

The Problem of Non-Invasive Monitoring in Neurological Emergencies

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Introduction

Brain injury is one of the main reasons of death for young patients in European Union and other countries of the world. The pathophysiological processes in the injured brain are very risky for human life and, therefore, proceed quickly. To minimize the disability or mortality rate of such patients, technologies and equipment have been designed for continuous monitoring of injured brain. Continuous monitoring of such indicators as the absolute values and time dependences of intracranial pressure (ICP), arterial blood pressure (ABP), cerebral perfusion pressure (CPP) and continuous monitoring of brain compliance and cerebrovascular autoregulation are very important for treating brain injuries. It is proved, that optimization of treatment based on the data of such complex monitoring, can reduce mortality rate of patients with severe head injuries in the intensive care unit from 53-54% to 15-26%.

The importance of ICP monitoring

Raised intracranial pressure is the final common pathway for many intracranial problems, such as head injury, cerebrovascular, hydrocephalus, craniocerebral disproportion, CNS infection, metabolic encephalopathy, and has a profound influence on outcome. There is a considerable risk in all such patients of secondary brain damage with long term severe disability if raised intracranial pressure is not recognized and managed properly [1]. An increase in the volume of one of the components of the intracranial cavity (e.g., brain) requires a compensatory reduction in another (e.g., CSF) to maintain a constant pressure. Brain tissue is essentially incompressible, so any increase in ICP due to brain swelling initially results in extrusion of CSF and (mainly venous) blood from the intracranial cavity, a phenomenon known as “spatial compensation.” [2] Additionally, resting intracranial pressure represents that equilibrium pressure at which cerebrospinal fluid (CSF) production and absorption are in balance and is associated with an equivalent equilibrium volume of CSF. CSF plays the largest role in spatial compensation because it can be expelled from the intracranial cavity into the “reservoir” of the spinal theca.

CSF is actively secreted by the choroid plexus at about 0.35 ml/min and production remains constant provided cerebral perfusion pressure is adequate. CSF absorption is a passive process through the arachnoid granulations and increases with rising CSF pressure [1]:

$$CSF\ pressure = Resistance\ to\ CSF\ outflow \times CSF\ outflow\ rate + sagittal\ sinus\ pressure. \quad (1)$$

According to the above formula (known as the Davson’s equation), the mean intracranial pressure (ICP) explained solely by CSF circulation, is proportional to the resistance to CSF outflow, CSF production rate, and sagittal sinus pressure [1].

ICP monitoring is the most widely used intracranial monitor because prevention and control of increased ICP and maintenance of cerebral perfusion pressure are fundamental therapeutic goals after TBI. The normal range for ICP values is from 5 millimeters of mercury (mmHg) to around 13 mmHg. American and European head injury guidelines recommend that action be taken to treat ICP then it is above 20-25 mmHg, as elevated ICP is potentially danger condition for patient life. Treatment of elevated ICP typically begins with administration of drugs to reduce systemic fluid volume or blood pressure. If the elevated ICP is not detected early enough, part of the skull may be to be removed to relieve the pressure [8].

Marmarou A. proposed a modification of (1) formula, stating that average ICP can be expressed by two components: CSF circulatory and vasogenic [4]. Thus, the (1) formula can be rewritten as:

$$ICP = ICP_{CSF\ circulation} + ICP_{vasogenic} = R_{CSF} \times I_{formation} + P_{SS} + ICP_{vasogenic}, \quad (2)$$

where R_{CSF} is the resistance to CSF outflow; P_{ss} is the sagittal sinus pressure [1].

It is difficult to understand why, under steady conditions, a vascular bed which is anatomically separated from the CSF compartment may modify mean intracranial pressure. The hypothesis has been proposed that continuous pulsation of arterial blood is transformed by both non-linear components of CSF pressure–volume compensation (exponential pressure–volume curve) and regulation of CBF (autoregulation) to appear as the

additional term “ICP_{vasogenic}” to complete (1) formula [4].

There is a complex interaction between the CSF and the cerebral circulations that may be modeled (Fig. 1). The relative contributions of anomalies of CSF absorption and cerebral blood volume may be approximated by calculating the proportion of CSF pressure attributable to CSF outflow resistance and venous pressure from (1) formula. Phenomena such as the interaction of autoregulation to changing CPP with *PacO2* may be quantified [5].

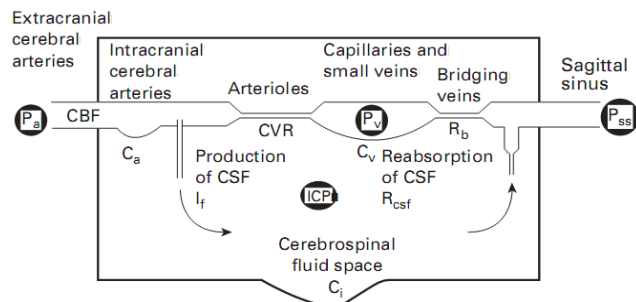


Fig. 1. Hydrodynamic model of cerebral blood flow (CBF) and CSF circulation with the electrically equivalent circuit [1]: P_a - internal carotid artery blood pressure; P_v - cerebral venous pressure; P_{ss} - sagittal sinus blood pressure; ICP - intracranial pressure; I_f - CSF formation rate; CVR - resistance of cerebral arterial bed; R_b - resistance of bridging veins; R_{CSF} - resistance to CSF reabsorption; C_a - compliance of cerebral arterial bed; C_v - compliance of cerebral venous bed; C_i - compliance of lumbar CSF compartment

Existing methods for ICP monitoring and their disadvantages

Unfortunately, ICP can't be precisely estimated from any specific clinical feature and must actually be measured.

Different methods of monitoring ICP have been suggested but two methods are commonly used in clinical practice. These methods are: intraventricular catheters and microtransducer systems. Meanwhile subarachnoid and epidural devices are now rarely used because they have much lower accuracy. Measurement of lumbar CSF pressure does not provide a reliable estimate of ICP and may be dangerous in the presence of increased intracranial hypertension [3].

Now the most popular technique for ICP monitoring is a catheter inserted into the lateral ventricle, usually via a small right frontal burr hole. This can be connected to a standard pressure transducer via a fluid filled catheter. Ventricular catheters measure global ICP and have the additional advantages which allow periodic external calibration, therapeutic drainage of CSF, and administration of drugs (e.g., antibiotics) [3].

Another method - microtransducer-tipped ICP monitors are almost as accurate as ventricular catheters. They can be sited in the brain parenchyma or subdural space, either through a skull bolt, a small burr hole or during a neurosurgical procedure. Fiberoptic, strain gauge or pneumatic technologies are used to transduce pressure in modern microtransducer devices. The Camino ICP monitor uses a fiberoptic cable to direct light toward a miniature displaceable mirror at the catheter tip. Changes

in ICP distort the mirror and the change in reflected light intensity is converted to a measured change in pressure [2].

Although such methods are commonly used in clinical practice, they have serious disadvantages. Conventional invasive ICP measurement techniques require surgical passage through the skull bone into the brain ventricles, parenchyma or the region between the skull and dura matter to implant a measuring transducer. Placement of the catheter may be difficult if there is ventricular effacement or displacement due to brain swelling or intracranial mass lesions. Furthermore, subdural fluid filled catheters are reasonably accurate below 30 mmHg. Such invasive techniques, however, are undesirable, as damage to the sensitive brain tissues may result. Moreover, due to the invasive nature of the procedures, infections may be caused despite precautions, which infections can be serious or even deadly [2, 3].

The main goals for the non-invasive intracranial pressure measurement techniques

The measurement of the absolute value of intracranial pressure is important in diagnosing and treating various pathophysiological conditions caused by head trauma, inflammatory diseases and the like [7].

According to the disadvantages of invasive ICP monitoring methods it would be very helpful to measure ICP, and to have a continuous monitoring of brain compliance and cerebrovascular autoregulation without invasive catheters. There are many actual questions which are very important for the ICP monitoring. Such questions are: what is the cerebral perfusion pressure at any given time? What is the relative contribution of each possible mechanism to raised ICP? What features may predict ecompensation? Is it possible to have an online assessment of cerebrovascular reactivity either to changes in cerebral perfusion pressure (autoregulation) or to carbon dioxide? Which therapy or cocktail is best suited to the sum of that individual's "split brain" problems? [1].

Accordingly, a non-invasive method which monitored continuously both cerebral perfusion pressure and cerebral blood flow autoregulatory reserve would be very helpful in refining management of the swollen brain.

Non-invasive monitoring techniques

Various systems and methods for the noninvasive measurement of ICP have been suggested. Several of these techniques detects relative displacements of tissue boundaries within the brain using ultrasonic imaging. The displacements may be associated with fluid build-up and compression or dilation of brain vessels, which permits determination of ICP through an independent calibration of compressibility. Another noninvasive ultrasonic technique measure the blood flow in the carotid artery by ultrasonic excitation of the artery and determination of Doppler frequency shift [7].

Other noninvasive ICP measurement techniques that have been proposed involve determining the displacement of various tissues or body members. It has been proposed, that ICP can be measured by observing the tympanic membrane of the ear. It has also been proposed

that ICP in infants can be measured by observing the fontanelle. However, all of these proposed systems and methods suffer from at least one significant disadvantage. More specifically, while such systems and methods can be used to measure changes in ICP, such systems and methods can not be used to determine the absolute value of ICP without performing some type of calibration (for example, using known invasive techniques). This is true because displacement of various internal and external tissues or body members in response to various degrees of ICP is not the same from person to person. Thus, without performing some type of calibration for each patient, the absolute value of ICP for that patient can not be determined using the above methods. The dilemma is that if an individual noninvasive ICP absolute value measuring device exists with acceptable accuracy for calibration of other noninvasive ICP meters, the other meters are unnecessary [7].

A noninvasive ICP absolute value measuring method and apparatus, which is commonly owned with the application, the entirety of which is incorporated by reference herein is patented by prof. dr. A. Ragauskas [6]. This patent discloses the use of an ultrasonic Doppler device which detects the velocities of the blood flow inside the optic artery for both intracranial and extracranial optic artery portions, which velocities are used to calculate an absolute ICP. However, it would be more desirable if a simpler technique could be developed. What is desired, therefore, is a system and method for determining the absolute value of ICP which is non-invasive and can be used without performing calibration [7].

Other patented method to measure raised ICP non-invasively uses venous pulsation signals obtained from veins in patient's forehead via a pulse detection sensor (e.g. a pulse oximeter sensor). The principle of it is to detect characteristics of the electromagnetic wavelength after the electromagnetic wavelength which are emitting by embodiments, has been scattered by the tissue. The characteristics may include variations in the electromagnetic wavelength corresponding to a pulse. That embodiments invention include analyzing the variations to identify venous pulsations, and determining whether intracranial pressure is elevated in the patient based on a correlation between the venous pulsations and levels of intracranial pressure. In some embodiments, measured adjustments may be applied to the patient to stop detected venous pulsations. It is believed that elevation required to stop the venous pulsations will correlate to ICP. Accordingly, the level of elevation may be measured and used to estimate ICP. For example, constant gravitational forces combined with the angle of elevation may be used in an algorithm to establish a value for ICP [8].

Another method and apparatus designed to determine and measure the absolute value of intracranial pressure is patented by prof. dr. A. Ragauskas [7]. The device obtains an indication of the intracranial pressure of a living body. It includes a positional sensor which determines an initial position of an elastic biological object (e.g. brain) when the intracranial pressure within the living body is zero, and also determines a subsequent position of the elastic biological object when the intracranial pressure within the living body is unknown but greater than zero.

The pressure generator applies an external pressure to the elastic biological object, whereas a comparator compares the initial position with the subsequent position so as to identify the unknown intracranial pressure of the living body as that external pressure which causes the subsequent position to be equal to the initial position. The scientific principle underlying the present invention is shown in Fig. 2.

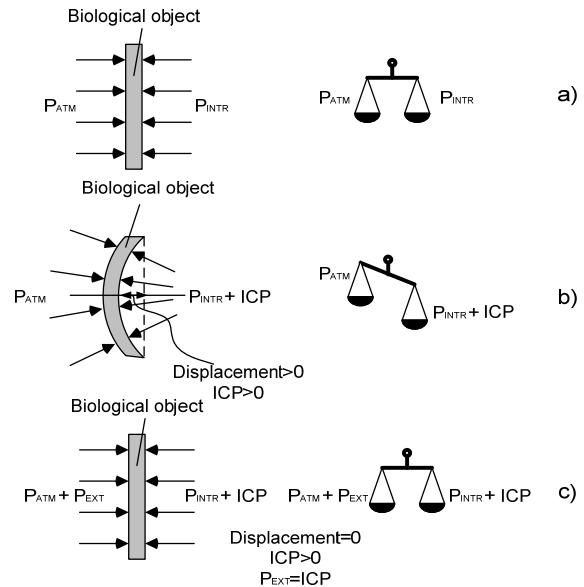


Fig. 2. The principle of apparatus for noninvasive determination of the absolute value of intracranial pressure [7]

A method and apparatus have been invented for continuous real-time monitoring of cerebrovascular autoregulation state (CAS) by prof. dr. A. Ragauskas. This method includes simultaneous non-invasive monitoring of complex of waves, which are propagated of intracranial blood volume respiratory together with lung volume respiratory waves, real-time decomposition the first harmonic of that waves and derivation of the cerebrovascular autoregulation state from that phase shift value. Depending of the phase difference between these two waves it can show if cerebrovascular autoregulation is impaired or intact. This apparatus can take non-invasively the reference signal from a sensor on patient's chest and the second information signal from the intracranial media of the human head or spine. Such phase difference is monitored continuously and displayed on screen [9].

The review of existing methods dedicated to measure ICP allows as to make a conclusion, that only prof. dr. A. Ragauskas patented methods can measure absolute value of ICP. The essential point of all other methods is correlation or functional dependence between any parameter of the head and ICP. Such correlation or functional dependence relies on many factors: patient individual anatomy, age, individual brain compliance, ABP, individual CBF autoregulation status, etc. Therefore, to express the results of such measurements in pressure units (mmHg or mmH₂O) the calibration procedure is needed, i.e. the non-invasive ICP meter with benchmark accuracy is needed. But the main problem is that there is no such meter. Only prof. dr. A. Ragauskas has patented the methods with no necessary calibration.

Conclusions

1. Raised intracranial pressure is the main common pathway for many head diseases.
2. It is vital important at refining management of the injured brain to have a non-invasive method which monitored continuously both cerebral perfusion pressure and cerebral blood flow autoregulatory reserve and also continuous real time measuring of the absolute value of intracranial pressure.
3. Various systems and methods for the noninvasive measurement of ICP have been suggested, but these methods are just in initial stage and are needed to be more reliable and accurate.
4. In various methods of absolute ICP measuring the correlation or functional dependence between any parameter of the head and ICP is needed. Only in prof. dr. A. Ragauskas patented methods calibration is unnecessary.

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Raised intracranial pressure is the final common pathway for many intracranial problems. ICP monitoring is the most widely used intracranial monitor because prevention and control of increased ICP and maintenance of cerebral perfusion pressure are fundamental therapeutic goals after TBI. According to the disadvantages of invasive ICP monitoring methods it would be very helpful to measure ICP, and to have a continuous monitoring of brain compliance and cerebrovascular autoregulation without invasive catheters. Only prof. dr. A. Ragauskas patented methods can measure absolute value of ICP with no necessary calibration. The essential point of all other methods is correlation or functional dependence between any parameter of the head and ICP. To express the results of such measurements in pressure units the calibration procedure is needed, i.e. the non-invasive ICP meter with benchmark accuracy is needed. But the main problem is that there is no such meter. Ill. 2, bibl. 9 (in English; abstracts in English, Russian and Lithuanian).

Е. Калвайтис, Р. Шунокас. Проблема неинвазивных измерений при критических неврологических состояниях // Электроника и электротехника. – Каунас: Технология, 2009. – № 6(94). – С. 81–84.

Повышенное внутричерепное давление является главной причиной, вызывающей большинство внутрительных проблем. ИСП контроль является наиболее широко используемым внутричерепным контролем, поскольку профилактика и контроль роста ИСП и поддержание церебрального перфузионного давления является одной из основных терапевтических целей после ТБИ. Имея в виду недостатки инвазивных методов мониторинга ИСП, было бы очень полезно, неинвазивно измерять ИСП, имея непрерывный контроль за мозго податливостью и мозговой авторегуляцией. Только методы, запатентованные проф. др. А. Рагаускасом, позволяют измерить абсолютное значение ИСП неосуществляя калибровки. Основой всех остальных методов является корреляция или функциональная зависимость между параметром головы и ИСП. Для выражения результатов таких измерений в единицах давления, необходима процедура калибровки, т. е. необходимо иметь неинвазивный ИСП измеритель эталонной точности. Но главная проблема заключается в том, что такой измеритель не существует. Ил. 2, библи. 9 (на английском языке; рефераты на английском, русском и литовском яз.).

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Padidėjęs intrakranialinis spaudimas (ICP) yra viena pagrindinių priežasčių, sukeliančių daugelį intrakranialinių problemų. Intrakranialinio spaudimo stebėseną yra plačiausiai taikomo intrakranialinė stebėseną, nei esminiai gydymo uždaviniai po smegenų traumos yra išlaikyti nepadidėjusį ICP ir jį kontroliuoti bei palaikyti smegenų perfuzijos spaudimą. Atsižvelgiant į invazinių ICP stebėsenos metodų trūkumus, būtų labai naudinga neimplantavus invazinių kateterių išmatuoti ICP bei turėti galimybę nenutrūkstamai stebėti smegenų slankumo bei smegenų kraujotakos autoreguliaciją. Tiksliai prof. dr. A. Ragauskos užpatentuotais metodais galima matuoti absoliučiąją ICP vertę neatliekant kalibracijos. Visų kitų metodų esmė – koreliacija ar funkcinė priklausomybė tarp kokio nors galvos parametro ir ICP. Todėl norint išreikšti tokių matavimų rezultatus slėgio vienetais reikalinga kalibravimo procedūra, t. y. reikalingas etalono tikslumo neinvazinis ICP matuoklis. Tačiau pagrindinė problema yra tai, kad tokio matuoklio nėra. Il. 2, bibl. 9 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).