A Review of Development for Intracranial Pressure Measurement

Preedipat Sattayasoonthorn
Department of Biomedical Engineering,
Faculty of Engineering,
Mahidol University,THAILAND
preedipat@bartlab.org

Jackrit Suthakorn*
Department of Biomedical Engineering,
Center for Biomedical and Robotics Technology,
Faculty of Engineering,
Mahidol University, THAILAND
*Corresponding Author: egjst@mahidol.ac.th

1. Introduction

Human brain is normally in the space called "cranium" which is not able to enlarged in adults. Brain consists of three main parts ; brain tissue, cerebrospinal fluid and cerebral blood flow. The intracranial pressure can be regarded as cerebral spinal fluid pressure from the ventricle. The measurement of increased intracranial pressure is significant for neurological abnormalities in patients which can be caused by cerebral edema, brain tumor or traumatic brain injury. Blood vessels rupture from hemorrhagic stroke and CSF Obstruction can cause the obstruction of fluid in the brain which lead to Hydrocephalus symptom. In order to diagnose and treat the patient promptly, it is necessary to reduce the chances that intracranial pressure will rise to be critical.

Moreover some supplementary factors also cause the increased intracranial pressure such as rising level of CO_2 that is greater than normal will cause the obstruction and stimulate more blood flowing to the brain. Then cerebral blood volume and pressure will be risen, oxygen will be decreased and cerebral blood vessels will be dilated, this result in widespread blood flow. The reduction of systematic blood pressure will be reached and make ineffective to transmit blood to the brain, so the lack of oxygen will be increased. The respiratory mechanism is one of those factors because it will increase intrathoracic pressure and venous pressure including cerebral venous that affects to increase the intracranial pressure such that the absorb phlegm unit (suction) can increase CO_2 during suctioning. Besides lying position, stress and muscle contraction would be related also. Even through these supplementary factors would not be as harmful as previous cases but their combination would be influential.

According to the higher level of intracranial pressure is greater than normal range of 0-15 mmHg or 10-15 cmH_2O, the pressure at rest that is greater than 20 mmHg is regarded as high. Normally in case of the intracranial pressure is between 16-20 mmHg, the patients would be precipitately treated. As an increase in intracranial pressure would give the most damaging outcomes is brain herniated which could be the shift of normal brain position to lower and it is harmful for a life. The diagnosis of an elevated intracranial pressure with the ICP monitoring device has been well-known for a while and its technologies have been developed in many functions and designs which could be performed both direct and indirect way. The purpose of this paper would like to exhibit the recent concepts of intracranial pressure measurement, which could utilize in different fields to overcome the efficiency in intracranial pressure technologies.

2.Traditional Intracranial Pressure Measuring Techniques and Positions

The common methods have been done by drilling the skull and inserting a catheter into the specific places which depended on the system of devices. Especially, Hydrocephalus cases would be treated with the shunt system to warn when there is an obstruction in the catheter by sensing the elevated pressure. As follows, first epidural bolt is placed on the epidural space beneath the skull, this placement is convenient to place a sensor and low serious infection. But it is not proper for continuous monitoring as there may be misplacement, malfunction and drift. Moreover an inaccuracy of the measurement of CSF can be found due to its indirect measurement [1].

Next position is a space between the arachnoid membrane and cerebral cortex which is placed a subarachnoid screw. This device is a hollow screw puncturing into the skull and adjoining the dura to measure ICP directly from CSF which filled the bolt through closed fluid tubing with an external transducer. This method does not invade brain and has low infection and hemorrhage risks but the devices are probably occluded by debris and make some errors so the recalibrated process is needed frequently [1].

Another monitoring position is sited in brain parenchyma, There are different design available such as Intraparenchymal fiberoptic probe, strain gauge and pneumatic technique. The first design is made of thin fiber optic cable, Signal would be interpreted by a pressure transducer at the tip with a specific microprocessor. This device is non-flexible, high-priced and breakable. The second one is a flexible wire with a micro pressure transducer at the tip and can be used with a standard bedside monitor to show an ICP level, brain tissue oxygenation and brain temperature. And the third one is designed to be able to calibrate in vivo and support intracranial compliance monitoring. Even these techniques require drilling through a small burr hole into the parenchyma, they are popular in ICP monitoring due to the easiness of setting up and accuracy but zero-drifting should be concerned [1,2].

Lastly, by using fluid-coupled device which is the gold standard reference for other ICP monitoring, Intraventricular catheter is an open-ended conduits inserted into the subarachnoid space which directly contact ventricular CSF. To drain CSF periodically, three way stopcock can be used with one of extracranial end and the other are attached to a pressure transducer through saline-filled tube for recording ICP continually.

The other advantage is designed for instilling medications into CSF such as using an antibiotic. However, it has high risk to transmit bacteria into brain and meninges. And it complicates to place the device according to the compression and shift of the ventricles. Then it would give an effect on the unclearness of ICP waveform and the data that is lower than actual one. In other hand, the erroneous can be occurred not only the leak of the catheter at the entry, stopcock and even tube, but also done by air bubbles, blood clots and other debris which impede the transmission of wave from the ventricle to the transducer. In case the patient's head is changed each time, the position of transducer must be adjusted to be precise. CSF drainage and ICP measurement should not be done at the same time because it will give low measured value, so these processes need to be done separately.

In commercial ventricular catheters have both of them, other devices and techniques concerned in the risks of displacement, infection, hemorrhage and obstruction which are major problems. But the prior consideration is still related to this technique and other technique like Intraparenchymal transducer is proper to a specific case [1,2]. However, these methods are claimed to increase risks to be infected by setting up the equipment and also limit the patients to be treated at hospital which is not proper for long-term measurement patients. Therefore, many research have been focused on the avoidance of infection, safe devices and procedure, comfortable, accuracy and compatible with other medical treatment for example CT scans, MRI scans and etc..

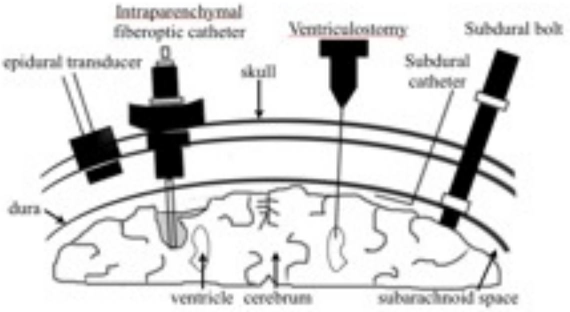

Fig. (1). Traditional intracranial pressure measuring techniques and positions

3.Developing Method in Intracranial pressure Measurement

These indirect methods have been proposed with various studies in mathematical or computational model, medical imaging and alternative technologies of measurement. Some of them are presented in this paper to show recent techniques and future aspects.

Wireless intracranial pressure devices have been widespread in commerce. With the concept of reducing the risks of infection, the catheter should be replaced by the wireless device because the use of catheter is quite invasive to brain. And the design supports short-term measurement for the traumatic brain injury patients who need a special treatment. The long-term measurement for the continuous measurement patients like Hydrocephalus should be used with a shunt system for draining CSF. There are two companies that will be discussed about the wireless ICP sensor prototypes. The concepts promoted the implantable wireless intracranial pressure monitoring system that used radio frequency telemetry operation. The system was separated into implantable sensor and external handhold reading unit. Campus Micro Technologies introduced a passive, inductively coupling method to provide the power from outside and transmit data over long distance at the same time. The capacitive pressure sensor would be placed in the brain cavity and connected with the radiofrequency communication electronics [3,4].

Similar to Issys Integrated Sensing Systems has produced wireless, batteryless intracranial sensors by using a MicroElectroMechanical Systems(MEMS) pressure transducer with a telemetry antenna. The power and data transmission are transmitted through the magnetic telemetry to/from the implant. They also focused on the cooperation with the shunt system to detect blockages, over draining and normal pressure. They planned to test in animal for the final year at UK North BristolNational Health System's Neurosurgery Department. Obviously, some electronics parts and designs are different, but the main concept is quite similar.

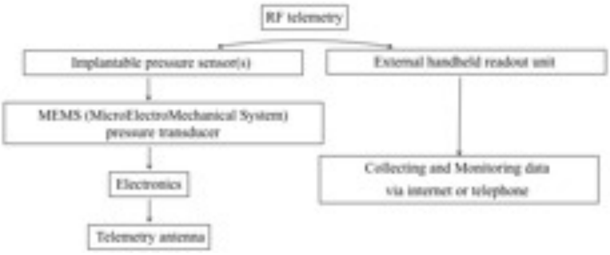

Fig. (2). Concept of implantable wireless intracranial pressure monitoring design

Kawoos et al. had developed the methods of wireless intracranial pressure minitor, they proposed a passive(batteryless) Micro-electro Mechanical System(MEMS) sensors to operate at the megahertz range requiring transcutaneous inductive links. In this case, the device was impossible to operate remotely, because the operation of inductive links was proper to near-filed of coils and affected to the position of the receiver coil which placed within a few centimeters of the body' surface. And the incompatibility in MRI was found as an excessive voltage was generated among MRI procedure form the large inductors in the circuit.

They proposed the next prototype of wireless implantable intracranial pressure monitoring device operating at the industrial-scientific-medical(ISM) band of 2.4GHz. The 12-mm outer diameter cylindrical case was used to assemble and a piezoresistive(PZT) sensor coupled to antenna was used to determine a voltage-controlled oscillator. With the commercial piezoresistive sensor, the evaluation of in-vitro and in-vivo test was performed to test its stability of those environments, and the possibility of trans-scalp monitoring at microwave frequency. The comparison between the utility of piezoresistive sensor and MEMS capacitive sensor was found that the piezoresistive sensor was poor according to its power consumption, signal conditioning circuit requirement and sensitivity of temperature[9]. Therefore MEMS capacitive pressure sensor was replaced in the evolved prototype and the case of device was designed to install a sliding collar to fix the device on variable thickness of skull. In addition the small planar inverted F (PIFA) antenna was used to replace the chip antena for lower height of device and continued with the inspection of communicated characteristics of implantable antena through scalp.

The devices were tested the implantable placement in both epidural and subdural in-vitro and in-vivo. MEMS-based sub-dural configuration was proved to be better than PZT-based epidural, but some erroneous would be seen in animal test due to the sensitivity of sensor in changed humidity. They also made the biocompatible devices by applying parylene coating on the device to prevent a leakage into the device and made a good contact between the device surface and surrounding environment. Next plans were designed to use titanium and protein resistant polyethylene glycolate to prevent fibrosis around the device. However this sensor would be improved in the circuit integrity and power consumption for the longevity and clinical testing of next prototypes [9-13].

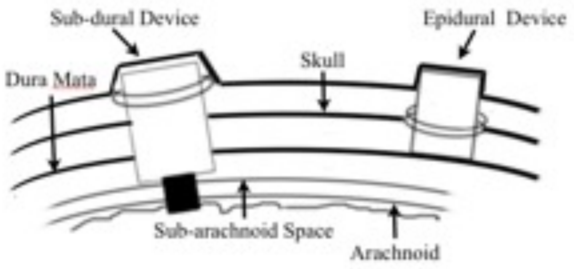

Fig. (3). Overview of the device placements in skull

More recently, an approach is provided a method of measuring the intracranial pressure with strain electrometric technology. The aim of this experiment challenged in an alternative ways of intracranial pressure measuring in rats for a brain experiment or surgery. They concentrated in the strains of skull bone which could be measured by placing strain foils on the rat's exterior surface of skull bone. If there is a fluctuation of ICP, the cranium will be deformed then the strain can be measured with the strain gauge. Uses of this measurement are the reduction of risks to be infected in brain due to its further device position and small incision, the skull bone is effective to measure as it is difficult to be affected by others and the longevity of strain foils. But they still have had suspicions in the placement and the proof of measures [5]. However they have still improved the method for further studies or benefits.

4.Noninvasive approaches in intracranial Pressure measurement

For decades of the development of non-invasive techniques, many indirect measurements have been patented like using a relationship of jugular vein outside of head and the elevated intracranial pressure inside dura membrane. The blood pressure within jugular vein in the neck can reflect the intracranial pressure. By placing the transducer electrodes on the surface of the skin, the low intensity magnetic flux is applied to induce the electrical impulse. It will appear on the surface and be detected by the electrodes. After the occlusion of jugular vein occurs, a measurement can provide the electrical response which is representative the rate of change of jugular flow. Then those results will be filtered, amplified and computed to evaluate the intracranial pressure [6].

The electrical brain signal as visual evoked potentials can be used to measure the intracranial pressure. According to the correlation between intracranial pressure and the latency of the second negative-going wave(N2 wave) of a visual evoked potentials, the subject will have a visual stimulation by observing a flash light to produce the visual evoked potential then the peak of N2 wave will be isolated and correlated the latency of N2 with intracranial pressure. Lastly those ranges will be displayed [7]. And a method can be done by measuring the movement of eardrum results from the contraction of stapedial muscle. As the cochlear aqueduct opens, the increased intracranial pressure will be affected to changes within the inner ear fluid which can be referred to the distortion of tympanic membrane (ear drum). This movement is defined as a volume and quantified by using volume flow measurement equipment to measure in term of displacement [8]. Presently these techniques are not proper for practical operation.

Another alternative approach was the method of tissue resonance analysis for noninvasive intracranial pressure measurement. The researchers applied the concept that related to the vibration and mechanical resonant response of the the fluid compartment and soft tissue due to the blood in and out from heart through the organs and body's tissue. These vibrant and mechanical resonance patterns were different depending on each specific areas, which could be extract the intracranial pressure information.

The digital high resolution echopulsogram would be obtained by using an ultrasonic probe with a 1 MHz carrier frequency to perform an ultrasound signal reflection from the third ventricle. The ultrasound frequency was used because of the minimal attenuation by bone. As the amplitude of ultrasound reflected from various structure would be changed in response and extracted by a digital gate signal. Then the intracranial pressure wave was found equal to that values after combined with those data. The method was done by superimposing the simultaneous recorded electrocardiogram signal on the intracranial pressure waveform, then the measurement at the electronic gate would be obtained. With the ratio fast Fourier of electrocardiogram and echopulsogram, it would derive the secondary mechanical resonance levels. The quantitative intracranial pressure measurement was calculated with the required time for transferring of arterial blood to venous blood in brain tissue, and also their relationships of components by using a developed formula. By the way, this method was not able to give an exact value [14].

There was an interested research that would really determine the intracranial pressure assessment by using noninvasive way. They considered the patients in traumatic brain injury who practically required to make CT scan to see the changes in brain such a hematoma and bone fracture revealability. They used multiple sources to collect, analyze and extract the informative features which indicated intracranial pressure. These extracted features included the midline which was shifted from a middle to one side due to the misposition of brain. Next feature was found in the hematoma or hemorrhage, as this bleeding area led the brain tissue to be compressed and the intracranial pressure would be risen. The last feature was the texture pattern of brain tissue, which could be a change of white and gray matter texture. The demographic information such as age and Injury Severity Score (ISS) were also considered as a feature.

All of these feature would be extracted from each CT scan slice then they would be grouped from several slices to show fully CT scan. After that, the comparison among different patients would be performed. The process could be done by concerning the location which required a slice alignment. With the statistical of features, the state of CT scan could be found. Feature selection, consisted of two stages; filter feature selection and wrapper feature selection, was used to select the most significant feature.

They used 10-fold cross validation as an evaluated criterion for each feature with Support Vector Machine(SVM) for training data and building model for prediction of intracranial pressure level. Finally the Rapidminer was used to implement nested cross validation and classification processes. The classification result was shown approximately 70% of accuracy in intracranial pressure level prediction. Obviously this method was performed non-invasively, however the presented result has not been accurate, and this method needed to improve in further works [15].

Schmidt et al. has been proposed and adapted the mathematical model on noninvasive intracranial pressure assessment. As following their earlier study of the continuous stimulation of intracranial pressure waveform by using a weight function, the calculation of noninvasive intracranial pressure could be estimated by using linear relationship among arterial blood pressure (ABP), intracranial pressure (ICP) and transcranial Doppler middle cerebral artery blood flow velocity (FV). Through this relationship, the use of linear model was applied to analyze a relationship between ABP and FV which resulted in the coefficient ω. As well as, another coefficient f would be derived from ABP and ICP. And a linear model was trained to map ω to f, then the estimation of ICP could be obtained from f and ABP. However this coefficient f needed to estimate from ω first . Many further studies were possible to modify the improvement of noninvasive intracranial pressure assessment techniques in mathematical fields [16,17].

Acknowledgement

This research is supported by Royal Thai Government through National Research Universities project.

References

[1] Zhong J, Dujovny, Park HK, et al. Advances in ICP monitoring techniques. Neurol Res 2003; 25 : 339-350

[2] Lavinio A and David K. Menon. Intracranial pressure: why we monitor it, how to monitor it, what to do with the number and what's the future? . Curr Opin Anesthesiol 24:117–123

[3] Eggers T. and Wenzel M. Implantable Telemetric Pressure Measurement. Medical device technology 2004

[4] Hodgins D., Bertsch., Post N., et al. Healthy Aims: Developing New Medical Implants and Diagnostic Equipment. Pervasive computing 2008:1536-1268

[5] Yue.X, Wang L, Zhou F. New minitraumatic method for a simulation curves with strain electrometric technology in rats. IEEE, 2009

[6] J.A. Allocca, ."Method and apparatus for noninvasive monitoring of intracranial pressure.", *U.S. Patent 4204547*,1980.3.27.

[7] J.G. Rosenfeld, ."Method and apparatus for intracranial pressure estimation.", *U.S. Patent 4564022*, 1986.1.14.

[8] Meyerson, et al. "Non-invasive method and apparatus for monitoring intracranial pressure", *U.S. Patent 65891897*,2003.7.8.

[9]M. R. Tofighi, U. Kawoos, S. Neff, and A. Rosen, "Wireless interacranialpressure monitoring through scalp at microwave frequencies,"Electron. Lett., vol. 42, no. 3, pp. 148–150, Feb. 2006.

[10] M. R. Tofighi, U. Kawoos, F. A. Kralick, and A. Rosen, "Wireless intracranial pressure monitoring through scalp at microwave frequencies: Preliminary phantom and animal study," in IEEE MTT-S Int. Microw. Symp. Dig., Jun. 2006, pp. 1738–1741.

[11]R. Warty, M.-R. Tofighi, U. Kawoos, and A. Rosen, "Characterizationof implantable antennas for intracranial pressure monitoring: Reflectionby and transmission through a scalp phantom," IEEE Trans. Microw. Theory Tech., vol. 56, no. 10, pp. 2366–2376, Oct. 2008.

[12] U. Kawoos, M. R. Tofighi, R. Warty, F. A. Kralick and A. Rosen, "In-vitro and in-vivo Trans-scalp Evaluation of an Intracranial Pressure Monitoring Implant at 2.4 GHz," IEEE Trans. Microwave Theory Tech., vol. 56, no. 10, pp. 2356-2365, October 2008.

[13]U. Kawoos, R. V. Warty, M. R. Tofighi, F. A. Kralick, and A.Rosen,"Issues in wireless intracranial pressure monitoring at microwave frequencies,"in Progr. Electromagn. Res. Symp., Beijing, China, Mar. 2007, vol. 3, no. 6, pp. 927–931.

[14]Michaeli D., Z.H. Rappaport, "Tissue resonance analysis; a novel method for noninvasive monitoring of intracranial pressure", J. Neurosurg. volume 96: 1132-1137, 2002

[15]W. Chen,et al. "Intracranial pressure level prediction in traumatic brain injury by extracting features from multiple sources and using machine learning methods", IEEE International Conference on Bioinformatics and Biomedicine, 2010

[16]P. Xu, et al, "Improved Noninvasive Intracranial Pressure

Assessment With Nonlinear Kernel Regression",IEEE transactions on information technology in biomedicine, vol.14, no.4, July 2010

[17]B. Schmidt, et al, "Adaptive noninvasive assessment of intracranial pressure and cerebral autoregulation, Stroke vol. 34, pp. 84-89, Jan. 2003