Contributed paper

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Monitoring of subarachnoid space and cerebrovascular pulsation with near-infrared transillumination/back scattering – new aspects of the method

A.F. FRYDRYCHOWSKI[1], M. ROJEWSKI[2], and W. GUMIŃSKI[2]

[1]Department of Physiology, Medical University Gdańsk, 80-211 Gdańsk, 1 Dębinki Str., Poland
[2]Department of Information Systems, Faculty of Electronics, Telecommunications and Informatics, Technical University of Gdańsk, 80-952 Gdańsk, 11/12 Narutowicza Str., Poland

Authors present new aspects of recently published non-invasive method of near-infrared transillumination/back scattering (NIR-T/BS) in its application for recording of changes in instantaneous width of the subarachnoid space (SAS), as source of information on the amplitude of cerebrovascular pulsation in subsequent phases of the cardiac cycle. For confirmation of the credibility of the recording as carrying information on the changes within the SAS, recordings were also performed after non-invasive elimination of skin circulation in the sensor area with skin compression. It was proved that the pulsation recorded with this technique is really of intracranial origin, regardless of the blood flow in the skin of the frontal region.

Keywords: transillumination, subarachnoid space, cardiac cycle.

1. Introduction

The technique of near-infrared transillumination/back scattering sounding (NIR-T/BS) is based on the analysis of streams of near-infrared radiation received by the sensors after their reflection from the surface of the brain. Transillumination has been known in medicine for a long time [1–10], as a supplementary qualitative diagnostic method based on live observation of propagation of light in the tissues, mainly in the head. Transillumination of the head was used predominantly in patients with cranio-cerebral disorders or malformations, the most important of them being hydrocephalus. Low transparency for light of the skull bones in adults was the main reason, why the use of head transillumination was largely limited to paediatric patients and decreased with time as new, much more informative and quantitative diagnostic methods were becoming available. For the decades of presence of transillumination in medical diagnostics, it was white light that was used as information carrier. Only much later, in 1975, Hayden *et al.* first constructed transilluminator utilising near-infrared radiation (NIR). Although infrared radiation has made a spectacular success in a totally different diagnostic method – near-infrared spectroscopy, and continues to expand with, e.g., near-infrared tomography, it was not successful as a mere substitute of white light in the technique of transillumination. The primary reason for its defeat was a very strong masking influence on the received NIR stream of circulation of blood in the skin, which accounts for 98% of the received signal – as calculated in our experiments after elimination of skin blood flow. This was why the technique of NIR transillumination in its early form could not succeed and make its way to clinical practice [1,2,6–8,10].

Our new approach to NIR transillumination, with invention and implementation of a few novel combined hardware/algorithm solutions described in earlier reports [11–15], enabled elimination of the influence on the recorded signals exerted by circulation of blood in the skin layer and assessment of changes in the width of the subarachnoid space (SAS) filled with the cerebrospinal fluid (CSF). Naturally "encoded" in these changes is information on several phenomena or physiological variables: slow, non-periodic changes in the volume of the brain parenchyma, and many kinds of phenomena affecting the width of the SAS in a periodic manner, to begin with circadian rhythms, through bowel movements, respiration, and finish with heart-beat. The capacity of the newly designed technique of near-infrared transillumination/back scattering (NIR-T/BS) to picture intracranial event of major importance may open door for its application in daily clinical practice.

In our previous papers, we have proved the feasibility of non-invasive monitoring of changes in the width of the subarachnoid space and magnitude of cerebrovascular pulsation, in studies on mathematical-statistical and mechanical-optical models [11,12] and in experimental studies in healthy volunteers [13–15].

*e-mail: afryd@amedec.amg.gda.pl

With time, as the research and development of the technique continue, it has become necessary to provide description of the dynamics of the intracranial phenomena, occurring during particular phases of the cardiac cycle with explanation of the dependence on them of the observed changes in the transillumination signals, i.e., the transillumination quotient (TQ) and its cardiac component (cc-TQ). It has also become important to provide evidence for credibility of the NIR-T/BS recording as capable of reflecting changes in the SAS. As the main variable dominating the NIR recording at usual conditions is the pulsatile flow of blood in the skin, the very fact of obtaining a pulsatile signal from the distal sensor at conditions of skin circulation eliminated should constitute a sufficient proof of efficiency of the applied algorithm.

2. Methods

The NIR-T/BS sensor module consists of a set of light-emitting diodes (LEDs) which constitute the source of impulses of NIR, and two sensors – photodiodes located in one line with the source and each other, but at different distances from the emitter. In close proximity of the source (10 mm distance), there is the proximal sensor (PS), and a little further away (25 mm distance), there is the distal sensor (DS). Such distances for adults have been set on the basis of the results of mathematical-statistical and mechanical-optical modelling [11,12]. The image of the inner surface of the sensor module is shown in Fig. 1. The complete two-sensor NIR-T/BS module contains two identical symmetrical sets of NIR-generating diodes and photo-sensors, one per each brain hemisphere, left and right, embedded in the flexible sensor module strip as indicated in Fig. 1. The diodes are embedded in rubber mouldings, whose shape and profile are such that they suit well the shape of the forehead.

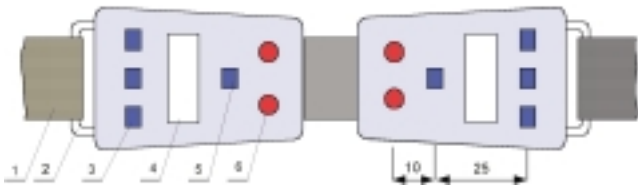

Fig. 1. 1:2 reduced image of the two-sensor NIR-T/BS module for adult patients, inner surface which adheres to patient's forehead. 1 – elastic band, 2 – band fix frame, 3 – three-photo-element distal sensor, 4 – metal strip (earth), 5 – proximal sensor (PS), 6 – two-LED NIR source (emitter, E). In sensor module for young children the distances between the emitter (E) and each of the sensors (PS, DS) are smaller.

The sensor module of such design is placed at the level of frontal tubers. Impulses of NIR are emitted by the source, propagate across amply vascularised layer of the skin of the head, through the skull bone, and further into and through the subarachnoid space. On its way, NIR is partly absorbed and scattered, but also partly reflected on the smooth pia-covered surface of the brain which is densely supplied with blood vessels. Some of the reflected photons reach the photo-sensors PS and DS. Electric signals from the sensors are collected with a data acquisition module and then undergo digital processing. The principle and mathematical description of the TQ-based measurement of transillumination signals from DS and PS were provided in other papers by our team [13–16].

On their way through the skin of the head, the NIR impulses undergo relatively strong modulation due to the changes in skin permeability for NIR resulting from the pulsation of skin arteries and arterioles as well as from changes in blood oxygenation. NIR impulses, attenuated and already modulated in the skin, pass on to and through the SAS, which constitutes a natural optical duct. Here the radiation undergoes further modulation, of complex amplitude-frequency character. On the surface of the head we receive electric signals from DS and PS, which first undergo analogue/digital conversion and are then divided (DS/PS). The result of that division is referred to as transillumination quotient (TQ). The TQ bears information on the changes in the width of the SAS, because the process of division of the two individual signals from DS and PS reduces proportional factors and eliminates the influence of the TQ modulation by the skin circulation. Therefore, it becomes possible to extract from TQ the other factors, which modulate the TQ only intracranially, i.e., within the SAS, through their influence on the width of that space. One of the factors affecting the width of the SAS in a nearly-periodic manner is cerebrovascular pulsation, i.e. pulsation of the intracranial arteries and arterioles on the surface of the brain as well as those deeply penetrating its parenchyma and making the whole of the brain bulge rhythmically at the frequency equal to heart rate (HR).

With the use of special algorithms and dedicated software, the TQ is additionally split into the low-frequency component which carries information on slow changes in SAS width, and the fast-variable component or cardiac component, which reflects and describes the HR-frequency cerebrovascular pulsation. Detail description of the method of analysis of transillumination signals from individual sensors (DS, PS) as well as of the TQ were presented in our previous papers [13–16]. To provide better explanation of the technique, below in Fig. 2, we present the schematic paths of propagation for NIR from the source to each of the sensors (proximal and distal), at the peak of cardiac systole and diastole.

On its way through the tissues the NIR is modulated in two different tissue layers: the skin and the SAS. The modulation added in the skull bone should be disregarded, as for a given individual the NIR attenuation coefficient of the bone remains constant within relatively long periods of time. Passing through the skin, the NIR receives pulsatile amplitude modulation, resulting from the periodic action of the heart. The volume of blood in the skin vessels beneath the sensors oscillates synchronously with the systole and diastole of the heart, translating into increased or decreased

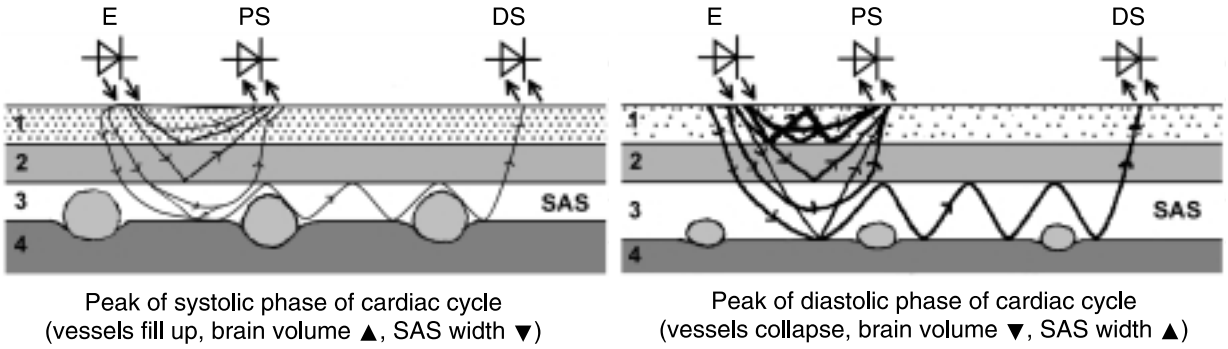

Fig. 2. Simplified scheme explaining the influence of phases of the cardiac cycle on the propagation of NIR in the tissues of the frontal region of the head: 1 – skin, 2 – skull bone, 3 – SAS (the inner surface of skull bones is lined with the dura and the arachnoid, beneath which there are blood vessels and cerebrospinal fluid), 4 – the surface of the brain is covered with the pia, on which there lie cerebral superficial arteries. Thin line with arrowheads points to decreased propagation, while the thick one indicates elevated NIR propagation.

filling with blood of the vessels of the skin. The results of our own investigations provide evidence that blood strongly attenuates the NIR, which means that an increase in the volume of blood in the skin leads to an increase in NIR attenuation and vice versa.

The other site of modulation of the NIR is the SAS. The pulsation of the superficial vessels of the brain as well as the cerebrovascular pulsation of the brain itself, cause periodic changes in the width of the SAS, according to the rhythm of the heartbeat. During the systole all the intracranial arteries, both the superficial, extracerebral and the deep, intracerebral ones fill up with blood. In the specific conditions within the rigid box of the skull, this increase in intracranial blood volume, has to be compensated with a decrease in the volume of the cerebrospinal fluid which is partly displaced to the spinal compartment. Increase in the overall CSF pressure in the cranio-spinal system is prevented by means of marked distension of nerve root pouches and partly also walls of the spinal canal, which give the spinal compartment markedly higher compliance than that of the cranial compartment. This decrease in the CSF volume means a decrease in the width of the translucent CSF layer in the SAS.

2.1. Systolic phase of cardiac cycle (distension of arteries with a bolus of blood)

In the systolic phase of the cardiac cycle, a major volume of blood is pumped into the arterial part of the circulatory system – stroke volume (SV = 75–90 mL). This causes an increase in the arterial pressure up to the maximum or systolic value of ca. 130-mm Hg. The systolic increase in the volume of blood refers also to small-diameter arterial vessels – arterioles, including those which form a dense meshwork in the layer of skin on the head. This is why during systole, the permeability of the skin for the NIR decreases. Simultaneously, the systolic increase in arterial blood volume leads to a decrease in the width of the SAS, as mentioned above. The volume in space occupied by the medium and small size arteries and arterioles on the surface of the brain fill up, which results in compensatory displacement of a certain volume of CSF, i.e. decrease in the width of the SAS – natural optical duct. The amount of radiation reflected from the surface of the brain rises slightly as compared with the diastolic period, but only for emitter-sensor distances up to 15 mm [11,12]. This is due to the shortening of the distance between the reflecting surface – pia covered brain – and the surface of the skin where the sensors are located. With narrowing of the SAS, however, the global amount of photons propagated within this natural translucent optical duct decreases. Therefore, if we used a single-sensor NIR-T/BSS module, just as it was practised before by investigators interested in transillumination [8–10], we would not be able to determine the proportion of the amounts of NIR emitted by the source, reaching the sensor via the propagation paths in the skin and in the SAS. In the area of sensor contact with the skin, great share of the energy reaching the sensor is that carried by photons travelling within the skin – according to our own estimates this share equals to roughly 98%. This means that the signal from PS results from contact with photons propagating predominantly within the skin, where this wave is deeply modulated. Another important issue is a difference in the autoregulation of the skin arteries and of the cerebral superficial arteries. The autoregulation of cerebral arteries is based mainly on the partial pressure of CO_2 and concentration of the H^+ ions, and – what is crucial here – is independent from the autoregulation of the arteries of the skin. These differences in autoregulation mechanisms of skin arteries and intracranial arteries further contribute to distortion of the relationship between the deep modulation in the skin layer affecting mainly the PS signal and the shallow modulation in the SAS, affecting mainly the DS signal.

2.2. Diastolic phase of cardiac cycle (decrease in arterial diameter)

In the diastolic phase, there occurs a decrease in the volume of the blood in the arteries, as the supply of a bolus of blood is over until next systole, and the arterial outflow to

capillary bed continues. In this phase the permeability of the skin for NIR rises. The elasticity of the arterial walls restores the resting diameter of the vessels and intra-arterial pressure decreases, down to the level of ca. 70-mm Hg. At the same time, the space within the cranium earlier occupied by the increased volume of blood in the vessels is immediately taken over by translucent CSF, earlier displaced towards the spinal compartment of the cranio-spinal system. Therefore in the diastolic phase of the cardiac cycle, the average width of the CSF-filled SAS increases. The amount of radiation reaching the sensor after reflection from the surface of the brain decreases slightly, but only at the close sensor position of up to 15 mm from the source. Conversely, the global amount of NIR propagated within the SAS increases because of the increase in the width of this natural optical duct, where photons travel at relatively long distances thanks to multiple reflection against the walls of the SAS. Therefore, if we use a two-sensor NIR-T/BS module, with the second sensor positioned further away from the source, yet at a distance precisely determined on a mathematical-statistical and mechanical-optical models, we are able to collect new kind of information on the amount of radiation propagated within the SAS. This information is extracted from the raw signals from DS and PS through calculation of the transillumination quotient (TQ).

2.3. Resume

The amounts of NIR received by PS and DS are strongly influenced by the flow of blood in the vascular meshwork within the skin. The PS receives photons propagating mainly within the skin layer, and just a small amount of radiation travelling via deeper path, reflected from the brain surface. The DS receives radiation propagated mainly within the translucent CSF layer within the SAS, which on its way through tissues is also modulated by skin flow of blood. The contribution of the longitudinal propagation of NIR within the skin to the global amount of NIR received by the DS is close to zero, which will be proved in point IV.

3. Evidence for recording of changes in the pulsation of the SAS

3.1. Skin compression

Skin compression of sufficient strength causes mechanical occlusion of the blood vessels in the pressed area. In such conditions the NIR from E reaches the PS via the skin, but without being modulated by the vascular pulsation in this layer. Only some minor amount of radiation reaches the PS via the deep intracranial path. In the case of the DS, in turn, distinct pulsation is observed, synchronous with the heartbeat, and originating in the pulsatile changes of the width of the SAS during the cardiac cycle. Therefore, mechanical stimuli, e.g., movements of the head affecting the width of the SAS – can be reflected almost exclusively in the recordings from the DS. The existence of a signal component dependent on cerebrovascular pulsation was to be proved indirectly through presenting the differences in the signals from PS and DS acquired in a volunteer, without and with the application of skin compression. As the procedure of skin compression is fairly painful, the recordings were taken from one of the authors of this study.

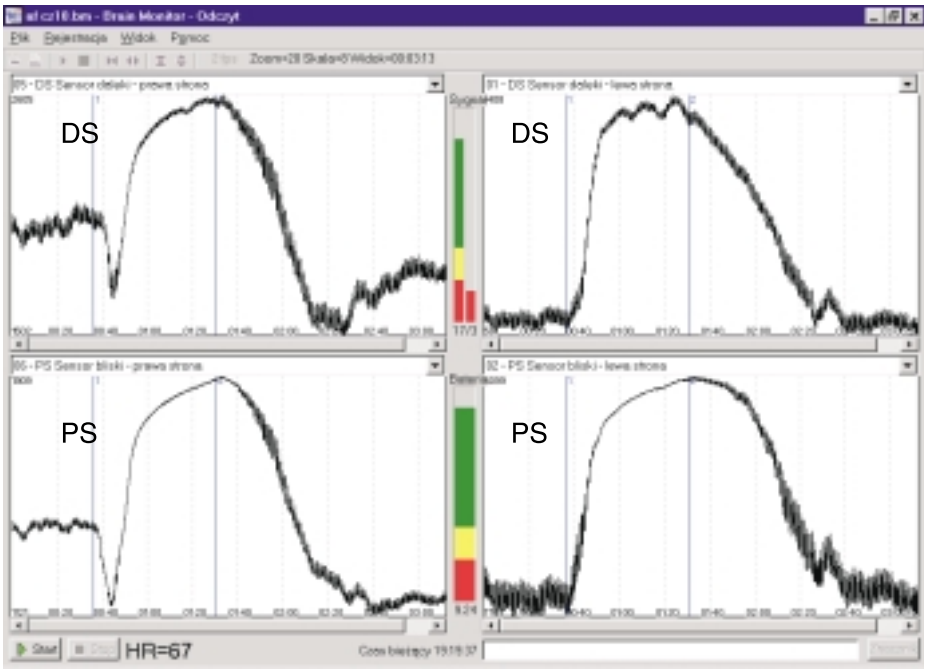

Fig. 3. Waveforms recorded from DS and PS during skin compression. 1 – vertical line indicates the beginning of cuff inflation up to 70 mm Hg, when skin blood flow and the related pulsation cease, 2 – slow deflation of the cuff; in the plots from the right side a notch is seen, with its peak downwards, right after the vertical line No. 1. This notch resulted from displacement of skin at the initial stage of cuff inflation.

For the procedure of skin compression, the source diodes and all the sensors PS and DS in the sensor module, on both left and right side were equipped with a 2-mm rim of hard rubber. The sensor module was mounted on the head of the subject with the elastic band, with the cuff of a blood pressure monitor wrapped around the head and covering the sensors. The cuff was then inflated to the pressure of 70-mm Hg, which resulted in pressing the sensor module and mainly the hard rubber rim into the skin. This firm compression resulted in occlusion of blood flow in the vessels of the skin. The use of a cuff attached to a pressure monitor allowed for standardisation of compression in subsequent experiments. Recording taken during skin compression is shown in Fig. 3.

It is from the beginning of cuff inflation that we observe fast and pronounced decrease in pulsation of the signals from both PS and DS. It is worth noticing that throughout the whole period of skin compression, small--amplitude but regular pulsation of HR frequency is present in the signal from the distal sensor (DS). As this pulsation is present in DS signal only, and the contribution of skin circulation to generation of these waves is eliminated, the implied origin of these oscillations is exclusively the pulsatile changes in the width of the SAS.

As the modulation of the signal from DS is mainly the result of the pulsatile blood flow in the skin and of the more shallow modulation coming from the cerebrovascular pulsation, separation of these two influences under normal conditions is almost impossible, because it would be difficult from the technical point of view to perform long--duration recordings with skin compression. It was only the application of the procedure of division of the DS and PS signals, calculation of the TQ and extraction of the components of the TQ that enabled to eliminate the strong influence of the skin blood flow on the received signals. Therefore, application of the TQ allows for "soft" elimination of the influence of skin circulation, which in our experiments was eliminated mechanically with hard skin compression, and for extraction from the TQ of a pulsatile component of heart rate frequency, called cardiac component-TQ, cc-TQ.

The best evidence for the efficiency of the proposed method is a simultaneous recording of the DS and PS and cc-TQ at the beginning and after skin compression. This situation is presented in Fig. 4.

A magnified part of Fig. 4 is shown in Fig. 5. This recording provides firm evidence for the efficiency of the elimination of the influence of skin circulation on the signals, as well as for the insensitivity of the TQ, and particu-

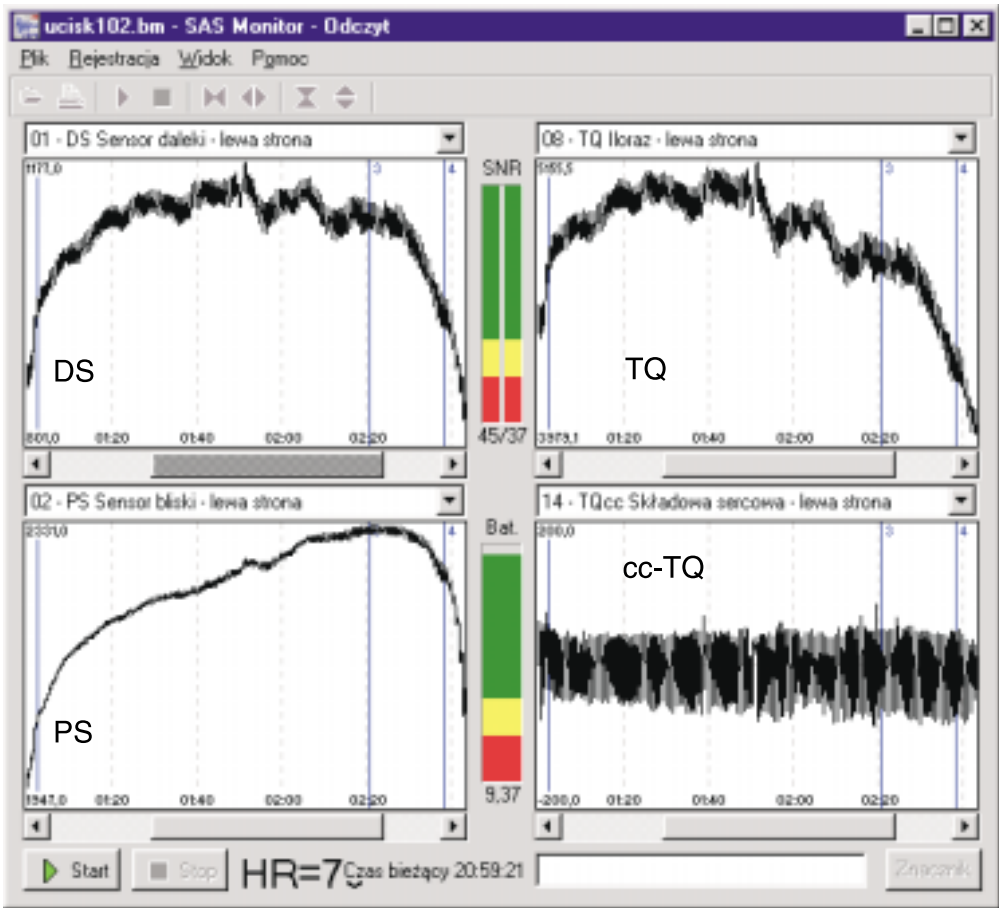

Fig. 4. Plots of signals from PS and DS as well as TQ and its cardiac component (cc-TQ), recorded during increasing skin compression around the sensor module and during the following release of the cuff. The inscriptions in Polish come as direct "screen messages" of the dedicated data acquisition and processing software.

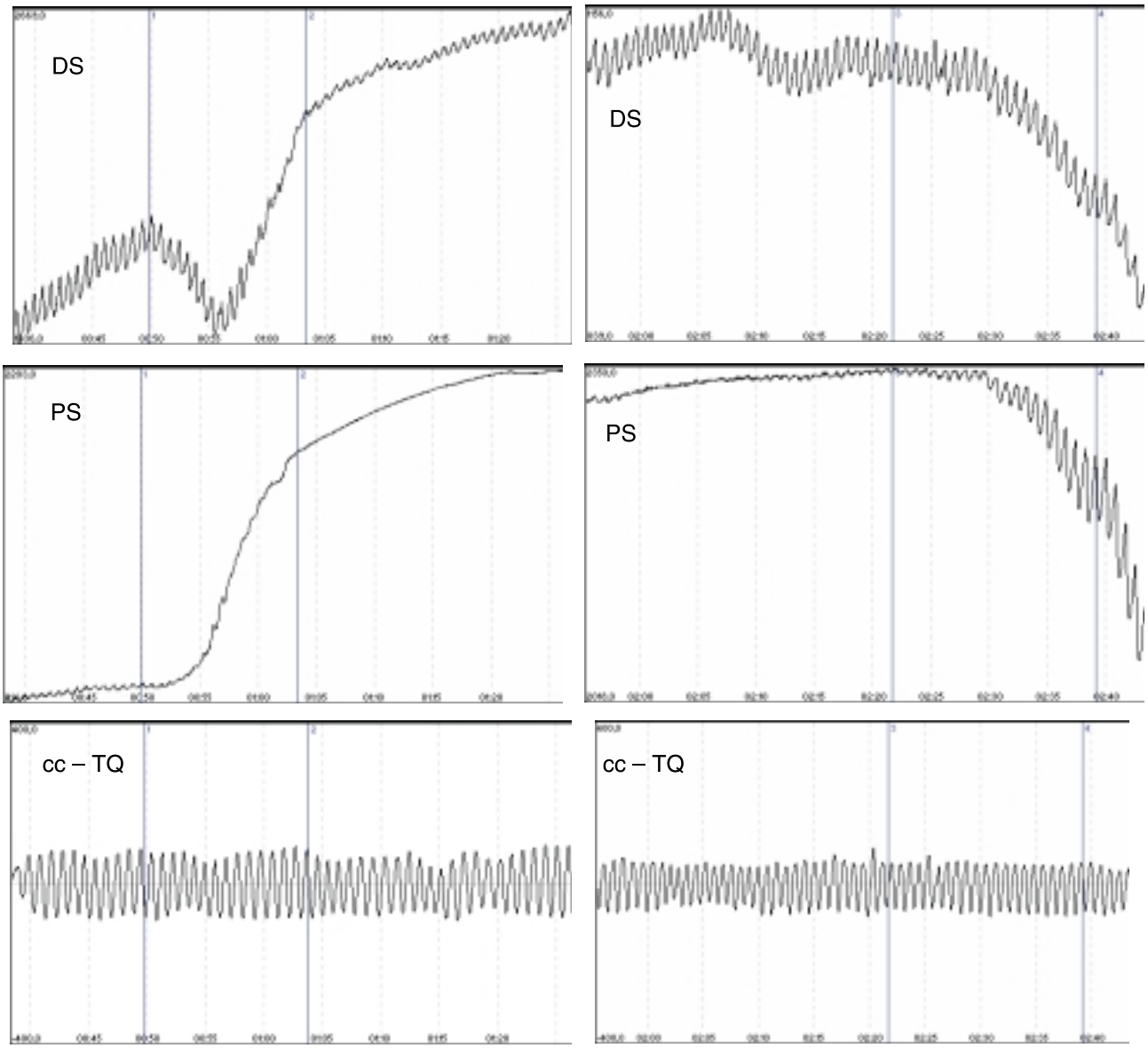

Fig. 5. Plots of signals recorded from PS and DS, and the plot of the cardiac component extracted from the TQ, obtained in the experiment with skin compression around the NIR-T/BSS sensor module area. On the left – plots from the early phase of skin compression, on the right – late phase of skin compression and cuff release. The scaling of the ordinates at the plots of DS signals on the left and right are different because of the automatic amplification system included in the hardware/software solution, whose target is to maintain the plot in the middle of the display window and to allow gross evaluation of the dynamics of the changes. Vertical lines: 1 – beginning of cuff inflation, 2 – cuff pressure 80 mm Hg, 3 – beginning of cuff deflation, 4 – cuff pressure 0 mm Hg.

larly cc-TQ, to the changes of signals at the individual sensors.

The cc-TQ, and particularly its magnitude, remains almost unchanged throughout the period of skin compression, regardless of the restoration of PS signal pulsation and change in the magnitude of DS signal pulsation. This is congruent from the physiological point of view, because what changed in the experiment was not cerebrovascular pulsation, but the flow of blood in the skin. As shown in the recordings, neither impediment of skin circulation nor its total elimination with severe compression did not affect the cc-TQ, which we believe to reflect the changes in frequency and magnitude of cerebrovascular pulsation.

4. Experimental evidence for lack of longitudinal propagation of NIR to DS, at E-DS distances greater than 15 mm (paediatric sensor module)

In paediatric version of the NIR-T/BS sensor module the distances between the NIR source and sensors have to be shorter, as indicated by the results of numeric modelling of propagation of NIR in the tissues of the human head [11,12]. The E-DS distance is then equal to 15 mm, while the E-PS distance equals to 3 mm only. On the ground of the above explanations, it is expected and implied logically

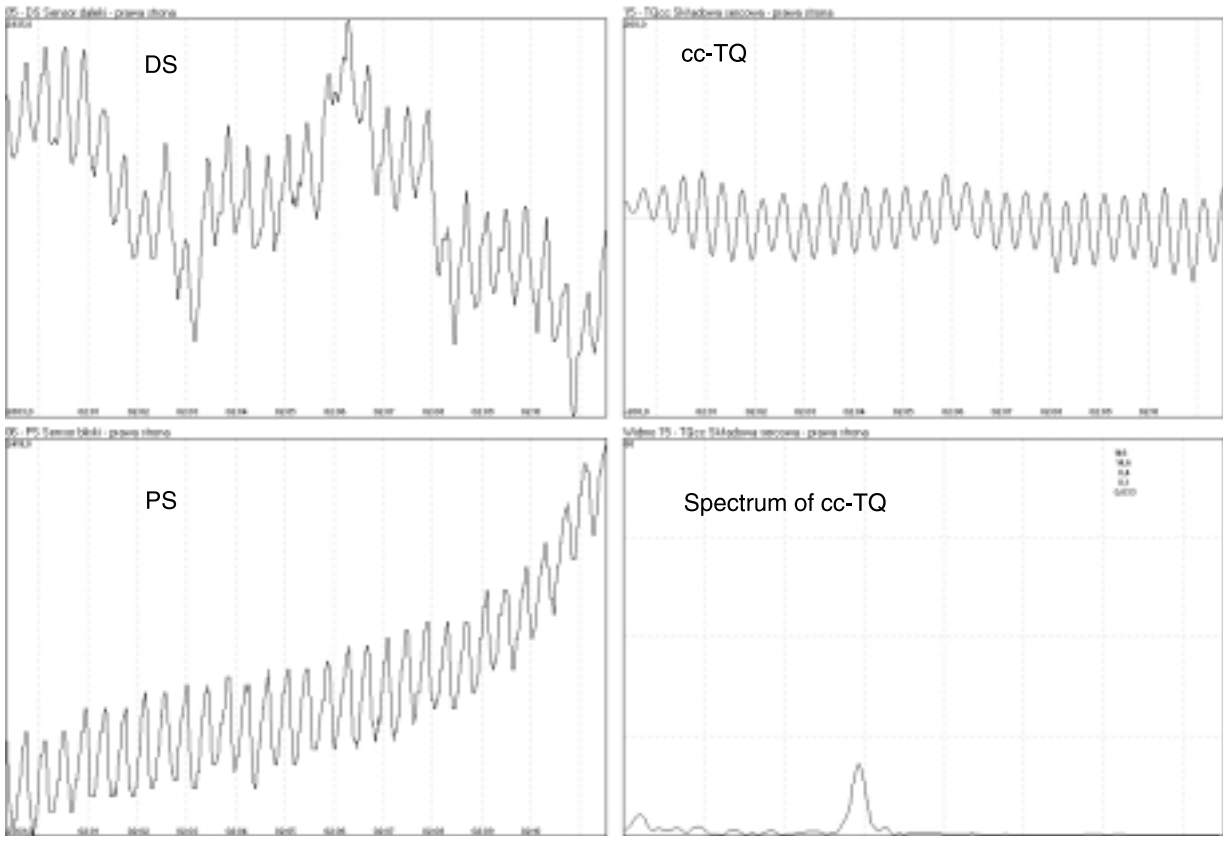

Fig. 6(a). Plots of signals from DS and PS, cc-TQ and cc-TQ frequency spectrum obtained in an infant (patient T.A.; age 5 days). Heart rate 146 bpm.

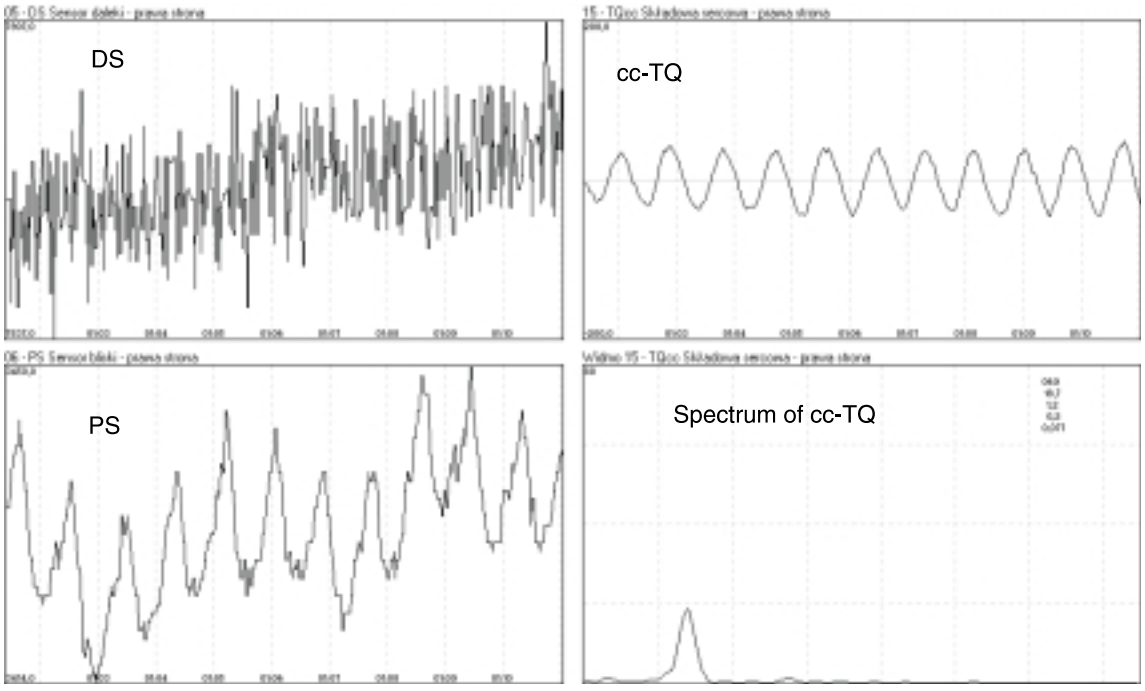

Fig. 6(b). Plots of signals from DS and PS, cc-TQ and cc-TQ frequency spectrum obtained in an adult volunteer (patient A.F.; age 53 years); Heart rate 69 bpm.

that substantially different recordings should be obtained with such a small-size sensor when used in both child and adult. In the child, whose skull bones are much thinner – approx. 1 mm, and the width of the SAS is very small, signals should be available from both PS and DS. An attempt to record NIR-T/BS signals with such small-size sensor in an adult should result in signal available from PS only, while – with the assumption on negligible longitudinal propagation of NIR within the skin of the head confirmed in numeric modelling – pulsation should not be present in the signal from DS. This is due to the E-DS distance of 15 mm being too short for the NIR pathlength to cover the deeper tissue layers, including the SAS. Examples of such recordings from a child and adult are given in Figs. 6(a) and 6(b).

In Fig. 6(a), i.e., recording from an infant, we can clearly see pulsation of the signal from DS and smaller--amplitude pulsation of the signal from PS. The latter results from low thickness of skin in infants. A recording from an adult, done with the same paediatric sensor module reveals pulsation of the PS signal, as well as pulsation of the DS signal, masked with noise. If there were longitudinal transmission of radiation from E to DS, we should observe distinct pulsation of the signal from that sensor. The above-presented plots show the quantisation noise, which is very well eliminated with the division algorithm – a result that shows a distinct tracing of the cardiac component.

The reversal of the phase in the cc-TQ, as compared with PS signal, indicates the origin of the pulsation from PS, i.e., denominator in the DS/PS ratio. Also seen clearly is different location of the cardiac harmonic in the frequency spectrum, which results from different heart rates.

5. Discussion

It is not the first example of the utilisation of near-infrared radiation as information carrier. The near-infrared segment of the frequency spectrum of electromagnetic waves is also referred to as "biological window" because of the easiness of their penetration through tissues in humans and animals. Therefore, NIR is used in various biomedical measurement techniques. The best known of them is oximetry or near--infrared spectroscopy [18]. For a few years NIR has also been used in the method of transillumination which is hoped to become an important diagnostic and evaluation tool.

The proposed description of the phenomena beneath the sensors during the systolic and diastolic phases of the cardiac cycle seems to well explain the origin of the recorded signals. Additional comment is required, however, to recordings made during skin compression. During the cuff inflation, with increasing pressure exerted on the skin of the forehead, there occurs displacement of blood from beneath the sensor module, see Figs. 4 and 5. This results in an increase of permeability for NIR of the skin beneath the sensor module, because whole blood possesses very strong attenuation properties towards NIR. This is reflected in our recordings with elevation of the plots of signals from PS and DS, as well as of that of TQ. This drift does not affect the cc-TQ, whose magnitude remains unchanged regardless of the skin compression and therefore also skin circulation. Such behaviour of cc-TQ was achieved thanks to the algorithm which leads to elimination of proportional factors, which in the particular case of the technique mean blood flow in the skin. The algorithm consists in division of the DS signal over that from PS [14–16].

The efficiency of that elimination had to be proved experimentally. The procedure of skin compression, described in this paper, provided direct evidence for this. Additional argument for the correctness of our theoretical assumptions and results of numeric modelling of the propagation of NIR in the tissues is contained within the results of the recordings performed with a paediatric version of the sensor module characterised with smaller distances between the source and each of the sensors, in both 5-day infant and an adult volunteer. These recordings confirmed very low contribution of the longitudinal propagation of NIR within the skin of an adult to sensor locations more remote from the source than 15 mm. Therefore a question arises about the origin of pulsation in the signal from PS. The surface of the skin in an adult is 4-5 mm away from the surface of the skull bone, while in an infant this is only 1 mm. The theoretical model-based analysis of the behaviour of NIR for different source sensor distances, as well as for different sensor-skull bone distances, indicates that the radiation reaching PS may come from the reflection from the surface of the skull bone.

Such explanation gives a good ground for further development of the construction of the sensor module and further elucidating intimate details of the new technique of near-infrared transillumination/back scattering sounding in different physiological and clinical conditions.

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Forthcoming conferences

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7–9 October
Macromolecules in the 21st Century
Vienna, Austria
Contact: Helga Roder
E-mail: dr.roder.keg@vip.at
Web: www.macrovienna.org

7–10 October
ISCS 2002: 29th International Symposium on Compound Semiconductors
Lausanne, Switzerland
Contact: Marc llegems
Tel: +41 21 693 54 15
Fax: +41 21 693 54 10
E-mail: iscs2002@dpmail.epfl.ch
Web:iscs2002.epfl.ch/iscs 2002.htm

10–13 October
10th Foresight Conference on Molecular Nanotechnology
Bethesda, MD, USA
Contact: The Foresight Institute
Tel:+1 6509171122
Fax:+1 6509171123
E-mail: foresight@foresight.org
Web: www.foresight.org

14–18 October
Photonics Asia
Shanghai, China
Tel:+1 3606763290
Fax:+1 3606471445
E-mail: spie@spie.org
Web: www.spie.org

20–25 October
22nd Meeting of the Electrochemical Society
Salt Lake City, UT, USA
Contact: The Electrochemical Society
Tel: +1 609 737 1902
Fax:+1 609 737 2743
E-mail: ecs@electrochem.org
Web: www.electrochem.org

21–23 October
GaAs 1C Symposium
Monterrey, CA, USA

24–25 October
2nd Annual Photonic Nanostructures: Advancing Materials to Control Light
San Diego, CA, USA
Contact: Alan Abend
Tel:+1 6172327400
Fax:+1617 232 9171
E-mail: aabend@knowledgefoundation.com
Web: www.knowledgefoundation.com

30–1 November
ODF 2002: 3rd International Conference on Optics-Photonics Design & Fabrication
Tokyo, Japan
Contact: Hirofumi Tsuchida
Fax: +81 426 91 7573
Tel: +81 426 91 8089
Fax: +81 426 91 7573
E-mail: h tsuchida@ot.olympus.co.jp
Web: www.opticsdesign.gr.jp/english.html

31–1 November
Defence Nanotechnology
London, UK
Contact: Alexander Giles
Tel: +44 (0)20 8297 8005
Fax: +44(0)7092162703
E-mail: dem@dem-ltd.demon.co.uk
Web: www.nano.org.uk

11–13 November
Compound Semiconductor Manufacturing Expo (CS-MAX)
San Jose, CA, USA
Web: www.cs-max.com

2–6 December
MRS Fall Meeting
Boston, MA, USA
Abstract deadline: 15 June
Web: www.mrs.org/meetings

2–6 December
International Electron Devices Meeting
Web: www.his.com/ iedm

