ISSN 1392-2114 ULTRAGARSAS, Nr.4(45). 2002.

Ultrasonic non-invasive intracranial wave monitor

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Introduction

The innovative non-invasive intracranial volume wave monitor has been developed in Telematics Scientific Laboratory of Kaunas University of Technology (Lithuania). It is based on the measurement of the human brain parenchyma acoustic properties (ultrasound speed and attenuation) using time-of-flight technique [1,2] and it is capable of measuring different types of intracranial volume wave (slow B waves, respiration waves, pulse waves), also to perform analysis of their shapes and to diagnose different pathophysiological states of the human cerebrovascular system [3]. The diagnostic information about the human cerebrovascular system can be obtained while measuring the dynamics of the acoustic properties of brain parenchyma:

1) slow trends and waves of intracranial pressure (ICP) due to the slow changes of the intracranial media component volumes inside the parenchymal acoustic path,

2) changes of cerebrovascular resistance due to the pathological changes of intracranial component volumes influencing the cerebrospinal fluid (CSF) outflow to the spinal canal which can be determined by measuring the parameters of cerebral blood volume or ICP pulse waves inside brain parenchyma [4].

The essential capability of the monitor is the suitability of continuous and real-time monitoring of human cerebrovascular autoregulation (CA). It is implemented by non-invasively measuring slow B waves of relative ultrasound speed ($\Delta C/C_0$) in brain parenchyma and applying their correlation with the same waves of arterial blood pressure (ABP) as an index of CA state [3,5]. This correlation coefficient r($\Delta C/C_0$;ABP) characterises the cerebrovascular resistance which determines the intracranial cerebral blood flow and can quantitatively represent cerebrovascular autoregulation [6,7].

There could be a few fields of application of the new non-invasive monitor.

The intracranial volume monitoring and CA status diagnosing is needed for traumatic brain-injury, spinal cord-injury and hydrocephalus patient treatment. Moreover, the resent clinical studies of factors that influence the outcome of patients with traumatic brain injury show that the cerebrovascular autoregulation state is the most critical factor for the patients outcome [7,8]. The relationship between CA state and the patients' outcome and their mortality as well was found to be more significant and stronger than the relationships between the outcome and widely used criteria such as Glasgow Coma Scale, mean arterial blood pressure, mean intracranial pressure or mean cerebral perfusion pressure [7,8]. The non-invasive diagnosing and monitoring of the human cerebrovascular autoregulatory system is also important while investigating the reactions to the influences of microgravity/space conditions or physical loads. Other applications of the new non-invasive monitoring system could be the fields of pharmacological investigation, where the introduction of the present technology would open new possibilities to explore different pharmacological influences to the brain and it would help to choose the optimal way for treating the patient.

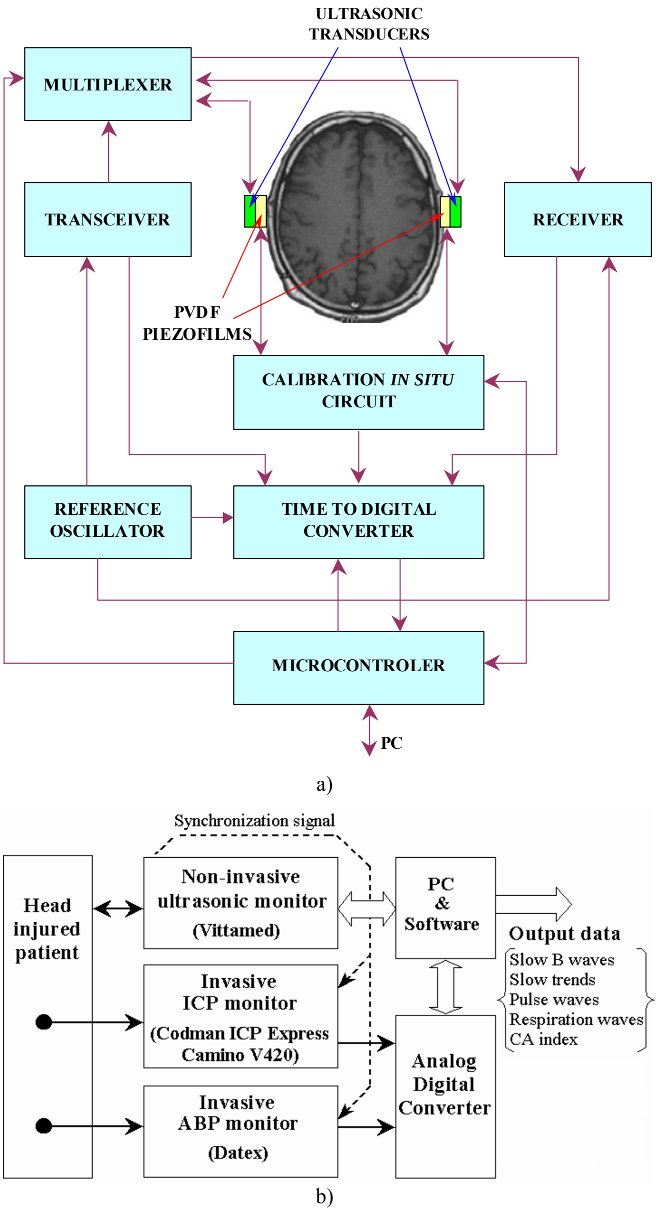
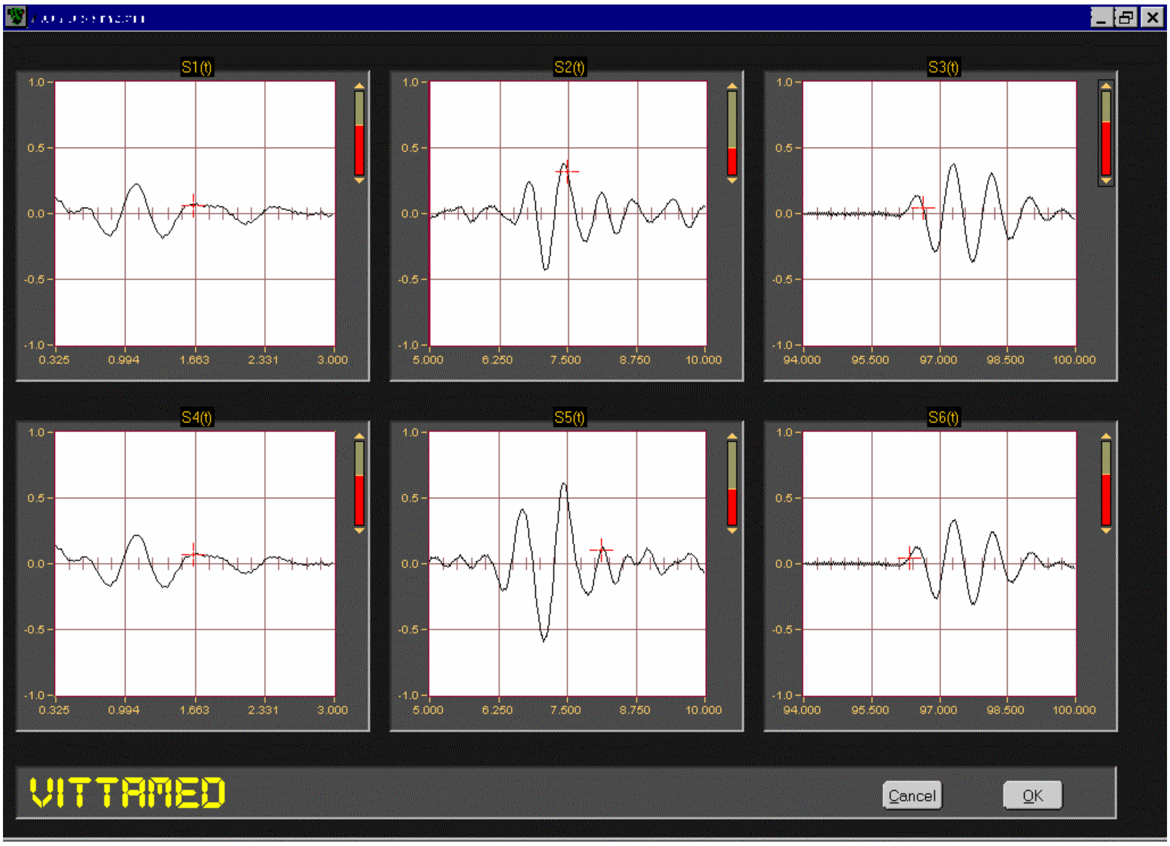
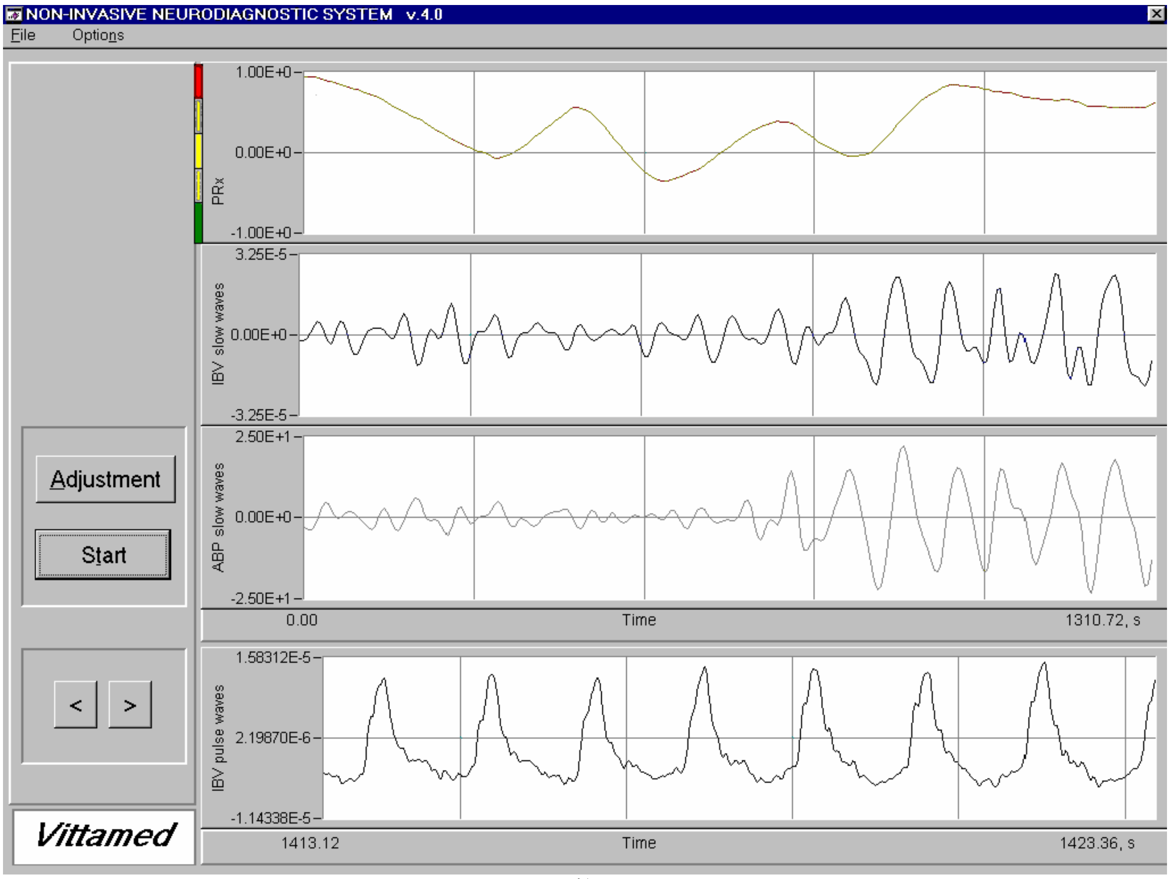


Fig 1. **The structural diagram of non-invasive brain parenchyma acoustic properties monitoring device (a) and the experimental setup for comparative invasive and non-invasive intracranial waves and CA indexes study (b).**

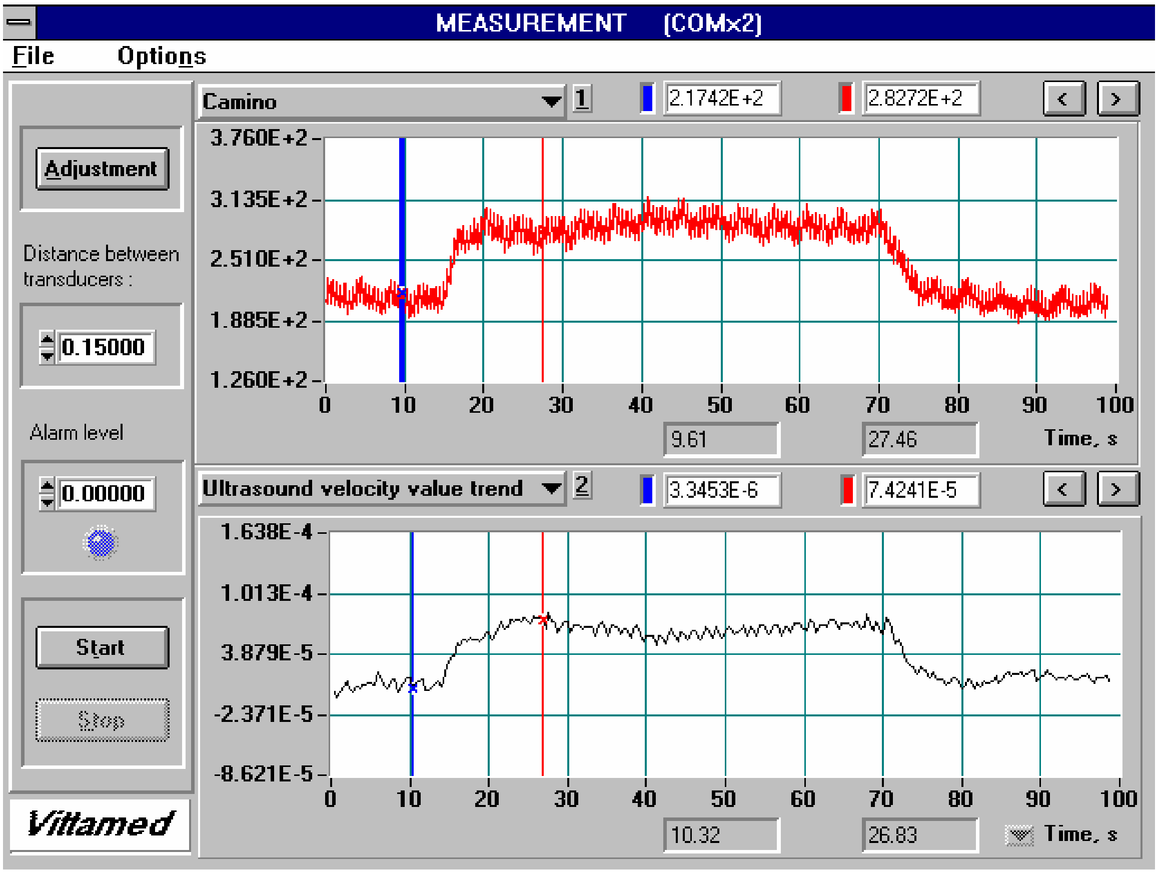


a)

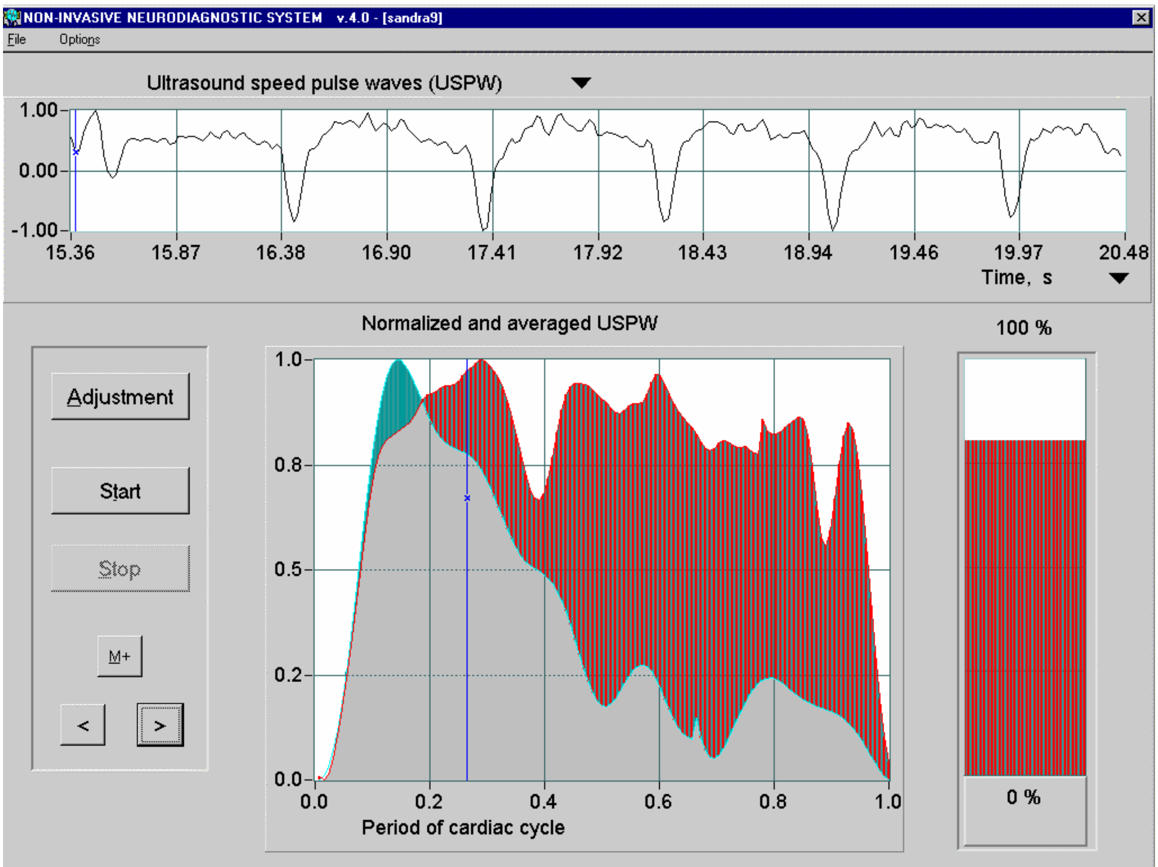


b)

Fig 2. **The virtual panels of Vittamed device:. a) Monitoring window of ultrasonic signals in adjustment regime: S1(S4) is transmitting signal into the human head, S2 (S5) is echo signal reflected from inner surface of skull bone, S3 (S6)is signal transmitted through the human head. S1-S3 and S4-S6 are the signals obtained by performing measurements on opposite sides of the human head. b) Monitoring window of CA status index (PRx) and slow waves of IBV, ABP and IBV pulse waves**



a)



b)

Fig 3. **The virtual panels of Vittamed device: a) is the simultaneous monitoring of the cerebraovascular reaction on a bed tilting test with the invasive ICP (Camino) monitor and non-invasive ultrasound speed monitor for a head-injured patient in ICU. b) is the non-invasive monitoring of ultrasound velocity pulse wave and the analysis of pulse wave evolution for a spinal cord-injured patient in ICU**

Methods

The new non-invasive intracranial wave monitor "Vittamed" is a virtual measuring device that consists of the monitor for non-invasive ultrasonic brain acoustic properties measuring and a personal computer (PC) for processing, visualisation and storage of measurement results (Fig. 1,2 and 3). The computer also includes additional inputs for ABP and ICP simultaneously measured data that are necessary for comparative study of invasive and non-invasive data or for the CA state monitoring (Fig. 1a and 2b).

The non-invasive ultrasonic intracranial wave monitor is based on time-of-flight method application for measuring relative values of ultrasound speed changes inside the parenchymal acoustic path. This is performed by transmitting ultrashort ultrasonic pulses into parenchymal acoustic path and measuring signals' time-of-flight through the human head. In order to compensate in real-time and *in situ* the influences of the human head external tissue hemodynamics on the results of such measurements, the same ultrasonic pulses and their echoes from internal surfaces of the skull are used. The time-of-flight with compensation of external tissue hemodynamics is calculated by:

$$TF_{IC} = \left(TF_{S3} + TF_{S6} - TF_{S2} - TF_{S4}\right)/2\,, \qquad (1)$$

where TF_{S3} and TF_{S6} are the time-of-flight of the signals after their transmission through the head in both sides; TF_{S2} and TF_{S4} are the time-of-flight of the echo signals reflected from the both sides of the inner surface of the skull bones. These signals are controlled on virtual panel of the measuring system working in the adjustment regime (Fig 2a).

The specially designed software is used to convert the non-invasively measured time-of-flight data into relative ultrasound speed that linearly corresponds to the intracranial blood volume (IBV) pulsation inside the brain parenchymal acoustic path [9]. Further these data are processed to get relative values of intracranial slow waves, respiration waves and pulse waves (Fig. 4).

The computer software is developed for operation in different regimes:

1) *Ultrasonic signal adjustment*;

The medical physicist mounts the ultrasonic transducers on the patient's head and checks the quality of transmitted, reflected, and propagated signal through the human head (Fig 2a).

2) *Real-time monitoring of IBV, ABP and ICP waves;*

The raw invasive and non-invasive data are monitored simultaneously and represented in the moving window for analysing their reactions on pharmacological, bed tilting or other tests in real time (Fig. 3a). After measurement the data are saved in the computer for further processing.

3) *CA index and slow waves of IBV and ABP monitoring;*

The IBV and ABP waves are monitored simultaneously and processed in real-time using digital bandpass filters to get slow B waves. The monitoring of the correlation coefficient between slow IBV and ABP waves as an index of cerebrovascular autoregulation is presented in the moving window with the slow waves data (Fig 2b).

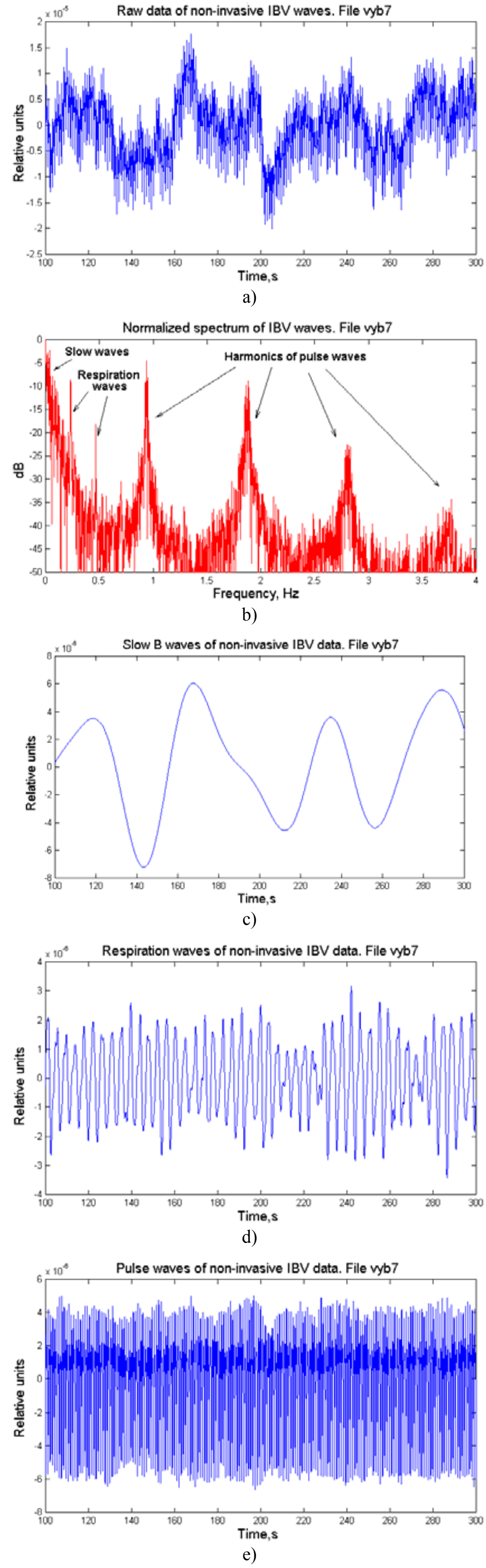


Fig 4. **The non-invasively measured data of the IBV waves: a) is the raw data, b) is the normalized spectrum of IBV waves, c), d) and e) are the processed slow, respiration and pulse waves respectively**

4) *Pulse wave shape monitoring.*

The pulse waves are processed from non-invasively obtained IBV data, applying the procedures of digital filtering, averaging and normalization to get the shape of the pulse wave. This averaged and normalized pulse wave is used for diagnosing the impairment of cerebrovascular resistance (due spinal chord injury, hydrocephalus, etc.) by comparing its shape with typical shapes of pathological and normal pulse wave (Fig. 3b) [10].

Results

The new non-invasive intracranial wave monitor was tested under ICU conditions in the USA, UK and Lithuania while performing a comparative study of monitoring intracranial waves simultaneously with the invasive ICP monitor (Codman or Camino), invasive ABP monitor (Datex) and non-invasive IBV monitor (Vittamed). 13 head-injured patients in different pathophysiological states were monitored invasively and non-invasively (Table 1). 53 one-hour sessions of invasive and non-invasive CA monitoring and 87 one-hour sessions of ICP and $\Delta C/C_0$ intracranial slow waves simultaneous monitorings were performed during the experimental study. The recorded data were used for calculating slow waves, pulse waves, slow trends and indexes of CA status estimation r($\Delta C/C_0$; ABP), r(ICP;ABP). 17 patients with impaired cerebrovascular resistance were monitored non-invasively by diagnosing their pulse waves and observing their evolution during treatment (Table 2).

Table 1. **Patients population for intracranial wave and CA state monitoring study.**

Patients Males Females	13 10 (76.9 %) 3 (23.1 %)
Age (mean, range)	30,5, 18-64
Pathology (closed head trauma)	100 %
ABP ranges, mmHg	35 – 140
ICP ranges, mmHg	3 - 80
Simultaneous invasive and non-invasive CA monitoring	55 one-hour sessions (10 patients)
Simultaneous invasive and non-invasive slow waves of ICP and IBV monitoring	87 one-hour sessions (13 patients)

Table 2. **Patients population for pulse wave monitoring study.**

Patients Males Females	17 13 (76.5 %) 4 (23.5 %)
Age (mean, range)	44.4, 18-75
Pathology ▪ Cervical spine trauma ▪ Cervical stenosis, intervertebral disk herniation ▪ Thoracic spine trauma ▪ Thoracic spine epidural abscess ▪ Lumbar stenosis	 8 (47.1%) 5 (29.4%) 2 (11.8%) 1 (5.85%) 1 (5.85%)
Surgery	10 (58.8%)
Spinal CSF circulation block ▪ Full ▪ Partial	 3 (17.6%) 14 (82.4%)

Conclusions

The suitability of the new non-invasive ultrasonic monitor for intracranial wave monitoring was tested under ICU conditions, analysing its capability to measure slow, respiration and pulse IBV waves. The applicability of non-invasively measured slow B waves of intracranial blood volume for diagnosing the CA state by calculating their correlation with slow ABP waves was proved on 10 ICU patients in different pathophysiological states. The applicability of non-invasively measured IBV pulse waves for diagnosing impairment of the cerebrovascular resistance and observing its evolution was proved on 17 ICU patients with spinal cord injuries.

One essential peculiarity of the non-invasive monitoring technology is that the present monitor is based on relative values of IBV waves measurement. The application of IBV waves for CA state evaluation (by calculating their correlation coefficient with ABP waves) or for pulse wave shape diagnosing does not require individual calibration procedures or other conversion of the non-invasively measured waves. Moreover, this technique is practically insensitive either to the magnitude of non-invasively measured waves data or to their drifts.

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Ultragarsinis neinvazinis intrakranialinių bangų monitorius

Reziumė

Straipsnyje aprašyta inovacinė neinvazinė žmogaus intrakranialinių tūrio bangų (ITB) monitoringo sistema, paremta smegenų parenchimos akustinių savybių matavimu. Monitoriumi matuojamos santykinės lėtosios, kvėpavimo ir pulsinės ITB bangos, kurias panaudojant žmogaus cerebrovaskuliarinės autoreguliacijos (CA) ir cerebralinės kraujotakos rezistyvumui tirti nereikia atlikti individualių “monitorius – pacientas” sistemos kalibravimo procedūrų. Monitorius buvo išbandytas JAV, Didžiosios Britanijos ir Lietuvos klinikinėse ligoninėse intensyvios terapijos sąlygomis tikrinant pacientų su sunkiomis galvos ir stuburo traumomis CA būseną ir cerebralinės kraujotakos rezistyvumą.

Pateikta spaudai 2002 12 16