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Near infrared transillumination-back scattering (NIRT-BS) – a new method for non-invasive monitoring of changes in width of subarachnoid space and magnitude of cerebrovascular pulsation

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The authors present the medical, physical, and technical background for the new method of near infrared transillumination – back scattering. The method, for the first time ever, allows for almost complete elimination of the influence of the alterations in skin circulation on the optical signal $i_{DS}(t)$ subtly modulated by the changes in the width of the subarachnoid space (SAS). This has been accomplished through division of the distal or deep optical signal $i_{DS}(t)$ over the optical reference signal $i_{PS}(t)$ which is independent of the width of SAS, but depends on the propagation in the other tissue layers in the same manner as $i_{DS}(t)$. From the obtained quotient, a weak component was extracted that depends on the cerebrovascular pulsation. Described in this paper is the mathematical method of reducing the influence of the changes in skin blood flow on the transillumination signals. A tilt test was used as an example to show the capacity of the method to determine the cerebro-spinal reserve volume.

Keywords: subarachnoid space, monitoring, transillumination.

1. Introduction

In clinical practice, of greatest value and importance are such procedures and techniques, which provide data essential to diagnosis, treatment and evaluation, and – preferably – combine being informative with non-invasiveness.

The rapid progress in biomedical engineering and technology has been particularly beneficial for both research and clinical practice in the fields of neurology, neurosurgery and neuroimaging. Technological advances have enabled exceptional improvement in the existing techniques and introduced new quality in the domain of imaging of the structure and function of the nervous system, and brain in particular. Today, it is possible to determine changes in metabolism of the brain as a whole or in its selected areas with PET or to investigate various structural or functional changes within the brain with MRI. Due to their relatively high cost, however, these techniques cannot be used for long-term monitoring of structural and functional changes within the central nervous system.

A number of neurological diseases and disorders, inter alia cerebral stroke, cranio-cerebral trauma or some poisonings are accompanied by a life-threatening condition of cerebral oedema. So far, the technique of choice for the monitoring of cerebral oedema has been the method of recording of the changes in intracranial pressure (ICP). This, however, is highly invasive as it requires an appropriate probe to be fixed in a trepanation foramen drilled through the skull bone.

The already classic works by Jöbsis (1977) [1], further developed by many other investigators [2–14] have laid foundations for the application of the near-infrared radiation (NIR) in detection and measurement of the functional changes within the central nervous system. The best example of an NIR technique used for this purpose is near-infrared spectroscopy (NIRS) [15–18]. It enables assessment of changes in cerebral blood supply on the basis of measurements of haemoglobin and oxyhaemoglobin content in the blood of the cerebral circulation. Although still modified and improved, NIRS has by now been developed into a valuable diagnostic and monitoring technique, used in daily clinical practice.

More recently, attempts have been made to utilise near-infrared radiation as the information bearing medium in techniques of optical tomographic brain imaging [19].

In our research, we focused on the feasibility of utilisation of the NIR for the assessment of changes in the width of the subarachnoid space (SAS) and magnitude of cerebrovascular pulsation. Because of the partial reference to an earlier method employing mostly white light [20,21], we named the new technique near-infrared transillumination – back scattering (NIRT-BS). In our earlier studies we have

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addressed the basic problems related to this issue: propagation of the NIR in models of the human head in conditions of changing width of the simulated layer of cerebrospinal fluid [22–24], and analysis of the changes of the NIRT-BS signals recorded in different physiological conditions and their comparison with the changes in synchronously monitored basic physiological parameters in experimental animals (papers in print).

The objective of this study is to present the newly devised NIRT-BS technique as a tool for detection and assessment of the magnitude of changes in the width of the SAS.

2. Description of the method

In this study, changes in the width of the SAS were detected and assessed with the new technique of NIRT-BS. This technique utilises a special infrared emitting-sensing module (further referred to as IR sensor unit) of own design by the first author of this paper (A.F.F.) [25]. As the source of radiation a light emitting diode (LED) was used, generating impulses of infrared radiation (IR) of 860 nm wavelength and 1/8 ms duration at the rate of 1000 Hz. This length was chosen for its high ability to penetrate tissues and very low dependence of the intensity of the propagating radiation on haemoglobin saturation with oxygen [16,17,19]. The IR sensor unit consists of the IR source or emitter (E) and two IR photo-sensors located in one line at different distances from the source. The near or proximal sensor (PS) is located 5 mm away from the source, while the far or distal sensor (DS) is located at the distance of 25 mm from the source. The stream of infrared radiation generated by the LED emitter penetrates highly perfused layer of the skin of the head – scalp, the skull bones and the SAS. This fluid-filled SAS constitutes the propagation duct for the infrared radiation, which is transmitted in the cerebrospinal fluid in all directions in a way closely resembling that encountered in optical waveguides. The beams are reflected and dissipated from the surface of the brain and a certain amount of the radiation returns to the sensors in the IR sensor unit. The signals from the sensors are recorded with a dedicated signal acquisition system and subsequently processed digitally with a PC-compatible microcomputer.

3. Propagation of the near-infrared radiation

NIR generated by the LED source successively penetrates: layer of skin of the head highly perfused with blood (Fig. 1, layer 1), the skull bones (Fig. 1, layer 2) and the SAS (Fig. 1, layer 3). On their way from the deep tissue layers to the sensors, photons cross these tissue layers in a reverse order.

Before it reaches the sensors, NIR radiation propagates from the source through the skin, skull bone and SAS and then back, again through the bone and skin (Fig. 1). On its way from the source to the sensors, the radiation is affected by a number of photo-optical phenomena, the most important being absorption, scattering, diffraction, and reflection. On the basis of results in earlier studies [22–24], we are presenting here an attempt of quantitative approach to propagation of IR through and within anatomical layers of the human head, with analysis of basic relations between waveforms of signals received from the sensors PS and DS.

Propagation of IR radiation across the scalp is time-dependent and changes with instantaneous filling with blood of the rich vascular network in the skin. Transmittance coefficient for NIR for this layer is a product of a time-independent position-dependent factor μ and time-dependent position-independent factor $\alpha(t)$. Therefore, transmittance coefficients under the source (E), PS and DS can be described as $\mu_1\alpha(t)$, $\mu_2\alpha(t)$ and $\mu_3\alpha(t)$, respectively. In the scalp, photons of IR propagate not only across the skin layer but also along within this layer, so to say longitudinally. This propagation is also time-dependent. The transmittance coefficient for this longitudinal propagation $\delta(t)$ decreases greatly with increase in the source-sensor distance. Therefore, the contribution of the longitudinal propagation of NIR from the source to the DS can be disregarded.

As to skull bone, we observe transverse or cross-propagation only. For the bone, transmittance coefficient β for IR is time-independent (constant in time) and position-dependent. Coefficients for the three locations: E, PS and DS can be assigned β_1, β_2, and β_3, respectively.

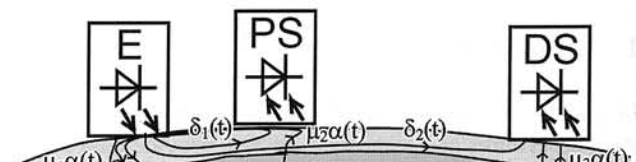

Fig. 1. Propagation paths of near-infrared radiation from the source to proximal and distal sensors; Greek characters stand for transmittance coefficients at different locations which are marked with arrows on the propagation paths. Horizontal (coronal) section of the head at the level of frontal tubers; 1 – scalp; 2 – skull bone; 3 – subarachnoid space; 4 – brain.

Due to complex nature of the photo-optical phenomena involved, which result in return to PS and DS of part of the radiation emitted by the source, the time-dependent IR propagation in the cerebrospinal fluid (CSF) filling the SAS, can be described with the return coefficients. Fluctuations of the value (in other words variability dynamics) of the return coefficient for PS – $\varepsilon_1(t)$, are much lower than those of the value for DS – $\varepsilon_2(t)$, which sensor receives radiation propagated in a much longer propagation duct within the fluid layer.

The next step here is to provide quantitative description of the changes in intensity of the radiation reaching each of the sensors through propagation in the tissue layers of the head. If we assign i_E to constant intensity of NIR radiation emitted by the source (E), then, considering the fact that in a multi-layer structure the overall transmittance coefficient is the product of coefficients for each of the layers in the cascade, we arrive at the following formulae:

$$i_{PS}(t) = \mu_1\alpha(t)\beta_1\varepsilon_1(t)\beta_2\mu_2\alpha(t)i_E + \delta_1(t)i_E \quad (1)$$

$$i_{DS}(t) = [\mu_1\alpha(t)\beta_1\varepsilon_2(t)\beta_3\mu_3\alpha(t) + \\ + \mu_1\alpha(t)\beta_1\varepsilon_3(t)\gamma(t)\varepsilon_4(t)\beta_3\mu_3\alpha(t) + \delta_2(t)]i_E \quad (2)$$

where i_{PS} and i_{DS} stand for the intensities of radiation reaching the proximal and distal sensors, respectively. The currents generated at the photo-sensors are further referred to as transillumination signals.

Assuming that longitudinal transmission between E and PS, i.e., $\delta_1(t)$ is very small, the $\delta_1(t)i_E$ component of the $i_{PS}(t)$ is negligible. Moreover, it is easy to notice that $\gamma(t)$ which represents very low permeability of the brain for NIR, as a component of the product with $\varepsilon_3(t)$ and $\varepsilon_4(t)$ contributes to inequality: $\varepsilon_3(t)\gamma(t) << \varepsilon_2(t)$. Therefore, we arrive at the following expression for the ratio of transillumination signals received by the two sensors

$$\frac{i_{DS}(t)}{i_{PS}(t)} = \frac{[\mu_1\alpha(t)\beta_1\varepsilon_2(t)\beta_3\mu_3\alpha(t) + \mu_1\alpha(t)\beta_1\varepsilon_3(t)\gamma(t)\varepsilon_4(t)\beta_3\mu_3\alpha(t) + \delta_2(t)]i_E}{\mu_1\alpha(t)\beta_1\varepsilon_2(t)\beta_3\mu_3\alpha(t)i_E + \delta_1(t)i_E}, \quad (3)$$

$$\frac{i_{DS}(t)}{i_{PS}(t)} = \frac{\mu_1\alpha(t)\beta_1\varepsilon_2(t)\beta_3\mu_3\alpha(t)}{\mu_1\alpha(t)\beta_1\varepsilon_1(t)\beta_2\mu_2\alpha(t)} \cong \frac{\beta_3\mu_3\varepsilon_2(t)}{\beta_2\mu_2\varepsilon_1(t)} = const \cdot \frac{\varepsilon_2(t)}{\varepsilon_1(t)}. \quad (4)$$

This result of division of the two signal magnitudes gained the name of the transillumination quotient (TQ) and marked as $q(t)$. Therefore: $q(t) = i_{DS}(t)/i_{PS}(t)$. In each individual recording the transillumination quotient depends on two factors:

- location of the IR sensors, which is reflected in the ratio of the $\beta_3\mu_3/(\beta_2\mu_2)$ and
- instantaneous width of the propagation duct, which is described by the ratio of $\varepsilon_2(t)/\varepsilon_1(t)$.

As it appears from Eq. (4), due to elimination of the proportional factors, the transillumination quotient is almost completely independent from the very strong modulation introduced by the pulsation of the blood vessels of the scalp, because division of the two signals eliminates the proportional factors. Considering the earlier assumption on the dynamics of $\varepsilon_2(t)$ being much greater than that of $\varepsilon_1(t)$, the depth of modulation or magnitude of the instantaneous changes of the transillumination quotient depends primarily on the changes in the propagation of the radiation between the source and the distal sensor within the translucent fluid-filled subarachnoid space (see Fig. 1).

4. The NIR-TI signal acquisition and digital analysis system

The system for assessment of variations in the width of SAS consists of three main parts:

- set of photodiodes placed on the head of the examined individual,
- microprocessor emitter-sensor control and data acquisition system,
- PC microcomputer for recording, processing and analysis of the gathered data, and for visualisation of the analysis results.

5. Recorded sets of samples of discreet signals

In the tracings from PS and DS, as well as in the TQ, pronounced fluctuations and oscillations of different frequencies are observed. The most prominent of them have the same frequencies as the two essential physiological parameters – heart rate and respiratory rhythm:

- respiratory rhythm is the strongest frequency in what we call slow-variable component of the transillumination quotient (svc-TQ). This component is a sum of fluctuations derived from any relatively slow rhythms of frequencies equal or lower than respiratory rate. It can be seen as a superposition of all those slow fluctuations over a theoretical constant baseline signal depending on the average width of the SAS in a given individual in resting conditions.
- other distinct component of the TQ is the cardiac component (cc-TQ) whose frequency of oscillations is equal to the heart rate (HR). These oscillations in the TQ tracing originate from the alterations in the width of the SAS resulting from periodic increase in the filling with blood of the intracranial and intracerebral arteries in each cardiac cycle.

Our investigations confirmed the earlier results obtained in the studies on mathematical-statistical as well as mechanical-optical modelling [22–24] of the propagation of the near-infrared radiation in the frontal region of the human head, which pointed to stronger influence of the width of the SAS on the intensity of radiation reaching the distal sensor than on that reaching the proximal one. We have proved that the quotient of the transillumination signals from the sensors (DS/PS) is free from the influence of the so-called proportionate factors affecting each of the signals separately. Therefore, changes of the quotient in

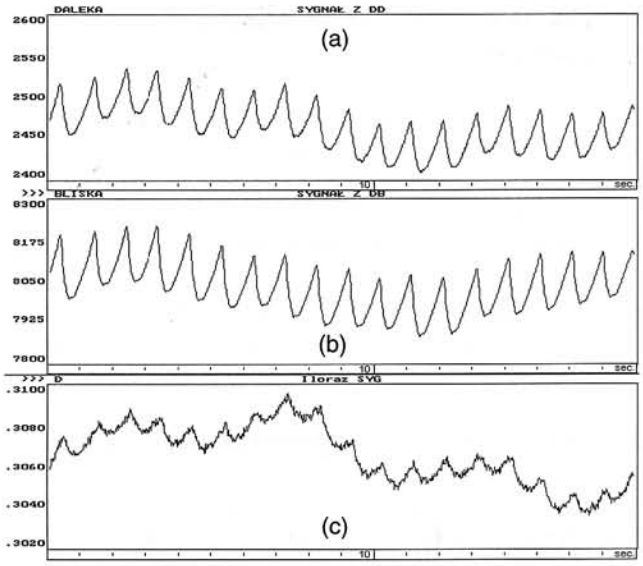

Fig. 2. Typical signal waveforms recorded from DS and PS, and their ratio – transillumination quotient (TQ): (a) DS waveform, (b) PS waveform, (c) TQ. Single fast waves are of cardiovascular origin and result from systolic-diastolic alterations in filling with blood of the intracranial vessels. The additive noise on the TQ plot is the result of interference from the equipment's power supply system.

time result exclusively from the influence on the transillumination signals of non-proportionate factors affecting propagation of radiation from the source to each of the sensors, i.e. of such factors which influence NIR propagation via the superficial and deep SAS paths to a different degree. The proportionality of the attenuation of the propagated radiation in the skin and bone on both of these paths points clearly to alterations in the propagation conditions in the SAS as responsible for the changes in the TQ. Under normal stable conditions, the only SAS parameter able to affect propagation within the CSF layer in the SAS is the width of that duct.

6. Assessment of changes in the width of the subarachnoid space

To prove the correctness of the earlier assumptions on the propagation of the NIR and the influence of the width of the SAS on the TQ, we examined the changes in PS and DS signals as well as in TQ during a tilt-test, in which the examined subject changed the position of the head from backward bend to forward bend, as described below in Fig. 3.

Such a change in the position of the head results in a gravity-induced displacement of the brain within the cranium [26,27]. This causes displacement of a certain amount of the cerebro-spinal fluid from the frontal region to other parts of the cranio-spinal system, primarily within the cranial compartment. This, however, is possible only on the condition that there is initially a certain amount of fluid surrounding the brain, or – in other words – that there is a non-zero-width subarachnoid space present in the examined individual. In the case of pathology, mainly in cerebral oedema, it may happen that there is no displacement of CSF at forward-tilt, because there is no brain movement possible within the cranium, due to the swelling of the brain and slow displacement of even as much as the total of CSF out of the cranial compartment into the spinal compartment of the cranio-spinal system.

The transillumination signals from PS and DS and their quotient TQ obtained during forward-tilt in a healthy individual are presented in Fig. 4.

The individual PS (tracing b) and DS (tracing a) transillumination signals along with their quotient TQ (tracing c), as defined in Eq. (4) above, are presented in Fig. 4. Clearly visible in the recording of TQ are three phases of the forward-tilt test: 1 – backward-tilt lasting about 1 minute, 2 – forward-tilt of the head for a period of about 1 minute, and 3 – return to initial backward-tilt position. The recording reveals stronger influence of a decrease in the width of the SAS on the signal from DS than on that from PS. This results in a decrease of the value of the TQ. The changes observed and presented in Fig. 4 are fully re-

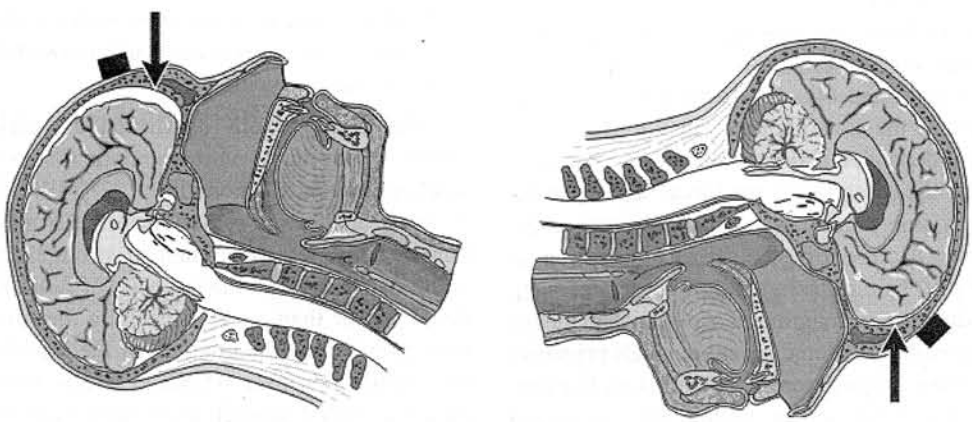

Fig. 3. Changes in the width of SAS in the frontal region during forward-tilt test. Arrows point to SAS in the frontal region.

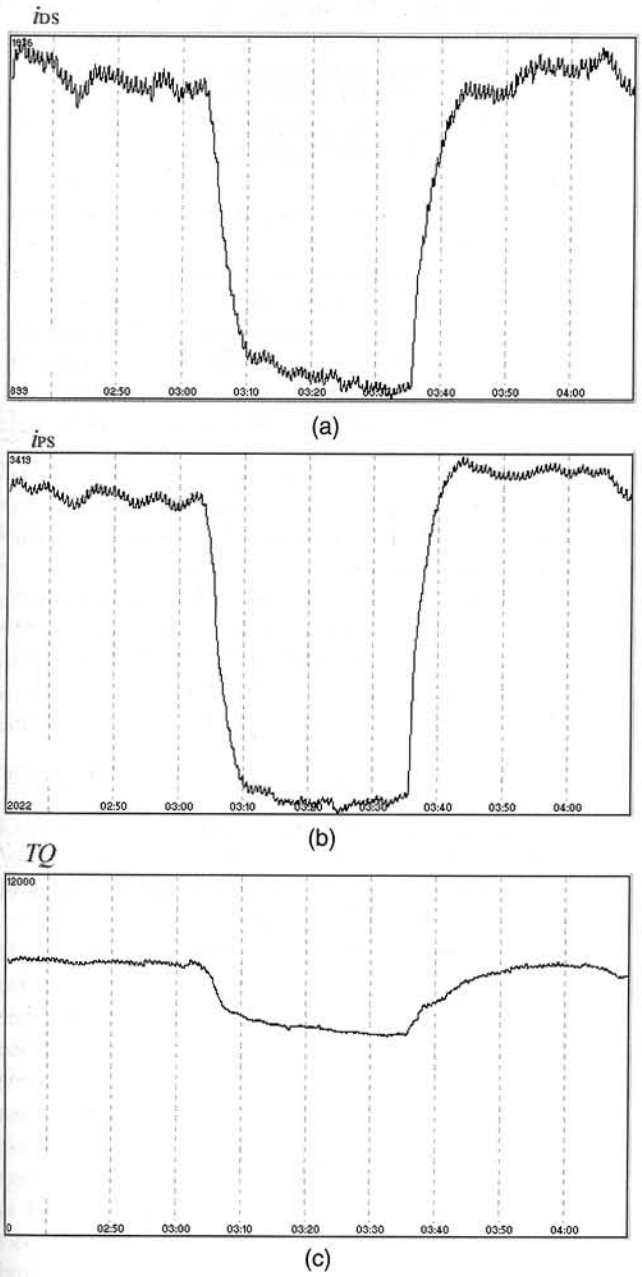

Fig. 4. Signal waveforms from DS (a), PS (b) and their ratio TQ (c) during forward-tilt test as shown in Fig. 3: 1 – reference sit-back position, 2 – forward-tilt, 3 – return to reference position.

producible and repeatable, with uniform direction of changes observed in all 59 examined individuals. In each of them, there was a decrease in TQ observed at forward-tilt with return of the TQ to about pre-tilt level at return to the initial backward-tilt head position. As the absolute value of the TQ depends on the thickness of the skull bone in the examined individual, it was not the difference of the absolute values of TQ during and before forward-tilt that was analysed, but a relative change of TQ expressed by the ratio of during to pre-tilt values. The mean value of svc-TQ decreased during the forward-tilt from 0.2466 to 0.1930 (t-Student test, $p < 10^{-13}$).

7. Conclusions

The above presented description of the new method of near infrared transillumination-back scattering (NIRT-BS) along with the example of influence of the changes in the width of the SAS on the recorded signals and their quotient TQ, provide argument for the feasibility of a non-invasive measurement of changes in the width of the SAS in humans. Assessment of these alterations, which may be a derivative of the changes in the volume of the brain, with a technique utilising NIR, may lead to complete elimination of the need for invasive assessment of changes in the intracranial pressure, as the cerebral volume and intracranial pressure are closely interrelated. For instance, at the earliest stages of cerebral oedema it is not the intracranial pressure but the cerebral volume that changes. Capacity of the NIRT-BS to detect changes in the width of the SAS caused by changes in the volume of the brain may lead to efficient early treatment of the life-threatening condition of cerebral oedema even before any clinical signs or symptoms occur. The simple test of forward-tilt can be easily used for this purpose. The NIRT-BS offers even more than assessment of the average width of the SAS, because evaluation of the parameters of the cardiac component of the TQ – frequency, magnitude, shape, additional modulation – can become a source of valuable information on cerebrovascular physiology and pathology.

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