Contributed paper

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Spectral analysis of mechanical and respiratory influences on width of subarachnoid space assessed with non-invasive method of near-infrared transillumination/back scattering sounding

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The authors present observations on influences of head movements and forced respiration on the magnitudes of signals acquired with the new, non-invasive technique of near-infrared transillumination/back scattering sounding NIR-T/BSS which signals depend upon and reflect the instantaneous width of the subarachnoid space and the amplitude of its pulsation of cerebrovascular origin. For elimination of influence of the changing volume of blood in superficial vessels of skin in the frontal region, each experiment was performed twice – without and with simultaneous non-invasive exclusion of blood flow in that region through skin compression.

It was observed that the recorded changes in the NIR-T/BSS signals reflecting those in the instantaneous width of the subarachnoid space and its cerebrovascular pulsation follow the time-pattern of the evoking factor, i.e. either the rhythm of the head movements or of the forced respiration, which can be demonstrated on the basis of spectral analysis of the acquired transillumination signals.

Keywords: subarachnoid space, transillumination, spectral analysis.

1. Introduction

The technique of transillumination has been known for a long time now [1–10]. Initially only white light was used and later also infrared radiation. Due to poor light propagation through the skulls of adult individuals, the use of white light transillumination was limited mostly to paediatric cases [1,3]. Ultimately, interpretation difficulties put an end to the clinical use of the technique in its traditional form. Application of near-infrared radiation (NIR) as information medium in the technique did not prove successful in the past, because of very strong attenuation of propagation of the NIR by the blood in the superficial circulation of the head skin [6,7]. In our team, we have managed to work out a new technical solution allowing to overcome this major obstacle and thus opening opportunities for application of the NIR-T/BSS technique in clinical practice [11,12].

Combined special design of the electronic data acquisition equipment and dedicated algorithms of signal processing have made it possible to extract components of the returning signal which are fully coupled with and dependent upon the long- and short-term changes in the instantaneous width of the subarachnoid space (SAS). An important factor affecting the width of the SAS is continuous cerebrovascular pulsation generated by contractions of the heart and the resulting pulsatile changes in the filling with blood of the intracranial arteries and brain as a whole. There are a variety of factors exerting influence on instantaneous condition of the intracranial vascular bed, among them also positional or gravitational ones. The influence of some of internal or physiological and external factors on quality and quantity of the cerebrovascular pulsation can be assessed with spectral analysis of the NIR-T/BS signals acquired in specially designed experimental procedure. Analysis of the frequency spectrum of quantitatively measured physiological processes affecting the SAS width reveals two general frequency ranges: heart rate (HR) frequency range, and lower frequency range – related closely to periodic physiological phenomena, like respiration, peristaltic movements of the bowels, head movements of a period longer than that of HR, etc. In this study we have focused our attention on mechanical processes, which – as external factors – exert influence on the SAS width and magnitude of cerebrovascular pulsation, and whose influence can be detected and estimated quantitatively using spectral analysis of the transillumination signals defined in part II. In physiological conditions, the feasibility of assessment of influence of external mechanical factors of different frequencies on the SAS width is highly limited. Methods enabling such assessment seem to be experiments with rhyth-

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mic head movements or those with pacemaker-synchronised forced respiration, i.e., such interventions, whose consequences can be observed as appearance of a local peak (maximum) in the transillumination signals spectral analysis chart. Such movements of the head lead to translocations of the brain due to inertia, while the forced respiration results in changes in cerebrovascular pulsation. In both cases changes in the SAS width occur. Dependence of instantaneous width of the SAS on each of the two factors appears to be linear.

2. Method

The changes in instantaneous width of the SAS were monitored with the use of non-invasive technique of near infrared transillumaination – back scattering sounding (NIRT-BSS). The sensor module in this technique consists of an emitting diodes module (emitter of impulses of NIR) and two sensors located in one line with the centre of the emitting module, but in different distances from the emitter. The proximal sensor (PS) is located only 3 mm lateral to the emitter, while the distal sensor (DS) is located in the distance of 15 mm from the emitter. These distances were set on the basis of experience and on the basis of the results of mathematical modelling [14,15]. Impulses of NIR generated by the emitter cross the skin of the head, which is amply supplied with blood, skull bones and the subarachnoid space. On its way through tissues, the radiation is partly absorbed, scattered, but also undergoes partial reflection from the pia-covered and amply vascularised surface of the brain. A certain amount of this reflected NIR reaches the sensors, crossing the above-mentioned tissue layers in the reverse order. Electric signals from the PS and DS sensors, further referred to as transillumination signals, are recorded with a specially designed data acquisition module, and undergo digital processing. The principle of acquisition and processing of the transillumination signals has been described in detail in other works by our team [11–13].

On their way through the skin of the head with its ample mesh of blood vessels, the impulses of NIR are subjected to a rather strong modulation resulting from changes in skin permeability to NIR, which are due to pulsatile alterations in vascular blood volume and to changes in blood oxygenation. The NIR, attenuated and modulated in the skin, travels further into the subarachnoid space, which constitutes a natural “optical duct” for the photons. There, the radiation undergoes further complex amplitude-frequency modulation. Individual signals acquired in the NIR-T/BS technique originate at the PS and DS sensors located at the surface of the skin in the frontal region of the head. After initial analogue-to-digital conversion of the signals, the magnitude of DS signal is divided over that from PS. The result of that division is referred to as transillumination quotient (TQ). The TQ and its fast-variable component, also called the cardiac component (cc-TQ), carry the information on the instantaneous changes in the width of the SAS, because the division of the signals, largely dependent on the same tissue permeability or NIR propagation parameters, results in elimination of the proportional factors, including influence on the signals of the pulsatile blood flow in the skin of HR frequency. Therefore, it has become possible to extract from the TQ the information on the deeper modulation, unique for the signal from DS only, and resulting from instantaneous changes in the width of the deep optical duct – the SAS filled with transparent cerebrospinal fluid (CSF). A detail description of the method of analysis of the transillumination signals has been provided in other papers [11–13].

3. Experiments

Experiments were carried out in 7 healthy volunteers, men of 35 to 45 years of age, in sitting position, with recordings being repeated several times in each of the subjects.

In the experiments, the influence on the width of SAS and magnitude of cerebrovascular pulsation was examined of two mechanical factors: (a) rhythmic movements of the head, and (b) forced respiration. The experimental procedure was the following:

- rhythmic, possibly most sinusoid-like movements of the head, forward and backward (anterior/posterior, A-P) were performed by the examined subjects according to the rhythm provided by a musical metronome, with frequency 28/min (i.e. approximately one third of the HR frequency) and 14/min, i.e., twice slower, yet still above the frequency of normal respiration. The amplitudes of these head movements were ca. 25 and 45 degrees,
- rhythmic, also possibly most sinusoid-like, torques of the head towards left and right (L-R), around the vertical axis of the cervical spine, with the frequency being 28/min and amplitude ca. 25 degrees,
- forced respiration of frequencies 28/min and 14/min, also by the metronome, was performed through a reduction pipe greatly elevating the airflow resistance, and thus increasing the respiratory oscillations of intrathoracic pressure as well as the work of breathing.

To assure complete elimination of influence of the cutaneous circulation on the recorded signals, each experimental procedure was performed twice: the repeated recording was made with skin compression in the frontal region, around the location of the emitter/sensor module. For higher strength of the compression, the rim of the sensor module was equipped with slim, semi-rigid rubber band of 1-mm width, which pressed effectively into the skin and assured total cut-off of blood flow in the area beneath the module. The compression itself was accomplished with the use of a blood pressure monitor, whose cuff was wrapped around the head, extending over the sensor module. The cuff was then inflated to 80 mm Hg pressure, which was sufficient to totally abolish vascular pulsation beneath the proximal sensor. This in turn was a direct proof of efficiency of the applied compression. Presented below, are the recordings made over one haemisphere only, as the recordings from both hemispheres were of the same quality and pattern.

4. Results

The interventions described above have different mechanisms of action on the instantaneous width of the SAS. The head movements affect the position of the brain and condition of the SAS via gravitational mechanism, through the action of inertia. Ability of the brain to move within the skull to a certain degree is not only implied logically, but has also been documented experimentally [16,17]. The mechanism of influence of the rhythmic, forced respiration is more complex. Deep, forced inspiration results in an increase of negative intrathoracic pressure during inspiration. This increases the amount of blood returning to the atria. As a result, there is an increase in the force of contraction of the heart ventricles. Stronger contractions of the left ventricle lead to increase in the systolic peak value of arterial blood pressure amplitude. Higher systolic pressure means stronger force distending the arteries, including those penetrating the brain or lying on its surface. With higher arterial blood pressure the heart rate necessary to maintain the constant cardiac output is lower, so reflex deceleration of the heart is observed. As a result of the increased systolic distension of the vessels, the counter-phased or negative-mirror pulsation of the SAS also increases, contributing to higher variability of the propagation conditions for NIR within the SAS as optical duct. At forced expiration reverse changes occur.

Application of periodic, rhythmic quasi-sinusoidal movements of the head as well as of rhythmic, forced respiration was expected to result in changes to the instantaneous width of the SAS occurring at the frequency of the applied action, which should be revealed with spectral analysis of the acquired signals in the form of a frequency line at that particular value.

Artificial, externally controlled frequency of the head movements or respiration, of value totally different from the two major physiological phenomena: heartbeat and normal respiration was expected to become manifested within spectral analysis with a frequency peak where normally flat frequency-valley exists, i.e., above the respiratory peak and below half the principal frequency formant of the heartbeat.

Prior to each experimental procedure, reference frequency spectrum was recorded in resting conditions, as shown in Fig. 1C. Proof of efficiency of skin compression, which in each case resulted in cessation of pulsation of the signal from PS, is given in Figs. 1A and 1Ac, while the changes in the cardiac component of the simultaneously calculated TQ (cc-TQ) are shown in Fig. 1B.

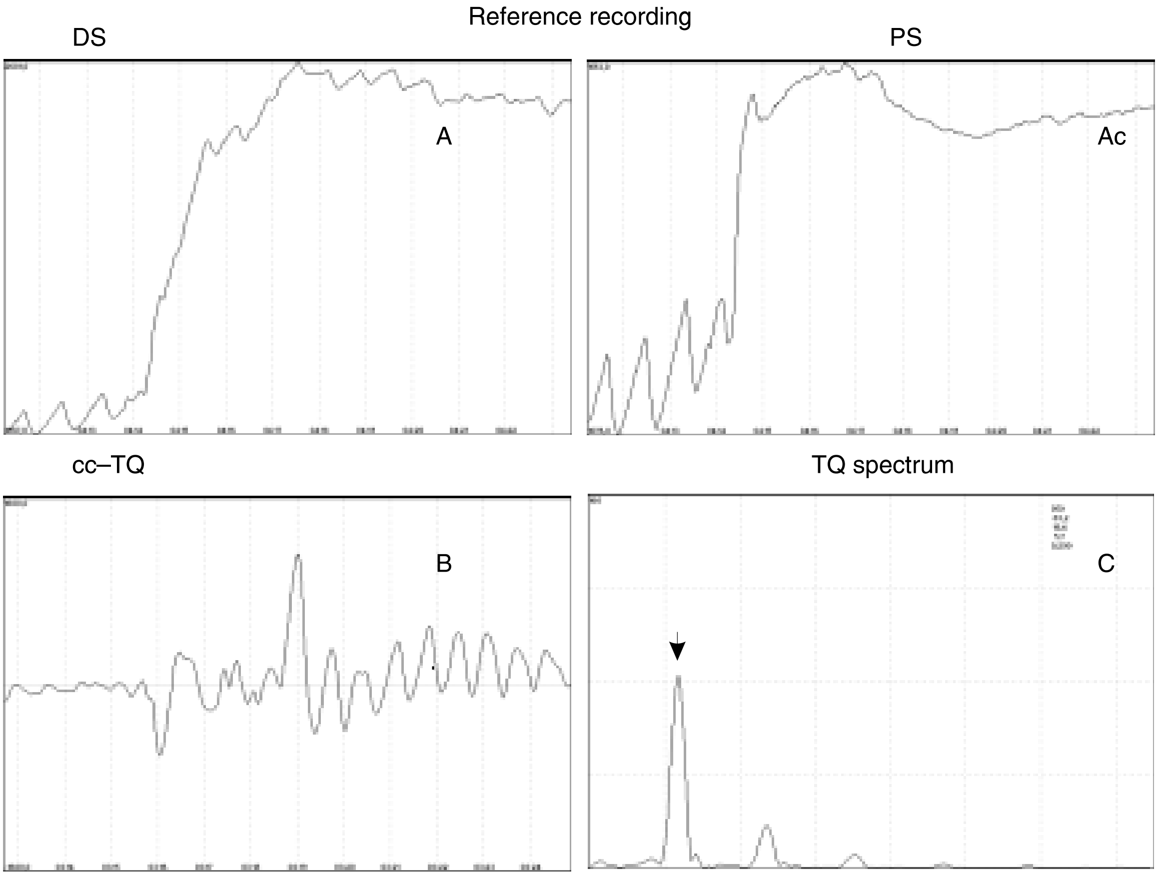

Fig. 1. NIR-T/BSS recordings during skin compression. Transillumination signals: A – from DS, Ac – from PS, B – cardiac component of TQ (cc-TQ), C – frequency spectrum of TQ at resting conditions before skin compression. Arrow points to the harmonic identical with the principal frequency of the cardiac component. Also seen in the spectrum are the higher harmonics of cc-TQ.

Rhythmic A-P movements of the head at the frequency of 28/min and 14/min were expected to affect the width of the SAS at these frequencies, and to cause a new relevant spectrum harmonic to appear in the spectrum. The results are presented in Fig. 2.

Recordings obtained during the experiment have been compared with those collected in the same intervention, but with simultaneous skin compression around the sensory module – see images on the right in Fig. 2.

The magnitudes of the TQ harmonics were found to be different in each of the examined individuals, probably due to slightly different magnitudes of the movements. Therefore, additional experiment was designed with a view to address this difference. The examined subjects were moving their heads in two different movement angle ranges: 30 and 60 degrees. It was expected that the magnitude of the frequency harmonic for the 60-degree movement would be double compared to the 30 degree one.

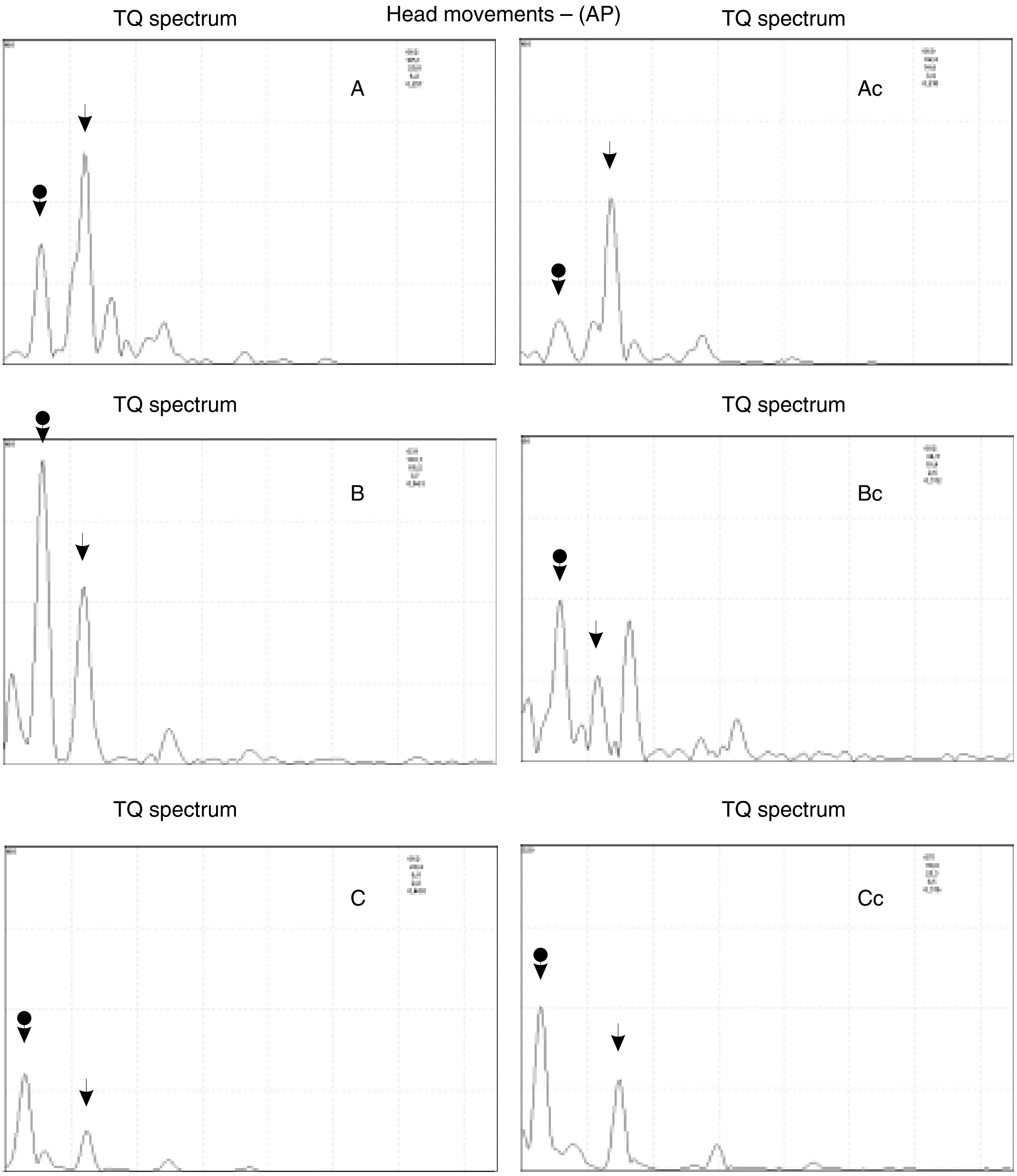

Fig. 2. Spectra of the TQ at rhythmic A-P head movements at the frequency of 28/min (A, Ac, B, Bc) and 14/min (C, Cc). Plots on the left – recorded without skin compression, plots on the right – with simultaneous skin compression (additional letter "c" in plot symbol). A – TQ spectrum at movements: 30 degrees range, 28/min frequency, B – TQ spectrum at movements: 60 degrees range, 28/min frequency; below the marked spectral harmonics, there appears the respiratory peak; C – TQ spectrum at movements: 30 degrees range, 14/min frequency.

Arrow points to principal cardiac harmonic, arrow with a circle indicates the frequency harmonic caused by head movements.

To simplify the analysis of the data and to enhance the readability of the figures in this paper, in each case we present the TQ and its spectral analysis after its constant and sub-respiratory frequency components were removed through filtering. In the spectral analysis, a distinct additive head-movement-related component appears, of the frequency below that of the principal cardiac harmonic. Clearly seen on the TQ spectral plot is a frequency peak at 28/min, i.e., the frequency of the movements. Part B of Fig. 2 shows the expected doubling of the peak at movement range 60 degrees, as compared to that of 30 degrees. The effect was the same with and without skin compression.

As compared with the movements at frequency of 28/min, the movements at frequency 14/min were reflected in the TQ spectrum plots by a shift in the peak towards lower frequencies. In these cases, skin compression resulted in cessation of pulsation of the signal from PS, with well preserved frequency peak of the TQ. This TQ frequency peak also shifted towards lower frequencies, after decreasing the head movement frequency to half the starting value.

If, in the case of A-P head movements, it might be argued that some changes in the transillumination signals may result merely from "blood volume effect", i.e., blood translocation due to changes in head position, it is rather indisputable that during rotatory movements of the head, when the head changes position in the horizontal plane only, the effect of such changes on the volume of blood in blood vessels of the head remains minimum, if any. The results of an experiment with torque movements of the head are shown in Fig. 3.

The obtained results are very similar to those from the experiment with A-P head movements. The frequency peak corresponding to the frequency of L-R head torques is visible equally well before and during skin compression.

The results of yet another experiment show the effect of rhythmic forced respiration, with use of a resistance pipe, on the TQ and its spectral characteristics are presented in Fig. 4.

In spite of a different mechanism of its influence on the width of the SAS, forced respiration through a resistance pipe yielded identical results as the three previous experiments. Decreasing the frequency of respiration from 28/min to 14/min caused a clear shift of the frequency peak towards this new lower frequency. Identical effect was observed for absence of circulation in the skin during skin compression.

5. Discussion

The performed experiments proved the feasibility of recording of changes in the width of the SAS induced by different factors. The influence of A-P head movements is distinctly reflected by changes in both the TQ and its spectral analysis. The frequency peak resulting from the head movements persists and is seen equally well in the spectrum also after elimination of circulation in the region of the sensor module with skin compression. This can be regarded as good evidence for efficiency of elimination of the influence of the skin circulation by the TQ algorithm. Elimination of skin circulation is simultaneously a convincing evidence for the importance for the recording, of the changes in the volume of blood in the skin vessels. This influence was less pronounced during sideway movements of the head. This can be accounted for by the fact that, contrary to the A-P head movements, there was no change in head level, and thus also in the pressure of blood in the vessels of the head.

The differences between magnitudes of the cardiac component cc-TQ before and during elimination of skin circulation with compression can be explained with the differences in amplitudes of the sideway movements of the head. An additional experiment with doubled amplitude of head movements confirmed that the instantaneous width of the SAS really depended on the low angle range movements, too. According to so-far presented findings, and particularly to those just described, the width of the SAS changes, *inter alia* with the movements of the head in both

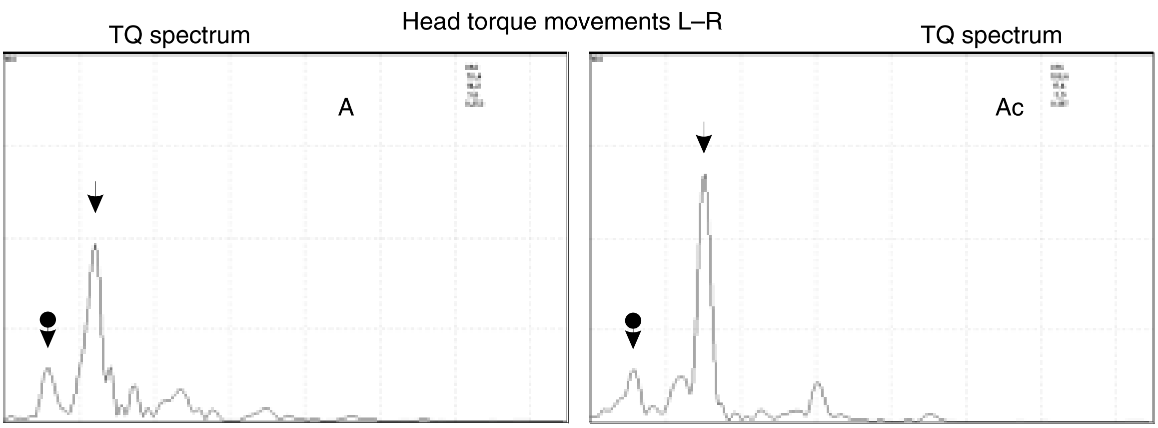

Fig. 3. Spectrum of the TQ at rhythmic torque movements of the head L-R, at frequency of 28/min. A – without skin compression, B – with skin compression, (additional letter "c" in plot symbol). Arrow points to principal cardiac harmonic, arrow with a circle indicates the frequency harmonic caused by head movements.

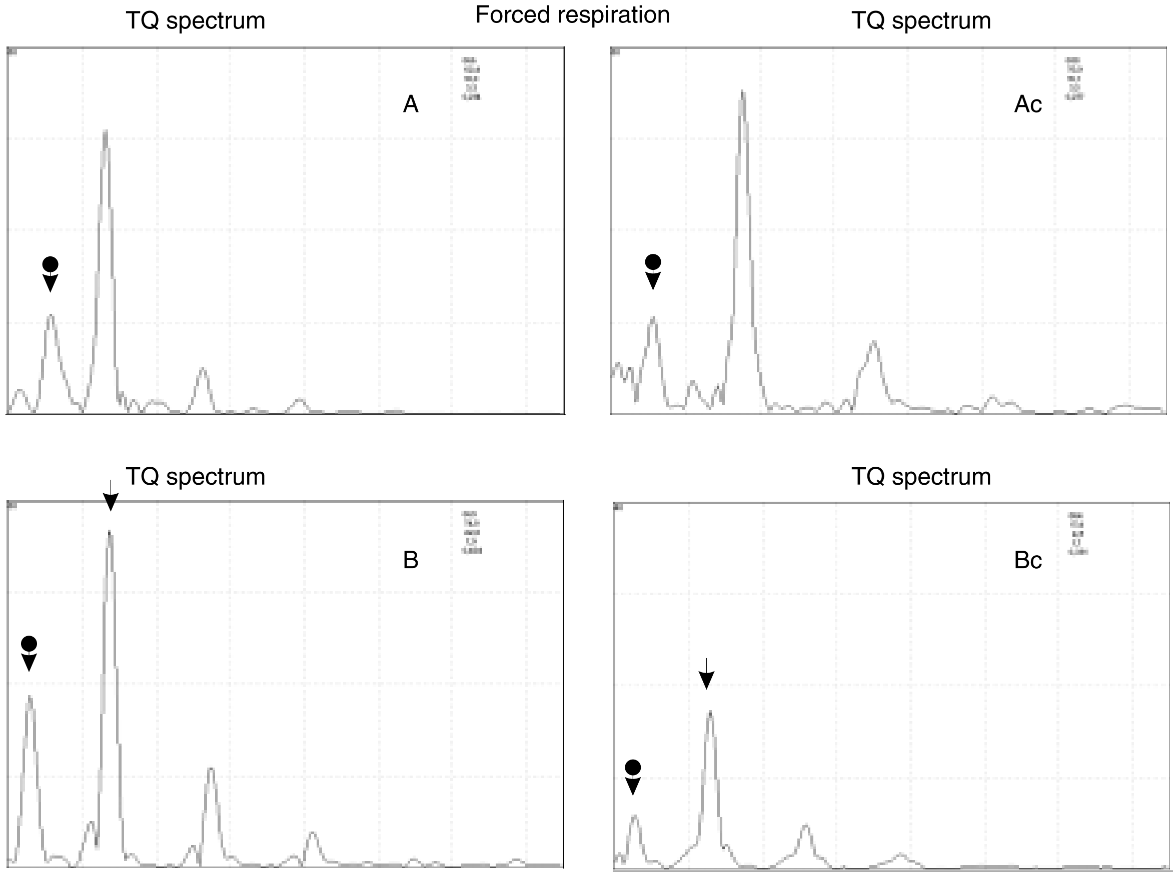

Fig. 4. Spectrum of the TQ during rhythmic forced respiration through resistance pipe at frequencies: A – 28/min and B – 14/min, without skin compression – plots on the left, and with skin compression – plots on the right. Arrow points to principal cardiac harmonic, arrow with a circle indicates the frequency harmonic caused by the forced respiration.

directions: vertical (A-P) and horizontal (L-R), with regard to the CSF-filled SAS layer in the location of the NIR sensor module. To define this conclusion more accurately, we can refer to the concept of frequency characteristics of stationary linear systems.

Let us assume the inducing factor, i.e., the head movements of horizontal or vertical direction, with reference to the SAS layer "gathered" by the NIR-T/BSS sensor module, are sinusoids of frequency f [Hz] and amplitude $A(f) > 0$ large enough to be clearly present in the TQ spectrum, but small enough not to cause the brain to press against the inner surface of the skull bone. Without losing generality, let us assume that the initial phase of the sinusoid is zero, which can be expressed as $X(t,f) = A(f)\cos(2\pi ft)$. The variable t stands for time. The mechanical harmonic waveform can illustrate the deflexion, velocity or instantaneous acceleration of the head, depending on which of them is the easiest to record or interpret. As a result of the response of the SAS to the excitation $X(t,f) = A(f)\cos(2\pi ft)$, in the spectrum of the instantaneous width of the SAS, and therefore also in the spectrum of the TQ(t), there should appear a peak of frequency f, amplitude $B(f)$ and initial phase $\varphi(f)$, which can be described with the following time domain $Y(t,f) = B(f)\cos[2\pi ft + \varphi(f)]$.

The ratio of the amplitude of the response $Y(t,f)$ to that of the excitation $X(t,f)$: $B(f)/A(f)$ and the initial phase $\varphi(f)$, which is the only one in the brackets at $t = 0$, obtained in such an experiment for different values of f, form together the frequency response or amplitude-phase response of the phenomenon. Frequency response is commonly expressed with one formula in the complex polar form $H(f) = (B(f)/A(f))e^{j\varphi(f)}$, where $j = \sqrt{-1}$.

Frequency f should theoretically assume values between 0 and 8 Hz, but for the matter of this paper, the most interesting frequency range is the valley in TQ spectrum between the respiratory and the principal heart-rate frequency peaks. Analysis of the amplitude-phase response, in which the $B(f)/A(f)$ ratio is referred to as magnitude response and $\varphi(f)$ – phase response, is a typical task for the metrology of mechanical oscillations. This analysis should be ideally performed with the object placed on a computer-controlled mechanical shaker. In the case of a human subject, the role of the external shaker can be roughly taken over by the subject's own "muscle drive", if only the subject pays enough attention to make all the head movements in a possibly most similar manner, in the rhythm given by metronome set to frequencies from the frequency spectrum valley.

It is also necessary here to give a comment on the influence on the recorded signal and TQ spectrum of the changes in the volume of blood in the vessels. It appears that, at frequencies close to brain's own resonance frequency, the inertia of the blood pressed along the vessels is much greater than that of the brain. This is confirmed by the spectral analysis of the DS and PS signals, in recordings with skin circulation eliminated. In the spectrogram, the frequency peak is distinct in the case of DS, while in that of PS this influence is almost unnoticeable. This seems obvious, given the fact that the signal from DS is affected by intracranial events, in this case – movements of the brain.

6. Conclusions

Results of the presented experiments provide clear and unequivocal confirmation of the influence of head movements with ensuing changes in position of the brain, and forced respiration with resulting changes in intracranial intravascular blood volume, on the instantaneous width of the SAS.

The additional experiment, in which skin circulation was eliminated with skin compression, proved efficiency of the applied TQ calculation algorithms at eliminating the proportional factors affecting individual DS and PS signals, in this case blood circulation in the skin of the frontal region, where the sensor module is located. The identical frequency spectra including the frequency peak of the inducing factor, both with and without skin circulation, constitute firm evidence for feasibility of non-invasive monitoring of changes in the width of the SAS.

That experiment also provides evidence for negligible influence of the volume of blood in the skin on the TQ and its components.

The results also indicate applicability of spectral analysis of the recorded signals in assessment of changes in intracranial conditions, induced by periodic inducing factors, of mechanical or haemodynamic character: e.g., rhythmic head movements or forced respiration.

Circulation of blood in the skin does not affect the recordings of signals dependent on intracranial events, which allows for the application of the non-invasive method of NIR-T/BSS for assessment of changes in the width of the SAS and cerebrovascular pulsation in further experimental and clinical studies.

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