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LIST OF ABREVIATION

1. ICP – Intracranial Pressure
2. ONSD – Optic Nerve Sheath Diameter
3. EVD – External Ventricular Drainage
4. TBI – Traumatic Brain Injury
5. ROC – Receiver Operator Characteristic

DIAMETER SELAPUT SARAF OPTIK; KAEDAH UNTUK MENGENAL PASTI KENAIKAN TEKANAN OTAK DIKALANGAN PESAKIT DEWASA TRAUMA DAN BUKAN TRAUMA.

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Pengenalan: Pengukuran diameter saraf optik dengan menggunakan mesin gelombang bunyi mudah-alih kini semakin meluas digunakan untuk mengenal pasti kenaikan tekanan otak. Kajian sebelum ini jelas menunjukkan kaitan yang rapat di antara diameter saraf optik dengan kenaikan tekanan otak. Bagaimanapun, kajian sebelum ini hanya menilai tekanan otak melalui anggaran daripada tanda-tanda klinikal serta informasi daripada imbasan CT.

Objektif: Tujuan kajian ini dijalankan adalah untuk mengenalpasti hubungan diantara pengukuran diameter saraf optik dengan nilai tekanan otak yang diukur terus melalui alat pengesan tekanan otak, suatu penilaian 'Gold Standard'. Kajian ini juga bertujuan untuk menentukan nilai sensitif dan spesifik diameter saraf optik yang mampu mengenal pasti kenaikan tekanan otak. Akhir sekali, kami juga ingin menilai sama ada mengukur saraf optic ini adalah lebih tepat dan sesuai untuk mengenal pasti

kenaikan tekanan otak di kalangan pesakit dewasa disebabkan trauma atau pesakit bukan disebabkan oleh trauma.

Kaedah: Kajian ini dijalankan secara prospektif dan pemilihan pesakit yang dimasukkan di dalam kajian ini adalah berdasarkan kelapangan pangkaji utama. Empat puluh satu pesakit yang dirawat di unit rawatan rapi pembedahan neuro disertakan didalam kajian ini. Kesemua pesakit mempunyai alat mengesan tekanan otak sebagai sebahagian daripada rawatan asal. Diameter saraf optik diukur menggunakan alat gelombang bunyi mudah alih SonoSite, berdasarkan teknik yang biasa digunakan. Nilai tekanan otak juga dicatit secara serentak. Analisa statistik 'Spearman rank correlation coefficient' digunakan untuk mengenal pasti kaitan di antara diameter saraf optik dengan tekanan otak. Nilai spesifik diameter saraf optik yang boleh meramal kenaikan tekanan otak juga dikenal pasti melalui analisa statistik.

Keputusan: 75 ukuran diameter saraf optic dijalankan keatas 41 pesakit. Analisa statistik 'Spearman's correlation' mendapati nilai diameter saraf optik sangat berkait rapat dengan nilai tekanan otak, dengan kadar signifikasi $p<0.01$. Analisa statistik 'receiver operator characteristic' (ROC) berjaya menunjukkan kawasan dibawah graf sebanyak 0.964 atau 96.4 peratus. Graf ini juga berjaya menunjukkan nilai diameter saraf optik 5.205mm adalah 95.8% sensitif dan 80.4% specifik dalam meramal kenaikan tekanan otak. Teknik ini juga didapati lebih tepat dalam meramal kenaikan tekanan otak di kalangan pesakit disebabkan trauma jika dibandingkan dengan pesakit bukan disebabkan trauma.

Kesimpulan: Nilai diameter saraf optik 5.205mm adalah sangat sensitif dan specifik bagi meramal kenaikan tekanan otak. Penggunaan alat gelombang bunyi mudah alih adalah sangat mudah dipelajari dan dipercayai dalam meramal kenaikan tekanan otak. Teknik ini sesuai digunakan seiring dengan kaedah yang sekarang diguna pakai bagi meramal tekanan otak. Penggunaan teknik baru ini sangat meluas dan merangkumi penggunaan di hospital daerah, jabatan kecemasan dan juga di unit rawatan rapi.

OPTIC NERVE SHEATH DIAMETER: A MEAN OF DETECTING RAISED INTRCRANIAL PRESSURE IN ADULT TRAUMATIC AND NON-TRAUMATIC PATIENTS

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Introduction: Bedside ultrasound measurement of optic nerve sheath diameter (ONSD) is emerging as a non-invasive technique to evaluate and predict raised intracranial pressure (ICP). It has been shown in previous literature that ONSD measurement has good correlation with surrogate findings of raised ICP such as clinical and radiological findings suggestive of raised ICP.

Objectives: The objective of the study is to find a correlation between sonographic measurement of ONSD value with ICP value measured via the gold standard invasive intracranial ICP catheter, and to find the cut-off value of ONSD measurement in predicting raised ICP, along with its sensitivity and specificity value. Finally, we would also like to assess if this bedside non-invasive technique is more accurate in predicting raised ICP in traumatic or non-traumatic causes of raised ICP.

Methods: A prospective observational study was performed using convenience sample of 41 adult neurosurgical patients treated in neurosurgical intensive care unit with invasive intracranial pressure monitoring placed in-situ as part of their clinical care. Portable SonoSite ultrasound machine with 7MHz linear probe were used to measure optic nerve sheath diameter using the standard technique. Simultaneous ICP readings were obtained directly from the invasive monitoring. Spearman rank correlation coefficient was used to assess the correlation between ONSD value and ICP value. High ICP was defined as ICP>20mmHg, and a receiver operator characteristic (ROC) curve was performed to find the ONSD cut-off point in predicting raised ICP, and to measure the sensitivity and specificity of both groups.

Results: 75 ONSD measurements were performed on 41 patients. The non-parametric Spearman's correlation test revealed a significant correlation at the 0.01 level between the ICP and ONSD value, with correlation coefficient of 0.820. The receiver operator characteristic (ROC) curve generated an area under the curve with the value of 0.964, and with standard error of 0.22. At 95% confidence interval, the lower boundary for this area under the curve is 0.921 and the upper boundary is 1.000. From the ROC curve, we found that the ONSD value of 5.205mm is 95.8% sensitive and 80.4% specific in detecting raised ICP. When similar ONSD value was analyzed; 5.47mm vs 5.48mm, the sensitivity and specificity of this value in predicting raised ICP is higher in the Traumatic group (94.4% sensitive and 95.2% specific) compared to Non-traumatic group (83.3% sensitive and 93.3% specific).

Conclusions: ONSD value of 5.205 is sensitive and specific in detecting raised ICP. Bedside ultrasound measurement of ONSD is readily learned, and is reproducible and reliable in predicting raised ICP in both trauma and non-trauma group. This non-invasive technique can be a useful adjunct to the current invasive intracranial catheter monitoring, and has wide potential clinical applications in district hospitals, emergency departments and intensive care units.

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CHAPTER 1: INTRODUCTION

1.1 Background

The diagnosis of elevated or raised intracranial pressure (ICP) is both challenging and critical. This is because early detection and subsequent prompt treatment of this elevated ICP can prevent secondary brain damage, which is the leading cause of death in neurosurgical patient especially in severe traumatic brain injury. (Hartl R, Steig EP 2013)

As our brain lies within a rigid skull, any additional space occupying lesion such as expanding brain in cerebral oedema, haematoma or tumour can cause cerebral herniation, which leads to coning, brainstem compression and death if the intracranial pressure continue to be elevated. This stresses the importance of prompt and accurate diagnosis of raised intracranial pressure.

The current gold standard measurement of detecting raised intracranial pressure is through an invasive procedure by placement of intracranial catheter into the ventricles or the cerebral parenchyma. As mentioned previously, intracranial pressure can be definitively measured and monitored through placement of invasive monitoring devices such as intraparenchymal catheter or an external ventricular drain (EVD) catheter. (Mattei T, 2013)

EVD catheters are inserted primarily for the cerebrospinal fluid (CSF) diversion such as in the emergency treatment of acute hydrocephalus or subarachnoid or intraventricular haemorrhage. However in the absence of intraparenchymal intracranial pressure catheter, this EVD may be used to monitor ICP. In the ICU setting, the EVD is simply connected to a three-way connector. One outflow is for CSF drainage, and another outflow is connected to the bedside observational monitor using the arterial line connection. The pulsation of CSF from the EVD is transmitted to the monitor via this arterial line connection and interpreted as intracranial pressure in millimeter Mercury (mmHg).

1.2 Statement of Problem

Non invasive assessment of intracranial pressure has been described. They include pulsatility index from transcranial doppler measurement, evoked potentials, impedence audiometry and scalp blood flow. However, none of the above mentioned techniques are widely used in clinical setting for the detection of raised intracranial pressure, mainly due to the fact that these assessments are operator dependent and the apparatus are expansive and therefore not easily accessible. Therefore, there is a need for a reliable, reproducible and easily accessible non invasive assessment of intracranial pressure.

Bedside sonographic measurement of optic nerve sheath diameter is emerging as a noninvasive technique to detect elevated ICP. Increased ICP is transmitted to the subarachnoid space surrounding the optic nerve, causing optic nerve sheath expansion,

and the expansion of this CSF space can easily be detected using ultrasound. Various methods of measuring the optic nerve sheath diameter (ONSD) has been studied previously; in postmortem specimens (direct measurement) (Liu D et al., 1993), children with ventriculoperitoneal shunts (ultrasound measurement)(Newman WD et al., 2002), and emergency department patients with head injuries (Geeraerts T et al., in 2007; Kimberly HH, 2008).

Many clinical studies have shown good correlation between ONSD and clinical symptoms of raised ICP or computed tomography (CT) abnormalities and findings suggestive of raised ICP. Most studies compared this direct or indirect measurement of this ONSD with either clinical symptoms or with measurements of lumbar puncture, or measurements from imaging studies like CT brain or MRI brain. Few studies measured the direct relationship between ONSD values with ICP value (measured via the gold standard intracranial pressure catheter)

1.3 Justification of the Study

Raised intracranial pressure and its early detection is critical in managing neurosurgical patients. We hypothesized that intracranial pressure can easily be estimated by measuring the optic nerve sheath diameter, and proposed a study to find a correlation between optic nerve sheath diameter and intrcranial pressure. The rationale of this study is to find a non-invasive method which is reliable and reproducible in detecting raised intracranial

pressure.

This method can be a useful adjunct to the current gold standard invasive technique. The benefit of having such an adjunct include the usage in the pre-hospital (prior to transferring patient to a neurosurgical unit) or the initial hospital period when invasive ICP measurement has not been established, and when indirect estimation of ICP can lead to clinical conclusion and modification of treatment.

Currently a neurosurgical unit will receive referral from district hospital and were often given patient's clinical information which includes conscious level (Glasgow Coma Scale score), vital signs and pupillary size. Based on these clinical information along with any radiological findings that are available, the neurosurgeon will then decide on the next course of action.

Information such as the measurement of optic nerve sheath diameter can be valuable additional tool in deciding the severity of the case and the next course of management; either to keep at the referring centre, to send urgently to the nearest neurosurgical unit, or even to suggest the general surgeon at the referring centre to proceed with an urgent craniotomy. An estimation of the value of intracranial pressure gained from optic nerve sheath measurement is useful in supporting this clinical judgment.

This non-invasive ICP measurement tool could also be beneficial in the outpatient department. For example, child with congenital hydrocephalus who came for follow up in

the clinic or intracranial tumour with conservative or expectant management. Besides the routine inspection for head circumference, anterior fontanelle and other signs and symptoms of raised intracranial pressure, the measurement of optic nerve sheath diameter could also be easily be done in the out-patient setting and would provide invaluable estimation of the intracranial pressure value.

1.4 Study Objectives

General Objective

The primary or general objective is to find correlation between intracranial pressure value with optic nerve sheath diameter value, in both traumatic and non traumatic adult patients.

Specific Objectives

1. To determine the cutoff point of ONSD value in detecting high ICP. (High ICP is defined as >20mmHg) in trauma and non-trauma patients.
2. To determine the sensitivity and specificity of ONSD measurement in detecting raised ICP.
3. To evaluate and compare the sensitivity and sepecificity of ultrasonographic measurement of optic nerve sheath diameter between trauma or non-trauma group.

CHAPTER 2: LITERATURE REVIEW

2.1 Intracranial Pressure

2.1.1 Introduction

Intracranial pressure (ICP) is the pressure within the cranium, which are equally distributed within its three main components; the brain tissue, the cerebrospinal fluid (CSF) and the blood. ICP is measured in millimeters of mercury (mmHg) and, at rest, is normally 5–15 mmHg for a supine adult. The pressure-volume relationship between ICP, volume of CSF, blood, and brain tissue is known as the Monro-Kellie doctrine or the Monro-Kellie hypothesis. Changes in ICP are attributed to volume changes in one or more of the constituents contained in the cranium (Soldatos T at el., 2009).

The Monro-Kellie hypothesis states that the cranial compartment is incompressible, and the volume inside the cranium is a fixed volume. As the cranial vault is essentially a closed, fixed bony box, its volume is constant. The cranium and its constituents (blood, CSF, and brain tissue) create a state of volume equilibrium, such that any increase in volume of one of the cranial constituents must be compensated by a decrease in volume of another.

Intracranial volume (constant) = brain volume + CSF volume + blood volume + volume of mass lesion

Therefore, in order to maintain a constant intracranial pressure (ICP), an increase in volume of any intracranial constituents or additional volume from a mass lesion such as haematoma, brain swelling or tumour, must be compensated by a reduction in one of its

constituents. This is the compensatory mechanism to prevent elevation of ICP. The first phase of this compensatory mechanism is the shunting or diversion of cranial CSF towards the spinal canal, followed by to a lesser extends diversion of venous blood to extracranial vasculature. When this compensatory mechanism is exhausted, any additional volume cannot be compensated and thus resulting in an increase of intracranial pressure. This is explained in Figure 1 below.

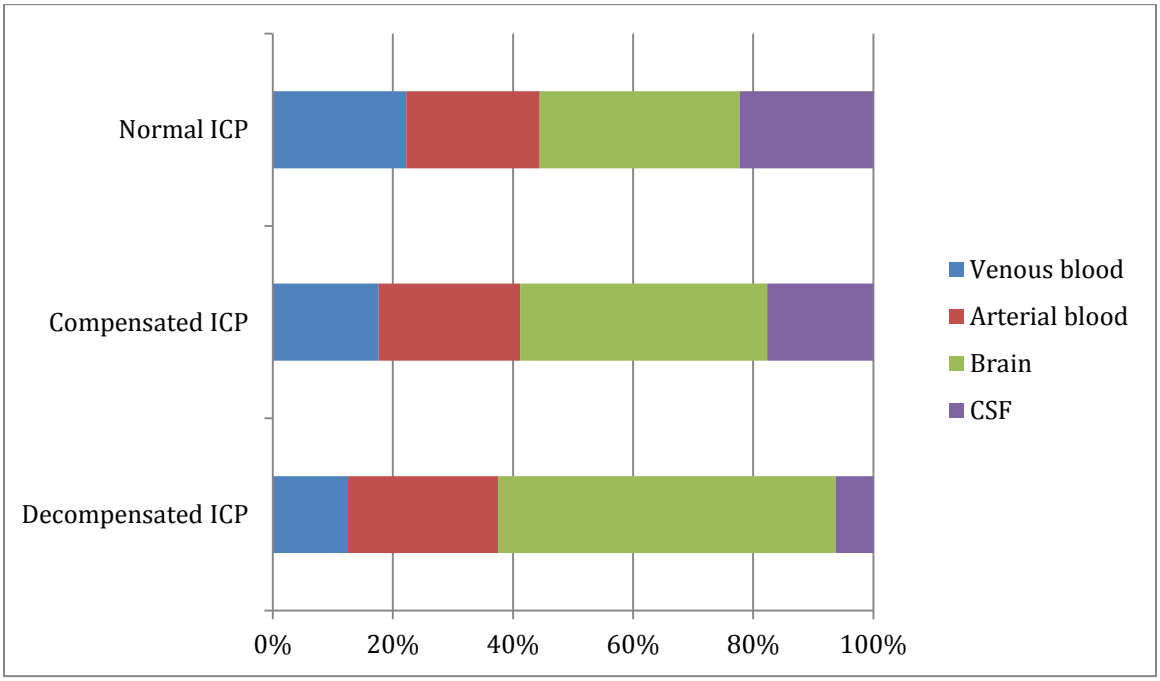

Figure 1. Monro-Kellie doctrine.
(Source: Original figure)
Monro-Kellie doctrine as depicted by figure above explain the three component of the cranium; brain parenchyma, blood and cerebrospinal fluid. All three components contributes a constant volume, and an expansion of one compartment must be compensated by reduction of another compartment to maintain the intracranial pressure.

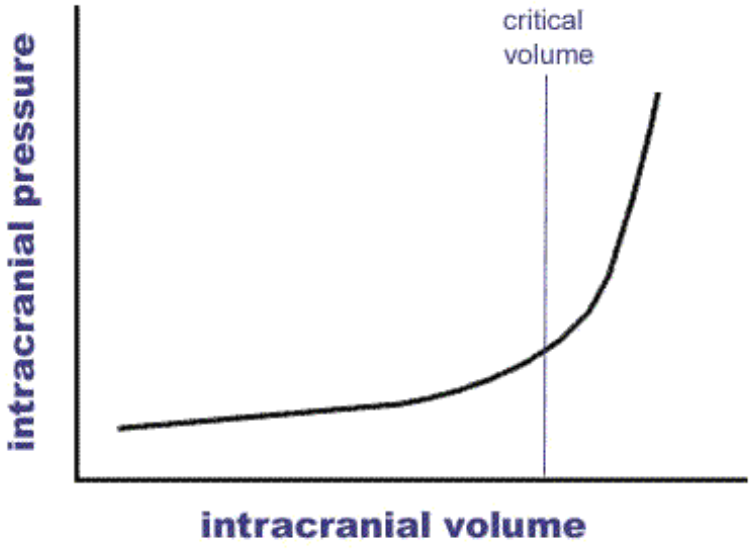

Figure 2. Volume of intracranial contents vs. Intracranial pressure.
(Source: Trauma.org 5:1 2000)
The relationship of intracranial pressure in mmHg (x axis) and volume of intracranial contents in mls (y axis). During the compensatory phase, intracranial pressure is maintained despite additional or increases in intracranial volume.

Any increase in volume of the constituent components of the intracranial compartment does not cause a significant increase in ICP because of compensatory decrease in volume of either blood or CSF, as depicted by box (i). As the brain continue to swell or increase in mass effect, compensatory mechanism by shunting of CSF and blood reaches its maximum compensation with minimal increase of ICP; depicted by (ii). Subsequently as the cerebral swelling worsens or a mass lesion enlarges there comes a point when the compensatory mechanisms start to fail and for smaller increases in swelling there are incrementally greater increases in intracranial pressure

2.1.2 Intracranial pressure monitoring

Elevated intracranial pressure (ICP) is seen in head trauma, hydrocephalus, intracranial tumors, and cerebral edema. Intractable elevated ICP can lead to death or devastating neurological damage either by reducing cerebral perfusion pressure (CPP) and causing cerebral ischemia or by compressing and causing herniation of the brainstem or other vital structures. Prompt recognition is crucial in order to intervene appropriately. Intractable ICP is the most common terminal event leading to death in neurosurgical patients (Kimberly HH et al., 2008). The association between the severity of intracranial hypertension and poor outcome after severe head injury is well recognized. Outcomes tend to be good in patients with normal ICP, whereas those with elevated ICP are much more likely to have an unfavorable outcome.

The rapid recognition of elevated ICP is therefore of paramount importance so that it can be monitored and so that therapies directed at lowering ICP can be initiated. Continuous ICP monitoring is important both for assessing the efficacy of therapeutic measures and for evaluating the evolution of brain injury.

Intracranial pressure monitoring, either through intraparenchymal transducers or intraventricular catheters, has been considered as the standard of care in neurosurgical centres dealing with severe traumatic brain injury. Most of the clinical interventions for elevated intracranial pressure or intracranial hypertension such as hyperosmolar therapy, hyperventilation and cerebral spinal fluid drainage all have a transitory effect (Mattei TA,

2013). The idea of tailoring this therapy according to ICP measurements has always been accepted as part of the rationale of maintaining an adequate cerebral perfusion pressure (CPP). The Brain Trauma Foundation by the American Association of Neurological Surgeons has published a Guidelines for the management of severe traumatic brain injury in 2007 that among others state that the cutoffs target of CPP is >70mmHg and ICP of <20mmHg. This level II evidence which derived from nonrandomized controlled trials also recommend for ICP monitoring in patients with severe head injury with Glasgow Coma Score of <8, and an abnormal head computed tomography (CT) scans. (Mattei TA, 2013).

The goal of ICP monitoring is to ensure maintenance of optimal CPP. The ICP also forms a basis for medical or surgical intervention in cases of increased ICP with agents such as 3% sodium chloride, mannitol, or diuretics, ventriculostomy, cerebrospinal fluid (CSF) diversion, or surgical decompression in cases of intractable ICP elevation that do not respond to conservative management (Mendelson AA et al., 2012).

Although some investigators have questioned invasive ICP monitoring in improving patient outcomes, numerous retrospective series and data bank studies have favored the technique. Despite lack of evidence from randomized clinical trials, the current guidelines for the management of severe traumatic brain injury recommend ICP monitoring in most patients (The Brain Trauma Foundation, 2000).

However some clinical trials have mixed or non-conclusive results and pose further questions on the current accepted guidelines of TBI managent. Such clinical trial is the BEST:TRIP study (Benchmark Evidence from South American Trials: Treatment of Intracranial Pressure). This was a prospective, randomized, outcome-masked trials that randomized 324 severe TBI patients into two groups; either TBI management based on ICP monitoring, or TBI management conducted according to a protocol based exclusively on serial imaging and clinical examinations.

The authors found no difference in primary outcome which include mortality, length of intensice care unit stay, and functional assessment after hospitalization. Regardless of the result, both authors and critical reviews agrees that aggressive treatment directed toward control of intracranial hypertension and subsequent prevention of secondary insults is of paramount important regardless of how it is being assessed – by direct measurement (ICP catheter) or indirectly (by computed tomography scans and clinical examinations) (Chestnut RM et al., 2012)

2.1.3 Historical perspective

The concept of ICP being a function of the volume and compliance of each component of the intracranial compartment was proposed by the Scottish anatomist and surgeon Alexander Monro (1733-1817) and his student George Kellie (1758-1829) during the late 18th century. The interrelationship came to be known as the Monro-Kellie hypothesis.

This doctrine states that the cranial compartment is encased in a nonexpandable case of bone, and, thus, the volume inside the cranium is fixed. The doctrine further states that, in an incompressible cranium, the blood, CSF, and brain tissue exist in a state of volume equilibrium, such that any increase in volume of one of the cranial constituents must be compensated by a decrease in volume of another.

The confirmatory exsanguination experiments of Abercrombie, also a student of Monro, demonstrated graphically the extent to which the body placed physiological priority on maintaining the perfusion of the brain. He drained dogs of their blood and was able to observe that the brain remained comparatively well perfused until shortly before death regardless of the dog's position in space (hanging upside down or right side up, to control for the effects of gravity), unless the blood was drained from an intracranial vessel directly, in which case death resulted almost immediately.

The reciprocal relationship between venous and arterial blood was considered the main variable in ICP and perfusion until 1848, when George Burrows, an English physician, repeated many of the exsanguination and gravitational experiments of Abercrombie and Kellie and found a reciprocal relationship between the volume of CSF and the volume of blood in the intracranial compartment.

Leyden, working in Germany in 1866, demonstrated that elevated ICP leads to a slowed pulse and difficulty breathing, with eventual arrest of breathing entirely. This work was built on in 1890 by Spencer and Horsley, who found that in the case of intracerebral tumors, death was brought about by the arrest of breathing due to increased ICP. Increased ICP was thus taken to represent a common endpoint for several insults to the brain. In 1891, Quinke published the first studies on the technique of lumbar puncture (LP) and insisted that a glass pipette be affixed to the needle so that the CSF pressure could be measured. This technique for repeated measurement of CSF fluid pressure as an assessment of ICP became widely used and was the earliest clinical method of ICP measurement.

In 1903, Cushing described what is now widely known as the "Cushing Triad" as a clinical tool for recognizing the presence of elevated ICP. The triad consists of a widening pulse pressure (rising systolic, declining diastolic), irregular respirations, and bradycardia. In 1922, Jackson noted that the pulse, respiration, and blood pressure are affected only once the medulla is compressed, and some patients with clinical signs of brain compression had normal lumbar CSF pressures. Cushing quantified the Monro-Kelly doctrine, writing that the sum of the volume of the brain plus the CSF volume plus the intracranial blood volume is constant. Therefore, an increase in one should reduce one or both of the others. In 1964, Langfitt demonstrated that lumbar puncture could induce brainstem compression through transtentorial herniation or herniation of the tonsils through the foramen magnum and that, further, when the ventricular system does not communicate, spinal pressure is not an accurate reflection of ICP. Lumbar puncture fell

into disuse for ICP monitoring, and researchers began to directly cannulate the ventricular system.

In 1965, Nils Lundberg revolutionized ICP monitoring with his work using bedside strain gauge manometers to record ICP continuously via ventriculostomy. In his technique, a ventricular catheter was connected to an external strain gauge. This method has proven to be accurate and reliable and also permits therapeutic CSF drainage. Catheter-based ventricular monitoring systems were not applied systematically until the mid-1970s, when monitoring via a strain gauge became widespread after Becker and Miller reported good results in 160 patients with traumatic brain injury. They demonstrated clear evidence of good outcomes among patients in whom elevated ICP could be quickly recognized and subsequently lowered.

2.1.4 Pathophysiology of increase intracranial pressure

The most important role of the circulatory system, aside from transporting blood into all parts of the body, is to maintain optimal CPP. The formula for calculating CPP is below.

CPP = mean arterial blood pressure (MAP) - mean intracranial pressure (MIC)

CPP is the pressure gradient acting across the cerebrovascular bed and, therefore, a major factor in determining cerebral blood flow (CBF). CBF is kept constant in spite of wide variation in CPP and MAP by autoregulation.

Auturegulation is the cerebral circulation's ability to maintain the parenchymal perfusion at relatively constant levels over a wide range of arterial pressures. In most adult humans autoregulation operates between mean arterial pressures of 50 and 150 mmHg (Paulsen OB et.al, 1996). When the cerebral perfusion pressure rises above or falls below the autoregulatory range, the control of flow is lost and flow becomes dependent on mean arterial pressure. (Paulsen OB et.al, 1996).

Pressures above the autoregulatory range cause increases in blood flow followed by vasogenic edema. Conversely, pressures below the autoregulatory range result in low perfusion of the brain and subsequent ischemic injury. Several mechanisms have been proposed to contribute to the control of autoregulation in the cerebral circulation. These include neuronal nitrous oxide production and metabolic by-products (Talman ET et. al, 2007)

The sympathetic and parasympathetic nervous systems were not thought to be involved in cerebral blood flow autoregulation; however, recent studies in humans have suggested a role for both dynamic sympathetic vasoconstriction and cholinergic vasodilation in the control of cerebral autoregulation (Iadecola C et.al 2008, Hamner et.al 2012)).

Blood flow itself also plays a role in autoregulation (Koller A et.a;, 2012). This review

describes the evidence that flow can induce contraction or dilation in the cerebral vasculature dependent on the artery studied. For example, the basilar artery dilates in response to increased flow, whereas the MCA constricts.

When the MAP is less than 50 mm Hg or greater than 150 mm Hg, the arterioles are unable to autoregulate, and blood flow becomes entirely dependent on the blood pressure, a situation defined as "pressure-passive flow." The CBF is no longer constant but is dependent on and proportional to the CPP.

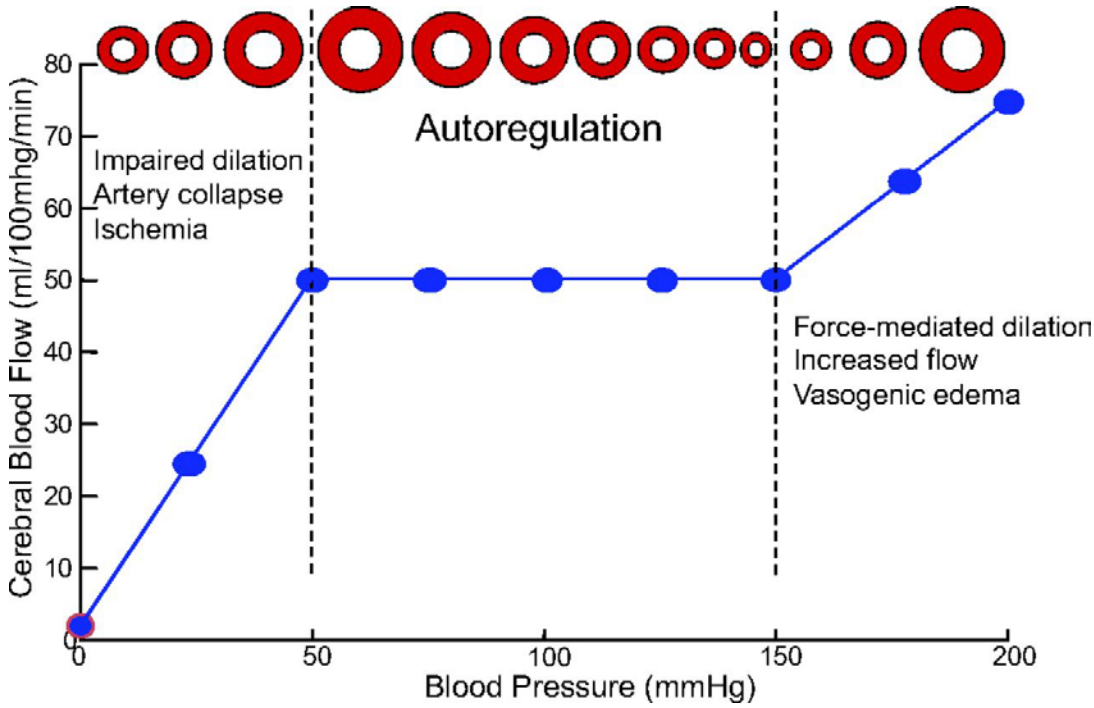

Figure 3. Autoregulation and cerebral blood flow in relation to artery lumen diameter.
Dotted lines represent the lower and upper limits of cerebral blood flow autoregulation. Red circles represent the cerebral arteries, and blue line represents the cerebral blood flow. (Mangat HS, 2012).

While autoregulation works well in the normal brain, it is impaired in the injured brain. As a result, pressure-passive flow occurs within and around injured areas and possibly globally in the injured brain. Ideally, the goal is to maintain the CPP more than 70 mm Hg, and this can be done by either decreasing the ICP or increasing the systolic blood pressure using vasopressors. Caution should be used to use only vasopressors that do not increase ICP.

The volume of the skull contains approximately 85% brain tissue and extracellular fluid, 10% blood, and 5% CSF. If brain volume increases, for example in the setting of cancer, there is a compensatory displacement of CSF into the thecal sac of the spine followed by a reduction in intracranial blood volume by vasoconstriction and extracranial drainage. If these compensatory mechanisms are successful, ICP remains unchanged. Once these mechanisms are exhausted, further changes in intracranial volume can lead to dramatic increases in ICP. The time course of a change in the brain has significance for how ICP responds. A slow-growing tumor, for example, is often present with normal or minimally elevated ICP, as the brain has had time to accommodate. On the other hand, a sudden small intracranial bleed can produce a dramatic rise in ICP. Eventually, whether acute or insidious in progression, compensatory mechanisms are exhausted, and elevated ICP follows.

The relationship between ICP and intracranial volume is described by a sigmoidal pressure-volume curve. Volume expansion of up to 30 cm^3 usually results in insignificant

changes in ICP because it can be compensated by extrusion of CSF from the intracranial cavity into the thecal sac of the spine and, to a lesser extent, by extrusion of venous blood from the cranium (Czosnyka M et al., 2006). When these compensatory mechanisms have been exhausted, ICP rises rapidly with further increases in volume until it reaches the level comparable with the pressure inside of cerebral arterioles (which depends on MAP and cerebrovascular resistance but normally measures between 50 and 60 mm Hg). At this point, the rise of ICP is halted as cerebral arterioles begin to collapse and the blood flow completely ceases.

The relationship between ICP and CBF and functional effects was described as follows (Symon L et al., 1977):

- CBF of 50 mL/100 g/min: Normal
- CBF of 25 mL/100 g/min: Electroencephalogram slowing
- CBF of 15 mL/100 g/min: Isoelectric electroencephalogram
- CBF of 6 to 15 mL/100 g/min: Ischemic penumbra
- CBF of less than 6 mL/100 g/min: Neuronal death

Increased ICP may result from the following; Space-occupying lesions such as tumor, abscess, intracranial hemorrhage, or CSF flow obstruction causing hydrocephalus, or cerebral edema due to head injury, ischemic stroke with vasogenic edema, hypoxic or ischemic encephalopathy, increase in venous pressure due to cerebral venous sinus thrombosis, heart failure, superior vena cava or jugular vein thrombosis/obstruction,

metabolic disorders such as hypo-osmolality, hyponatremia, uremic encephalopathy, hepatic encephalopathy, and idiopathic intracranial hypertension.

2.1.5 Indications of intracranial pressure monitoring

The most common indication for invasive ICP monitoring is closed head injury. As per the Guidelines for the Management of Severe Traumatic Brain Injury, an ICP monitor should be placed in patients with a Glasgow coma score less than 8 (after resuscitation) and after reversal of paralytics or sedatives that may have been used during intubation

Table 1: Indications for ICP monitoring

Indications for ICP monitoring	Risk of raised ICP
Severe Head Injury (GCS 3-8)	
• Abnormal CT scan	50-60%
• Normal CT Scan 90mHg or abnormal motor posturing	50-60%
• Normal CT scan	13%
Moderate Head Injury (GCS 9-12)	
• If anaesthesised or sedated	approx. 10-20% will deteriorate to severe head injury
• Abnormal CT scan	
Mild Head Injury (GCS 13-15)	
• Few indications for ICP monitoring	Only around 3% will deteriorate

The indications for ICP monitoring were divided into severe, moderate or mild head injury, with its associated risk of raised ICP.

Other candidates for ICP monitoring are as follows:

- A patient who is awake yet at risk for increased ICP under general anesthesia for a necessary nonneurosurgical procedure (eg, orthopedic limb-saving procedure), rendering clinical observation impossible
- Patients who have nonsurgical intracranial hemorrhage but are intubated for nonneurosurgical reasons, preventing clinical examination
- Patients with moderate head injury who have contusions to the brain parenchyma that are at risk of evolving (Extreme caution and clinical judgment must be exercised for lesions in the temporal fossa, since their proximity to the brainstem can lead to catastrophic herniation and brainstem compression with little change in the global ICP.)

Perioperative ICP monitoring is indicated in patients who have just undergone tumor or arteriovenous malformation resection and are at risk for cerebral edema with an inability to follow a clinical neurological examination.

2.1.6 Contraindications of intracranial pressure monitoring.

Placement of an ICP monitor has no absolute contraindications, because it is a relatively low-risk procedure. However, clinical judgment should be exercised, especially in patients with a known bleeding disorder. Patients with thrombocytopenia (platelets count of < 10,000/µL), known platelet dysfunction (inhibition due to antiplatelet agents such as aspirin/clopidogrel or uremic encephalopathy), prothrombin time greater than 13 seconds, or an international normalized ratio (INR) greater than 1.3 are at elevated risk for

hemorrhage secondary to placement of an ICP monitor.

2.1.7 Methods of intracranial pressure monitoring

2.1.7.1 Non-invasive intracranial pressure monitoring

Clinical examination

The most important tool for diagnosing potential elevation of ICP and monitoring its progression is the clinical neurological examination (Suarez J, 2004). The advancement of noninvasive imaging studies have made clinical observation less important for initial diagnosis of elevated ICP; however, clinical observation has not lost its importance for ongoing monitoring of a patient's condition. Therefore, the examination should be done frequently and correctly.

The patient suspected of raised intracranial pressure should be evaluated for the following signs and symptoms (Suarez J, 2004):

- Headache, nausea, and vomiting
- Degree of alertness or consciousness (Glasgow coma score should be assessed in the unconscious patient)
- Pupillary reactivity (Pupillary asymmetry or anisocoria of more than 2 mm should be noted.)

- Extraocular movements and visual fields in all quadrants (If the patient is unable to follow commands, visual pursuit should be checked along with blink to visual threat, or dolls eye maneuver. VI nerve palsy should be noted.)
- Funduscopic examination
- Vital signs (Note particularly the absence or presence of Cushing triad: respiratory depression, hypertension, bradycardia.)
- Gag or cough reflex and response to noxious stimuli (This must be performed with caution, as these can provoke increases in ICP that may persist for some time.)

Funduscopic examination

In funduscopic examinations, information regarding the optic disc and the presence of papilloedema may be useful in detecting raised intracranial pressure (Van Stavern GP, 2007). Optic nerve is surrounded by subarachnoid space and experiences pressure changes in the same way that the intracranial compartment does. Pressure on the optic nerve as it exits the cranial vault blocks retrograde intraaxonal transport, resulting in axoplasmic stasis at the nerve head. This leads to secondary vascular changes and edema that manifest as a swelling of the optic disk, referred to as papilloedema (Van Stavern GP, 2007).

Papilledema is almost always bilateral and generally develops 1-5 days after an increase in ICP. In the setting of subarachnoid hemorrhage, it develops far more rapidly, in a range of 2-8 hours. It can be recognized on funduscopic examination as accentuation of

the nerve fiber striations of the disk margins, hyperemia of the disk, and dilation of the capillaries of the optic disk. The disk is elevated, with partial or complete obscuring of the "cup" of the optic disk. This can be evaluated by bringing the "top" of the disk into focus and measuring, in diopters, the distance to the base. Three diopters is the equivalent of approximately 1 mm elevation. (Van Stavern GP, 2007).

Hemorrhage on or near the disk may occur, manifesting as a flame-shaped, or splinter appearance. Concentric retinal stress lines around the base of the swollen disk may be present. Spontaneous venous pulsations, present in most normal eyes, are absent. If venous pulsations are present, papilledema may be ruled out. Whilst the presence of papilloedema is strongly correlated with elevated intracranial pressure, these changes might occur up to 4 to 5 days after the initial elevation of ICP, especially if the elevation is slow and progressive. It is therefore not a suitable tool for diagnosing acute changes in ICP.

Imaging

Noncontrast CT scanning of the head is a fast, cost-effective method to evaluate for elevated ICP and associated pathology. Findings suggestive of elevated ICP are as follows (Friedman DI et al., 2002):

- Intracranial haematoma/bony fractures
- Mass/space occupying lesions

- Obstructive hydrocephalus
- Cerebral edema (both focal or diffuse)
- Midline shift
- Effacement of normal CSF spaces, basilar cisterns, loss of gray white differentiation and loss of normal gyri and sulci pattern.

MRI can be costly and time consuming and is not indicated as a first line of diagnostic modality in the acute care setting. Many patients who undergo MRI for other reasons (ie, stroke, meningitis, meningoencephalitis, and postresuscitation syndrome) are later found to have elevated ICP. Fat-suppressed T2-weighted MRI can facilitate measurement of the optic nerve and its surrounding sheath (Geeraerts T et al., 2008). MRI is also useful in the setting of idiopathic intracranial hypertension (Friedman DI et al., 2002).