHg[31]
Hummingbird Synergy Duo	Pneumatic	4%[32]	10%[32]	n/a	95% within +/-12mmHg (1.5million paired data points)[33]	

Table reproduced with modifications from Raboel et al, Table 2: Comparison of microtransucer ICP monitoring devices
*Correlation coefficient of parenchymal ICP values to ventricular ICP values

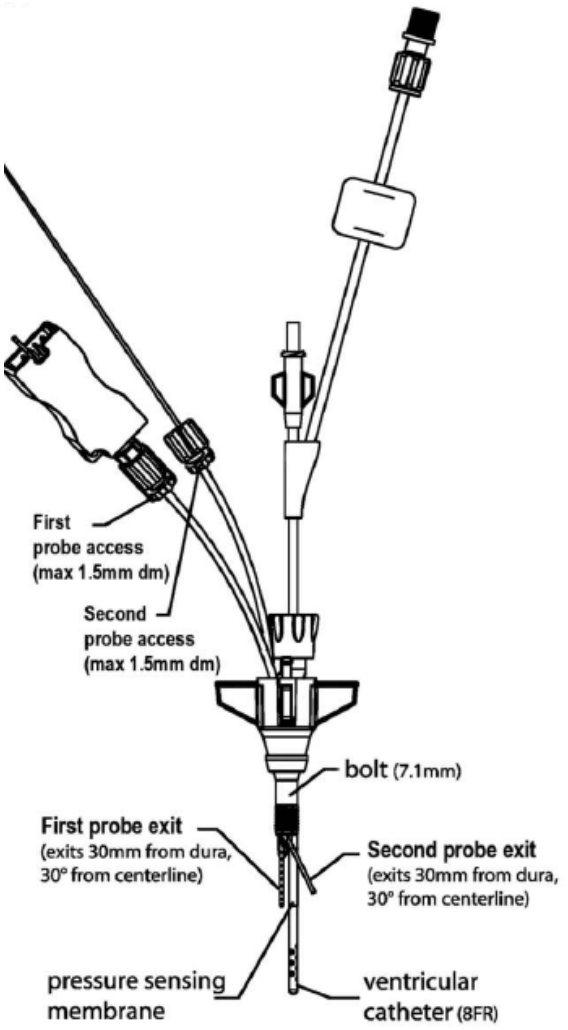

Figure 1: Schematic of the Hummingbird Synergy Duo device, the ventricular catheter is passed through the fixed bolt mechanism. This allows drainage of CSF and ventricular ICP monitoring while the parenchymal portion of that same catheter relays parenchymal ICP values through a pressure sensing membrane. For illustration purposes, two probes have been placed in the auxiliary ports, which can be used for further multimodality monitoring.
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where compressed ventricles may preclude intraventricular monitoring, a situation where intraparenchymal monitoring can play a vital role [36]. Placement of an external ventricular drain is considered a more invasive procedure potentially requiring multiple attempts as compared to intraparenchymal monitoring causing an expected higher rate of hemorrhage and infection. In fact in one study comparing EVD placement versus intraparenchymal monitoring in 377 patients, a significantly higher device related complication rate was noted in EVD placement as compared to parenchymal monitors with no effect on neurologic outcome, concluding that intraparenchymal monitors be placed routine with EVDs being placed only if CSF drainage was deemed necessary [37,38].

In regards to correlating pressure between intraparenchymal and intraventricular spaces, there is literature to indicate a higher pulse pressure within the ventricles as compared to the brain parenchyma in patients with hydrocephalus; however, in review of the literature of patients with simultaneous intraparenchymal and ventricular pressure reading, there appears to be no consistent bias with some reports indicating a higher average ventricular pressure and others indicating a higher parenchymal pressure reading which could be due to pressure gradient across the brain or device designs [19,26,39,40]. Overall, it appears the literature has shown excellent correlation between intraparenchymal monitors and ventricular drains [40-43].

The inability to recalibrate intraparenchymal monitors in situ has been, historically, its main limitation causing significant drift in prolonged usage, which could potential affect clinical management. Technologies that allow for recalibration in situ such as the pneumatic sensors show promising results in tackling the problem of zero drift theoretically allowing for longer periods of usage although no study has investigated this in a clinical setting as compared to fiberoptic and strain gauge transducers.

There should be an expected device failure rate when placing parenchymal monitors including dislocation of the bolt mechanism, breaking of the fiberoptic cable, technical dysfunction in the strain gauge system, or violation of the air bladder in the pneumatic sensor. In general, the technical complication rate of parenchymal monitors are minimal but not negligible.

Currently, there are a number of intracranial monitoring systems that combine ventricular and parenchymal monitoring within one catheter requiring only one entry point. The dual system allows for providers to aim for ventricular monitoring which can provide the gold standard of monitoring as well as therapeutic treatment options. The built-in parenchymal monitoring allows for less passes to be attempted during placement of the ventricular drain and ultimately allows for accurate ICP monitoring in the case that the ventricles cannot be accessed. It also allows for monitoring in any scenario where external transducing is not possible such as a clotted external ventricular drain or when persistent CSF drainage is needed. In our experience at the University Of New Mexico Hospital, a one catheter system that provides dual ventricular and parenchymal monitor system has provided the ideal solution to intracranial monitoring and treatment.

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