

Ophthalmic Artery as a Sensor for Non-invasive Intracranial Pressure Measurement Electronic System

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Introduction

More than one hundred and seventy years ago, Magendie discovered a small foramen in the floor of the fourth ventricle and pointed out the connection between the cerebrospinal fluid (CSF) in the ventricular system and in the subarachnoid spaces of the brain and cord. By this significant discovery, he paved the way to understanding the circulation of CSF and to problems associated with increased CSF pressure. In the late 19th century, Quinke suggested the technique of lumbar puncture to measure the pressure of the CSF. This was the earliest clinical method of an assessment of intracranial pressure (ICP) [1].

Although these two pioneering scientists realized the importance of ICP measurement, they couldn't suspect that in the modern 21st century this fundamental physiological parameter would be monitoring so routinely in clinical practice, especially in intensive care units (ICU). The main reason of this phenomenon – traumatic brain injury (TBI).

Data are critical to understand TBI as an important public health problem. For example, each year an estimated 1,7 million people sustain a TBI annually in the USA alone. Of them: 52 thousand die, 275 thousand are hospitalized [2].

Continuous monitoring of various physiological parameters, including ICP is necessary in order to minimize mortality rate of such patients. Physicians could apply adequate treatment only if they know physiological parameters such as arterial blood pressure (ABP),

intracranial pressure, autoregulation condition of brain blood flow and others.

Unfortunately, measuring ICP using invasive technology is the only way currently available in clinical practice [3]. The reason of this current situation is because scientists were focused on searching correlations between biophysical parameters, which could be measured non-invasively, and ICP. Indeed, ICP affects a lot of biophysical parameters: diameter of cranium [4], stress level of skull bones [5], otoacoustic emission signal [6], etc. However, such correlations between biophysical parameters and ICP are individual for every single human being and varies in time because of the influence of other physiological parameters. Correlation based non-invasive absolute ICP (aICP) measurement systems must be individually calibrated for every single patient. Unfortunately, non-invasive „gold standard“ aICP measurement system which is needed for calibration does not exist.

In order to solve the problem of calibration, it is necessary to find measurement method which works perfectly without any calibration and to find the way of applying this principle for a non-invasive aICP meter.

Ophthalmic artery as gravimetric scales

Gravimetric scales are one of the earliest measurement device used in the history of mankind. This instrument works without calibration very accurately if it is

preliminary balanced. If we want to measure the weight of a physical body, we put the physical body on one plate of the gravimetric scales (Fig. 1, a) whereas on the other one we put a known values of weights till both plates balance each other perfectly (Fig. 1, b). In case of balance the weights on both plates are equal because Earth's gravitational force affects both plates and physical bodies equally. In order to know the measured body weight we could simply look at the opposite plate of the gravimetric scales and count the values of the known weights.

In order to apply this measurement technique to the non-invasive aICP meter, instead of comparing weights it is necessary to compare absolute pressures. However, gravimetric scales must be replaced with something else.

One very particular blood vessel, which is called ophthalmic artery (OA) exists in human being head. OA arising from the anteriorly convex arch of the internal carotid artery inside human head, where aICP exists, passing under the optic nerve within the optic nerve canal into the orbit, where small intraorbital pressure affects this part of OA [7] (Fig. 1, c). It is proved, that various parameters of the blood flow equalize in both intracranial and extracranial parts of OA in case of equality of ICP and external pressure (Pe) applied to the tissues surrounding the eyeball [8] (Fig. 1, d). At this point instead of weights it is possible to compare pressures, whereas OA becomes aICP sensor.

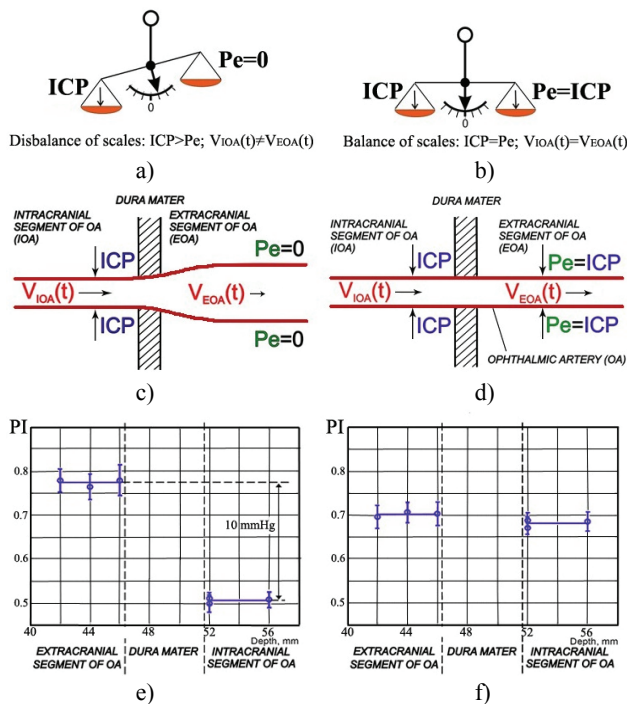


Fig. 1. Ophthalmic artery analogy with gravimetric scales: a – disbalance of scales; b – balance of scales; c – ophthalmic artery, when $Pe=0$; d – ophthalmic artery, when $Pe=ICP$; e – pulsatility indexes, when $Pe=0$; f – pulsatility indexes, when $Pe=ICP$

For the pressure balance $Pe=ICP$ indication could be used insonation angle independent parameters of the blood flow measured by Doppler ultrasound. A pulsatility index which is invariant to ultrasonic insonation angle can be used in a simplest case

$$PI = \frac{V_{syst} - V_{diast}}{V_{mean}}, \quad (1)$$

here V_{syst} – peak systolic blood flow velocity, V_{diast} – minimum diastolic blood flow velocity, V_{mean} – mean blood flow velocity during the cardiac cycle. For example, pulsatility indexes measured in both OA segments are presented in Fig. 1: e) – without external pressure, f) – in the point of pressure balance.

Innovative equipment for the search of the OA segments and measurement of the blood flow parameters

The first task before beginning the non-invasive measurement of blood flow parameters is to find anatomical positions of both OA segments: intracranial (IOA) and extracranial (EOA). For this reason, an innovative hardware and software has been created in Telematics Scientific laboratory of Kaunas University of Technology. The core of this system is two-depth twelve channel transcranial Doppler (TCD) device [9]. The structure of a novel aICP meter is presented in Fig. 2.

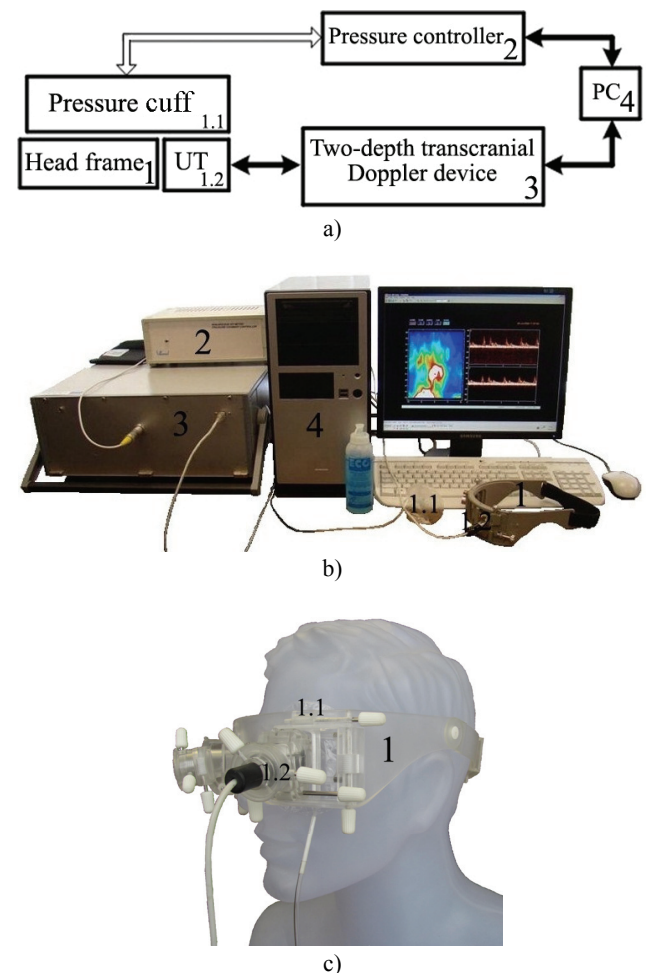


Fig. 2. Non-invasive measurement system of absolute ICP: a – block diagram (black arrows – electrical signals, white arrow – pressure „signal“); b - photograph of the current version of aICP meter; c – head frame with pressure chamber and ultrasonic transducer put on a head

The combined electronic and mechanical scanning ultrasonic TCD transducer, which consists of array of

twelve piezoelements is installed into mechanical head frame (Fig. 2, c).

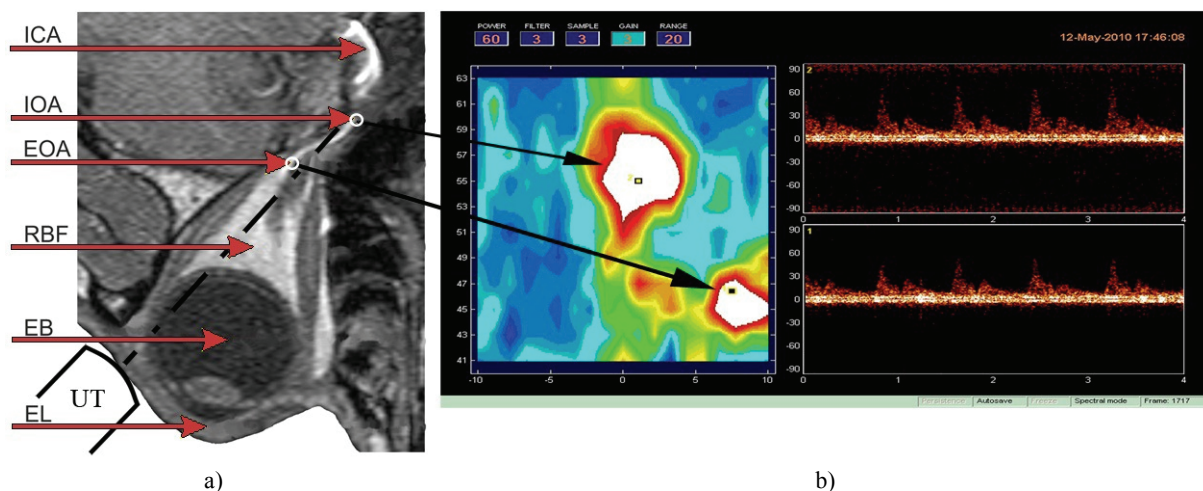


Fig. 3. The search mode of the OA: a – MRI view of region of interest together with schematic representation of ultrasonic transducer (ICA – internal carotid artery, IOA – internal ophthalmic artery, EOA- external ophthalmic artery, RBF – retrobulbar fat , EB – eyeball, EL – eyelid, UT – ultrasonic transducer; b – control and indication panel of special design software

Central frequency of ultrasonic pulses is 2 MHz. Maximum emitted ultrasonic power of 50 mW/cm² is safe for ultrasonic Doppler measurements through the eye and meets the clinical safety requirements. Electronic scanning of single ultrasonic beam is used in order to locate IOA and EOA. In addition mechanical scanning is needed (using head frame which has six degrees of freedom) in order to find optimal transducer position on the orbit. Magnetic resonance image (MRI) of region of interest (ROI) together with schematic representation of ultrasonic transducer is presented in Fig. 3, a).

Using a specially created software it is possible to see two separate white spots simultaneously when ultrasonic TCD transducer is in optimal position on the orbit and ultrasonic beam is focused into the intracranial and extracranial segments of the OA. This software is also capable to visualize blood flow spectrograms from a different segments of the OA (Fig. 3, b).

aICP measurement process can be initiated when both spectrograms are stable in time. For this purpose a pressure cuff which surrounds the tissues of the eyeball is inflated till 4 mmHg of absolute pressure. This pressure is maintained an average of 1 minute while blood flow velocities are measured in both segments of the OA. This system is capable to measure blood flow velocities up to 90.5 cm/s. Absolute pressure in the pressure cuff is increased by 4 mmHg sampling steps and measurement of the blood flow velocities is conducted fully automatically. This measurement process continues until the pressure balance aICP=Pe is obtained [10, 11]. Measured Pe value (mmHg) in the balance point which estimates aICP is displayed as a final measurement result.

Results of comparative clinical studies

According to definition ICP is a pressure of CSF. Intracranial segment of OA is surrounded by CSF. That means that aICP is measured non-invasively as a pressure in the CSF using OA as a pressure sensor. “Gold standard”

invasive ICP meters with systematic error close to zero were used for CSF pressure measurements via lumbar puncture and ventriculostomy in comparative prospective clinical studies [12].

84 neurological patients (101 paired measurements) were included in the latest clinical studies. The average age of patients was 46.4 years (from 18 to 78). Patients were selected with different diseases and a wide range of different physiological parameters. These studies were performed at the Department of Neurology at Kaunas Clinics of University and Department of Neurology and Neurosurgery at Vilnius University. The studies design was approved by the local research and ethics committee (registration number BE-2-26).

Measurement data analysis of the latest comparative clinical studies showed that an accuracy of non-invasive aICP meter expressed by the mean systematic error (bias) is 0.03 mmHg (CL=0.97). Precision of aICP meter expressed by standard deviation (SD) of random error is SD=2.3 mmHg (CL=0.97). That is statistically significant clinical evidence on high accuracy and precision of non-invasive ICP measurement which is based on application of ophthalmic artery as an intracranial pressure sensor.

Conclusions

Innovative non-invasive aICP meter was created, which measures ICP absolute value fully automatically. Location of IOA and EOA segments only is done with operator assistance.

Many influential physiological parameters: heart rate, arterial blood pressure, intraocular pressure etc., and individual patient specific factors such as anatomical and physiological differences of patients, can influence parameters of the OA blood flow including pulsatility indexes. However, these factors do not affect the value of negligible systematic error of proposed non-invasive aICP meter.

The standard deviation of random error across all

patient records is $SD=2.3$ mmHg and it is even less than 4-5 mmHg error tolerance that is a worthwhile practical clinical goal [13].

In conclusion it is fair to say that OA is a proper sensor for electronic non-invasive aICP measurement system which is able to measure absolute ICP values accurately and precisely without patient specific calibration at the first time.

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Theoretical and experimental validity of ophthalmic artery (OA) as a sensor for non-invasive absolute intracranial pressure (aICP) measurement electronic system is presented in this paper. Because of OA similarity with gravimetric scales which can compare aICP with non-invasively applied external pressure P_e the value of aICP can be measured without the need of patient specific calibration. For the indication of aICP and P_e balance various blood flow parameters existing in intracranial and extracranial segments of OA are used. Pressure balance $ICP=P_e$ occurs in the case of maximum conjunction of various blood flow parameters in intracranial and extracranial segments respectively. For the measurement of the blood flow parameters and indication of aICP specially designed hardware and software has been created in Telematics Scientific Laboratory of Kaunas University of Technology. The software of non-invasive aICP meter was developed concerning the fast location of IOA and EOA and fully automatic aICP measurement process. Prospective comparative clinical studies of 84 neurological patients were performed in order to test performance of created system in clinical conditions and to validate ophthalmic artery performance as non-invasive aICP sensor. III. 3, bibl. 13 (in English; abstracts in English and Lithuanian).

L. Bartušis, R. Žakelis, G. Daubaris, A. Ragauskas, S. Rutkauskas, V. Matijošaitis, A. Preikšaitis. Akies arterija kaip sensorius, skirtas neinvazinei intrakranijinio slėgio elektroninei matavimo sistemai // *Elektronika ir elektrotechnika*. – Kaunas: Technologija, 2012. – Nr. 6(122). – P. 45–48.

Šiame straipsnyje yra pateiktas teorinis ir eksperimentinis akies arterijos (Arteria Ophthalmica. OA), kuri veikia kaip neinvazinis absoliučiojo intrakranijinio slėgio (aIKS) sensorius, pagrindimas, kai aIKS matavimui naudojama speciali elektroninė sistema. Remiantis tuo, kad OA veikia kaip gravimetrinės svarstyklės, galinčios palyginti aIKS su neinvaziškai pridėtu, akies obuolį ir gretimus audinius supančiu išoriniu slėgiu P_e , aIKS reikšmė gali būti išmatuota nenaudojant individualaus paciento specifinės kalibravimo procedūros. P_e sutapimo su aIKS indikacijai naudojami OA dviejuose segmentuose (vidiniame ir išoriniame) egzistuojantys įvairūs kraujo tėkmės parametrai. Šių parametru reikšmių (skirtinguose OA segmentuose) maksimalus galimas sutapimas indikuoja pasiektą slėgių balansą $IKS=P_e$. Kraujo tėkmės parametrams matuoti buvo panaudota KTU Telematikos laboratorijoje sukurta speciali techninė ir programinė įranga, kuri yra aprašyta šiame straipsnyje. Neinvazinės aIKS matavimo sistemos programinė įranga buvo sukurta siekiant visiškai automatizuoti matavimo procesą bei minimizuoti vidinio ir išorinio OA segmentų paiešką. Siekiant išbandyti sukurto sistemą bei norint eksperimentiškai pagrįsti akies arterijos, kaip intrakranijinio slėgio matavimo sensoriaus, veikimą, buvo atlikta 84 neurologinių pacientų būsimoji lyginamoji klinikinė studija. Jos rezultatai taip pat pateikti šiame straipsnyje. II. 3, bibl. 13 (anglų kalba; santraukos anglų ir lietuvių k.).