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Non-Invasive Monitoring of Intracranial Pulse Wave During Body Tilting Test

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Introduction

Guidelines for the management of severe head injury in adults as evolved by the European Brain Injury Consortium [1] and the American Association of Neurological Surgeons [2] recommend continuous monitoring of intracranial pressure (ICP) together with other multimodal monitoring techniques in the intensive care units.

Authors [3] published data in favor of cerebral perfusion pressure (CPP) management in severe head injury. The authors reported a significantly improved neurological outcome with active treatment of CPP as a primary therapeutic end point.

Recent studies suggest that the ICP and ABP waveforms' responses to spontaneous variations of CPP provides reliable information on cerebral autoregulator reserve [4,5]. Authors [6,7] reported that the correlation analysis applied to ICP and ABP waves can indicate massive dilatation of the cerebral vasculature in cases exhibiting only a mild elevation of ICP. Authors [8] recognized the importance of the system analysis approach to the ICP and ABP waveforms' including Fourier analysis. Studies show that the exhaustion of autoregulation may also be identified through analysis of the ICP waveform [9]. However, measuring ICP waves using invasive technology is the only practical way currently available in clinical practice.

Transintracranial time-of-flight (TTF) sonography is a recent advance in ultrasound technology which displays non-invasively and in real-time the relative changes in ultrasound velocity and attenuation which occur in the intracranial parenchyma and reflects the ICP mean value and the ICP waveform [10-13]. TTF is an attractive alternative compared with invasive ICP monitoring techniques. It is shown in an observational study [14] in 10 head injured patients using more than 300 simultaneous paired records identified a strong correlation ($r = 0.92$, $p < 0.001$) between the data obtained using the ultrasonic TTF monitoring device (Vittamed) when compared with an industry standard invasive ICP monitor (Camino Labs.). The feasibility to record accurately the ultrasound velocity waves which directly reflect intracranial blood volume waves and indirectly reflect ICP pulse waves, respiration waves and Lundberg's waves applying this TTF monitoring device have been previously reported [12-17].

The aim of this study was to investigate at first time the low elastance region of the intracranial pressure / volume relationship of the healthy human brain applying TTF technology and body tilting test.

Materials and Methods

TTF non-invasive technology and monitor model Vittamed 105 are created for the qualitatively real-time

evaluation the changes of cerebral blood volume and brain tissue volume with the use of ultrasound (Fig. 1, Fig. 2).

An essential aspect of this technology is the acoustic path which is crossing the human head from one side to the opposite side. The ultrasonic pulses propagate through this path. This path consists of the following elements: layer of all external tissues and skull; brain tissue; cerebrospinal fluid; cerebral arterial and blood layer. This acoustic path can be modeled as a cylindrical body the diameter of which depend on the focusing properties of applied ultrasonic transducers. This diameter could be from 0.1 mm up to 15.0 mm or more. The time-of-flight τ for an ultrasonic pulse to travel between the transmitter and receiver is dependent on the ultrasound velocity within each element and the length of this element within the acoustic path.

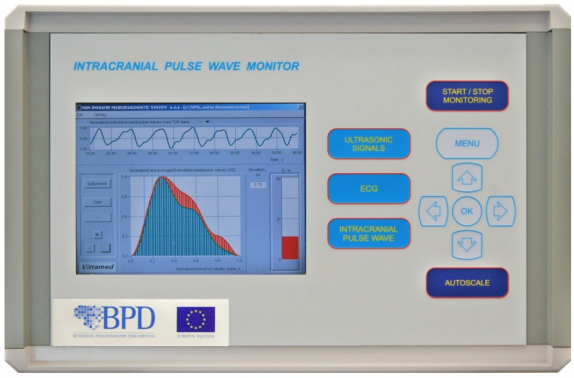

Fig. 1. Vittamed non-invasive intracranial pulse wave monitor

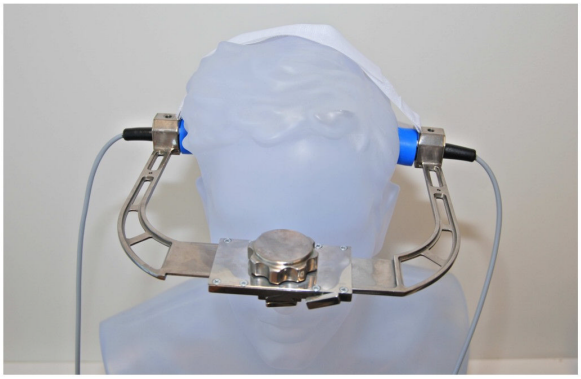

Fig. 2. Mechanical frame for affixing of ultrasonic transducers on the human head

Ultrasound pulse propagation velocity remains relatively constant within each element. But the ultrasound velocity is different inside each element: ultrasound velocity in parenchyma tissue is bigger than in blood. The same parameter of blood is bigger than in cerebrospinal fluid. That's why the time-varying changes in the time-of-flight measurement are produced by time-varying changes in composition of acoustic path. Small changes of cerebral blood volume are produced directly by circulatory pulsations and indirectly by respiration. These changes of cerebral blood volume directly modulate the internal composition of intracranial acoustic path. Thus, time-varying changes of the time-of-flight of ultrasonic pulses within the cylindrical acoustic path produce a signal proportional to change in cerebral blood volume [12,18,19]. Of particular importance is the microvascular parenchymal acoustic path consisting of parenchyma tissue, arterioles, capillaries and venules because the dilation or constriction of intracerebral arterioles is the physiological mechanism responsible for cerebral blood flow autoregulation and stabilization of the metabolic function of the human brain [4-9].

According to the theoretical model [19,20] of the TTF device the changes in ultrasound velocity are associated with the relative changes in the volume of blood within the parenchymal acoustic path and the changes in ultrasound attenuation are associated with the relative changes in the volume of parenchyma tissue.

The distance between ultrasonic transmitting and receiving transducers is constant and fixed by mechanical frame. The measured value of relative change of the time-of-flight $\Delta\tau/\tau_o$ is proportional to the relative change $-\Delta C/C_o$ of ultrasound velocity C inside the parenchymal acoustic path because in all physiological or pathophysiological cases $\Delta\tau<<\tau_o$ and $\Delta C<<C_o$, where τ_o and C_o are initial values of the time-of-flight and ultrasound velocity at the beginning of non-invasive monitoring.

An example of the data produced by the TTF device (pulse volumetric wave monitor Vittamed 105) is shown in Fig. 1.

It is possible to relate the changes in intracranial blood volume with ICP, as it has been suggested that the pulsatile nature of ICP results from changes in blood volume within the brain [19].

Elastance, a measure of the slope of the intracranial pressure - volume relationship (PVR) has the least slope around the zero ICP value [21-24]. The region of minimal slope is the low elastance region of intracranial pressure - volume relationship of the human brain.

We hypothesized that the amplitude of the intracranial blood volume (IBV) pulse waves should follow the dependence of elastance on ICP. According to our hypothesis, the amplitude of the ICP pulse wave should be also minimal in this low elastance region and should increase with increments of ICP above or below an ICP of zero. If this low elastance region could be reached applying body tilting test when ICP is approaching zero value or changing the sign from positive values to negative values that means that the patient has no pathological increments in the brain elastance or pathological decrements in the brain compliance. That's why the low elastance region is very important for the early diagnosing of the brain compliance problems, first of all, for the making decision to implant or not to implant invasive ICP or compliance monitoring probes as early as possible for the head injured patients.

It is possible to change the ICP pulse waves amplitude repeatedly in the low pressure region of the PVR by applying body tilting tests. It has been shown in [22], that ICP varies from approximately 15 mmHg when horizontal to - 5 or -8 mmHg when in the vertical body position. Therefore, we can use the whole body tilting as a method of stimulating intracranial dynamics, assuming that the direct relationship between mean ICP and the ICP pulse amplitude remains intact over the low pressure range of the PVR.

In this study 6 healthy volunteers were examined with the non-invasive TTF device. They were placed at 0° through to 90° in steps of 10° or 15° with the subject kept at each angle long enough to detect at least 15 pulse waves.

The results of non-invasively measured ultrasound velocity pulse waves amplitude versus body tilting angle are shown in Fig. 3.

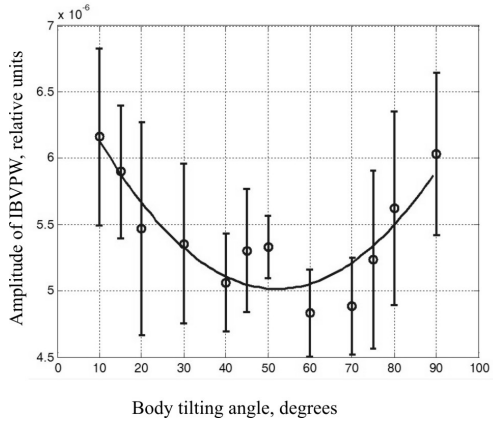

Fig. 3. Dependence of the amplitude (mean and +/-2standard deviation) of intracranial blood volume pulse wave on body tilting angle

Fig. 3 shows a plot of ultrasound velocity pulse waves amplitude *versus* tilt angle. A minimum is seen in the measured pulse wave amplitude in the plot shown in Fig. 3. This minimum was found for six subjects. These experimental data of the non-invasive transintracranial time-of-flight sonography (Fig. 3) reflect qualitatively the same relationship described for the dependence of the ICP pulse on mean ICP in a low elastance and intracranial pressure range of the PVR [22-24].

Using the same body tilting technique, it has been shown that consistent changes in the pulse amplitude of the parameter measured by the TTF device occur. These changes are qualitatively the same as those predicted from the known ICP pulse amplitude, mean ICP relationship. As the changes in pulse waves amplitude are consistent over the subjects, it can be concluded that the TTF device is reliably measuring changes of a physiological nature in low elastance region inside the parenchymal acoustic path. It is impossible to get such a measuring data applying other known non-invasive measuring technologies.

Also the TTF data depend on insonating a parenchyma region with no large cerebral vessels and no cerebral ventricles. These are avoided as ICP pulsation is assumed to be mainly transmitted from the microvasculature [25].

If indeed the system does give a measure of ICP, this would allow new studies to be carried out which are currently impossible with the invasive systems. These would include studies evaluating changes in intracerebral dynamics in normal patients undergoing stresses, such as CO_2 challenges and studies comparing the autoregulatory state in normal and head injured patients.

With the possibility of such studies and the use of a non-invasive ICP measurement system in intensive care units, further investigation of the TTF device is merited.

Conclusions

1. The low elastance region of the intracranial pressure - volume relationship was investigated non-invasively at first time applying non-invasive transintracranial time-of-flight technology and the body tilting test for the healthy volunteers. It was shown that a minimum is seen in the non-invasively measured pulse wave amplitude data between the body tilting angles of 40° and 66° head up. The pulse wave amplitude changed by up to 60%.

2. The experimental data of the non-invasive transintracranial time-of-flight sonography reflects qualitatively the same relationship previously described for the dependence of the ICP pulse on mean ICP in a low elastance region of the intracranial pressure - volume relationship.

3. It has been shown that consistent changes occur during body tilting in the TTF data. Therefore, the TTF device is detecting changes of a physiological nature within the intracranial parenchymal acoustic path. The TTF device appears to have the capability of investigating intracerebral hemodynamics in a non-invasive manner.

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Studies have shown that transintracranial time-of-flight (TTF) sonography displays non-invasively and in real-time the relative changes in ultrasound velocity which occur in the intracranial parenchyma and reflects the intracranial pressure (ICP) waveform and mean value trends. In order to investigate the value of such non-invasive ICP monitoring for physiological examination of intracranial dynamics the non-invasive recordings of ICP pulse waves were obtained during body tilting tests of healthy volunteers. It has been shown that consistent changes occur during body tilting in the TTF data. A minimum is seen in the measured by TTF pulse wave amplitude in the low pressure range of the intracranial pressure-volume relationship. However, the transintracranial time-of-flight sonography appears to have the capability of investigating intracerebral parenchyma dynamics in a non-invasive manner. Ill. 3, bibl. 25 (in English; summaries in English, Russian and Lithuanian).

А. Рагаускас, Г. Даубарис, В. Петкус, Р. Райшутис, Р. Хомскис, Р. Шлитерис, В. Декснис, Й. Гузайтис, Г. Ленгвинас, А. Ругайтис. Неинвазивный мониторинг интракраниальных волн пульса методом изменения наклона тела // Электроника и электротехника. – Каунас: Технология, 2008. – № 4(84). – С. 71–74.

В статье приводятся иновационные методы и технология для неинвазивного физиологического мониторинга человеческого мозга. Они основаны на измерениях акустических свойств паренхимы мозга, которые также могут использоватся для измрения интракраниального объема/давления. С целью оценки разрешающей способности неинвазивной технологии при измерении динамики физиологических процесов были проведены исследования на здоровых людях по мониторингу изменения волн интракраниального давления методом изменения углового положения тела. Результаты показали, что измеренные времена задержки ультразвуковых волн соответствовали физиологическим изменениям в человеческом мозгу.
Показано, что транскраниальная сонография позволяет неинвазивным способом оценивать динамику кровотечения в интрацеребральной паренхиме. Ил. 3, библ. 25 (на английском языке; рефераты на английском, русском и литовском яз.).

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Straipsnyje pateikti inovatyvūs neinvazinės žmogaus smegenų fiziologinės stebėsenos metodai ir technologija. Šie metodai remiasi smegenų parenchimos akustinių savybių matavimu, taip pat yra tinkami intrakranijinio slėgio sukeltoms bangoms matuoti. Siekiant nustatyti neinvazinių metodų skiriamumą matuojant fiziologinių procesų dinamiką, sveikiems savanoriams buvo atlikta intrakranijinio slėgio pokyčio bangų stebėsena taikant kūno pavertimo testą. Šių testų metu išmatuoti ultragarso bangų sklidimo suvėlinimo laiko pokyčiai atitiko fiziologinius pokyčius intrakranijinėje žmogaus smegenų dalyje. Parodyta, kad transintrakranijinė sonografija įgalina neinvaziškai stebėti kraujotakos dinamiką intracerebralinėje parenchimoje. Il. 3, bibl. 25 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).