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Application of Coherence Function for Calculating Time Shifts between Axial Corneal Displacements and Electrical Heart Activity

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The heart activity is one of the most important factors influencing the ocular pulsation. It is known that the high correlation between axial corneal displacements and cardiovascular system activity exists. However, phase relationships between those factors are still unknown. The main goal of the research was to measure noninvasively longitudinal corneal apex displacement (LCAD) of the left eye, applying an ultrasonic sensor. Synchronically, the electrical heart activity (ECG) was recorded in Einthoven's triangle. To find phase dependencies between these signals the coherence function was used. It is observed that coherence value, computed between the first five harmonics of both signals, is different for shifted signals along each other. Therefore, the time delay between the ECG and LCAD signals, for which particular harmonic achieves the maximum of coherence function, was examined. It can be noticed that for increasing number of the signals' harmonic, the time delay between considered signals decreases. This tendency is clear for both of examined subjects. To receive more information about this phenomenon more subjects should be measured and the statistical test should be introduced to calculate the time delay values. The presented noninvasive method might be helpful in the future for measuring the IOP pulse and estimating hemodynamic status of the eye.

K e y w o r d s: longitudinal corneal apex displacement, ECG signal, coherence analysis, time shifts calculation

1. Introduction

With every heartbeat the blood is pumped into the eye globe causing changes of its volume [1] and IOP pressure. Pulsatile IOP variations are linked to radial displacements of the corneal surface [2]. This phenomenon is known as ocular pulse, which

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is influenced by many factors, such as ocular blood flow [3], heart rate [4, 5], IOP propagation [6] or biomechanical properties of cornea.

So far many invasive [5, 7, 8] and noninvasive methods of ocular pulse measurements [1, 2, 9–11] were used. Application of high speed videokeratoscopy [12] showed that slow changes in corneal shape exist and some individual features of signals registered for different subjects can appear.

More accurate results of axial corneal displacements were received using ultrasonic technique [13, 14]. Average amplitude of longitudinal corneal displacements obtained in this way was around 20 μm. Additionally, numerical analysis using coherence function showed a close relationship between longitudinal corneal displacements and heart activity at particular frequency components [12, 14, 15]. Spectral analysis of the ocular pulse was examined by Evans using tonometry method [16]. He noticed that power of analyzed harmonics, related to the heart beat, is lower for glaucoma patients, compared with normal subjects.

Up to now some spectral and coherence analyses concerning the radial corneal displacement and the cardiovascular system activity have been carried out, but without any information about the phase relationships between these signals. The coherence function was used previously to investigate ocular mechanism [17], relationship between the pulse and miniature eye movements [18], accommodation [19] as well as thermoregulation [20]. It was also applied in researches concerning cardiac rhythms [21, 22] and cardiac arrhythmias [23].

Phase investigations are very interesting, because they can help to explain a process of IOP propagation, as well as blood propagation on the way from the heart to the eye globe. The accurate values of phase shifts between the ocular surface normal displacements and the blood pulsation are still unknown. Therefore, it was our inspiration to further studies.

The aim of this work was examination a phase relationship between the noninvasively, synchronically recorded longitudinal corneal apex displacements (LCAD) and the electrical heart activity (ECG) using the coherence function. The obtained information about the eye-heart phase relationships might be useful in the future to diagnose hemodynamic status of the eye globe and can help to predict ocular vascular diseases.

2. Materials and Methods

An ultrasonic distance sensor working at a frequency of 0.8 MHz was applied to measure noninvasively longitudinal corneal apex displacement (LCAD) of the left eye with accuracy below 2 μm. The same method was used in the study of binocular corneal pulsations [14]. Distance between the transducer's head and the corneal surface was around 15 mm. The diameter of the ultrasonic beam focused on the cornea was around 1 mm.

Anterio-posterior head movements can strongly affect measurement of LCAD [24]. To reduce the amplitude of the head movements, a headrest with a belt and a rigid bite bar were applied (Fig. 1). The subjects were breathing naturally during measurements. More technical details of presented setup can be found in previous papers [13, 14].

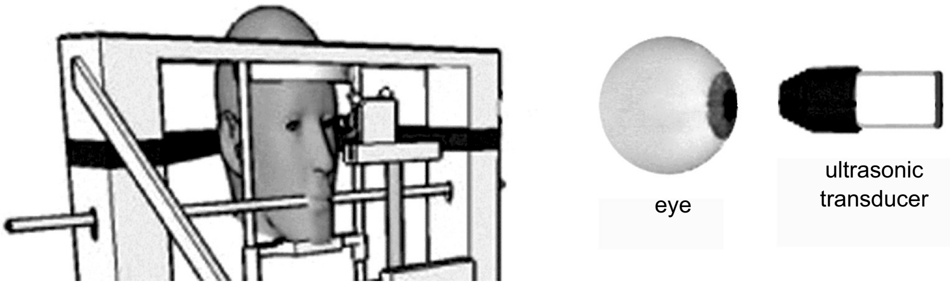

Fig. 1. The scheme of setup for ultrasonic measurement of longitudinal corneal apex displacements (LCAD)

Synchronically, electrocardiogram (ECG) was recorded in a three-lead system (Einthoven's Triangle) [25]. The electrodes were placed on the subject's wrists and left ankle, respectively. All of the recorded signals were sampled at frequency of 100 Hz. During 20 second measurements of LCAD the subject was fixating on a stationary far target and was asked to abstain from blinking. The measurement time for ECG signal was 25 seconds. The experiments conformed to a protocol approved by the Human Research Ethics Committee of the Queensland University of Technology in Brisbane.

For each subject the measurements of LCAD and ECG signals were carried out several times. Then, the obtained data were analyzed using Matlab (MathWorks, Inc. Natic, MA). First step in the signal processing was linear detrend of the considered signals. Then, a band-pass filter (in the range from 0.3 to 20 Hz) was applied to remove frequencies related to the breathing and noise, but not associated with the pulse.

The frequency and time-frequency characteristics of the analyzed signals were calculated using Fourier and Short Time Fourier Transform. Time-frequency representations allowed to observe how the signals' spectra vary in time, which proves their nonstationarity.

In this study the coherence function between axial corneal displacements of the left eye and the ECG was calculated as follows:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}, \tag{1}$$

where P_{xy} defines cross-spectral density of signals x and y, P_{xx} and P_{yy} – auto spectral densities of signals x and y. In the presented measurements signal x describes longitudinal corneal apex displacement (LCAD) and y describes ECG signal. Values of coherence function $C_{xy}(f)$ are bounded between 0 and 1, where value of 1 indicates the phase stability between the same frequency components of the considered signals. When the coherence function is 0 two signals are totally independent. The coherence function value is independent on the amplitude of frequency components contained in considered signals.

Recording of the LCAD and ECG signals was triggered simultaneously. It was checked how the coherence value between these two signals is changing during the ECG shifting along the signal of LCAD in one and opposite direction. The coherence function can have a maximum value for the selected harmonics and for the shifted (no synchronized) LCAD and ECG signals in the range of τ shift from -0.2 to 0.7s. Therefore, the time shift was found individually for the first five harmonics of the heart rate, for which the coherence function computed between both signals is the highest.

Based on the ECG spectrum frequencies associated with the heart rate and its successive harmonics, corresponding to the maximum amplitude, were found. First, the coherence function was calculated between the no shifted LCAD and ECG signals (using formula 1) and the coherence values for the assigned frequencies were marked. Next, the ECG signal was being shifted from $\tau = -0.2$ s to $\tau = 0.7$ s along the LCAD signal with step 0.01 s, as is shown in Fig. 2. For each shift the coherence function was calculated again, the appropriate coherence values were marked and the coherence coefficient was calculated as follows:

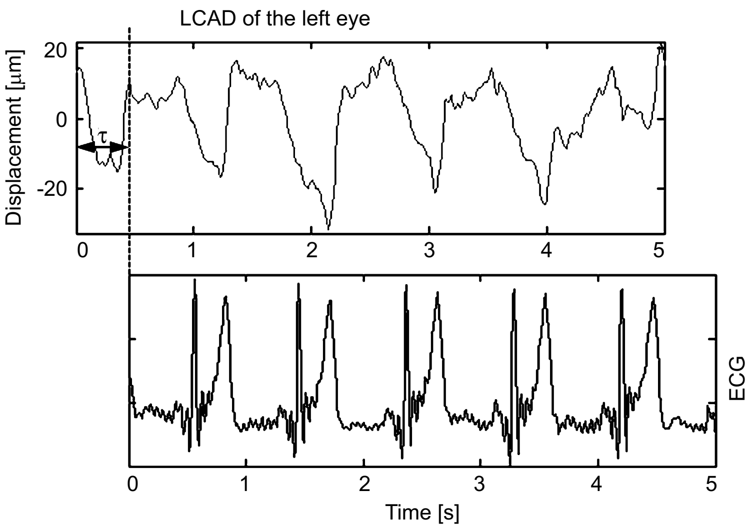

Fig. 2. Example of the ECG shifting procedure along the LCAD signal for fragments of time representations for both signals

$$CW_i = \frac{SC^i}{C^i}\,, \tag{2}$$

where i describes number of harmonics (for i = from 1 to 5), C^i – the coherence value for i-th harmonics of nonshifted signals; SC^i – the coherence value for i-th harmonics of shifted signals. CW coefficient provides information about value of the coherence function for particular harmonics of no shifted signals in relation to the coherence value of shifted signals.

3. Results

Ten subjects, aged from 24 to 60, without any eye and cardiovascular pathology were examined. Exemplary time and spectral representation of the LCAD and ECG signals for Subject I (23 years old male, emmetrope) are presented in Fig. 3.

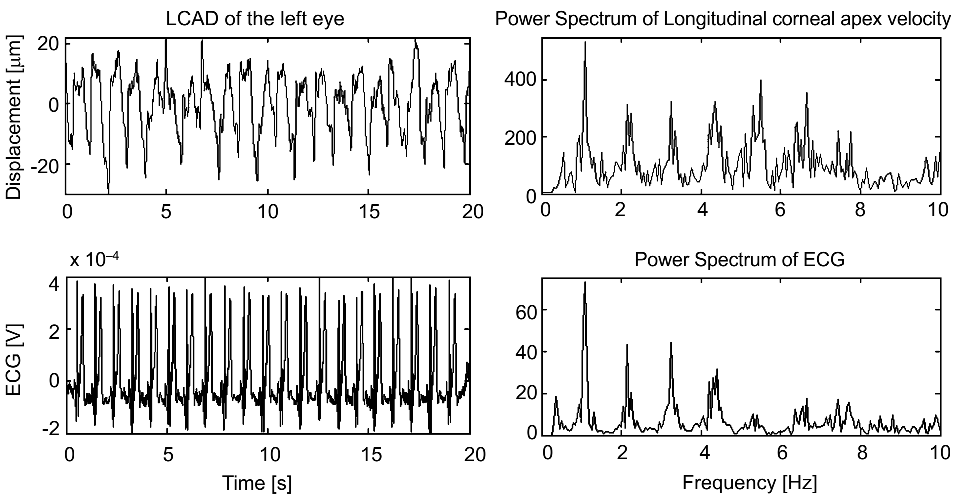

Fig. 3. Time and spectral representations of the synchronically recorded signal: longitudinal corneal apex velocity of the left eye and electrical heart activity (ECG) for Subject I

Based on the time representations of the analyzed signals it is hard to notice any relationships between them. However, their spectra reveal high similarities. Frequency component associated with the heart rate (around 1.2 Hz) and its successive harmonics are clear in both spectra. Because of the fast decline for higher frequencies of the LCAD spectrum the Fourier Transform of this signal was calculated for its derivative. According to the Fourier Transform properties it is known that the spectral composition of the signal and its derivative is the same, but in case of the signal's derivative the higher harmonics are pronounced. Figure 4 shows the coherence function computed between longitudinal corneal apex displacement (LCAD) of the left eye and ECG signal for Subject I. Solid line describes the coherence value for the no shifted analyzed signals, but dotted line – for the signals shifted by τ = 0.3 s. We can see that the coherence value for particular harmonics varies in case when both signals are shifted each other. The dependence between the *CW* coherence coefficient and the ECG shifts for each harmonic for Subject I and Subject II (45 years old male, emmetrope) are presented in Fig. 5.

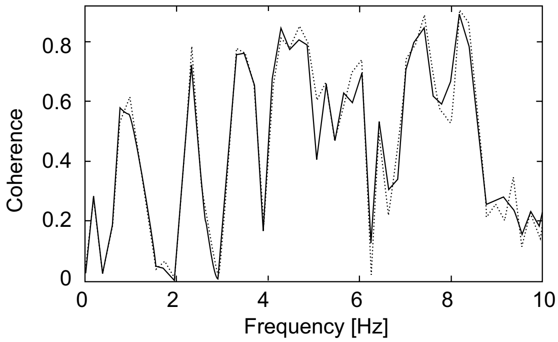

Fig. 4. The coherence function computed between the no shifted (solid line) and shifted (dotted line) LCAD of left eye and the ECG signal for Subject I

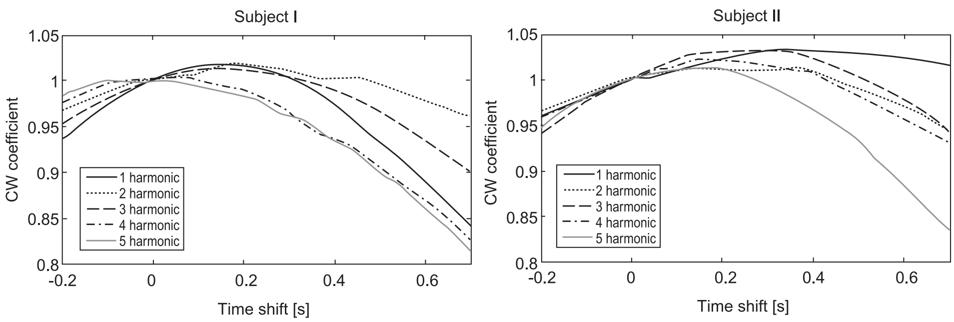

Fig. 5. Dependence of the *CW* coherence coefficient on the ECG shifting along the LCAD signal of the left eye for Subject I and Subject II

The characteristic point, where every curve converges (*CW* coefficient equals 1) is for the no shifted LCAD and ECG signals (time shift equals to 0s). For the ECG shifts to the right (positive values of time shift), the value of the *CW* coefficient is at first increasing to the maximum and then is decreasing. From the results obtained for different harmonics some interesting relationship can be observed. With increasing number of harmonic the time shift between the LCAD and ECG signals, when the coherence is the highest, is decreasing. In Figure 6 the time shift values for the first five harmonics of the LCAD and ECG signals, obtaining for the highest *CW* coherence coefficient, for Subject I and Subject II are shown.

We can notice that the range of the time delay received for Subject I is from 0.01 to 0.23 s and for Subject II – from 0.14 to 0.36 s.

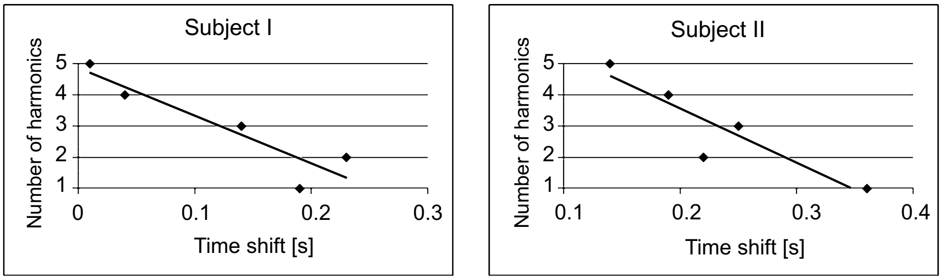

Fig. 6. The time shift values between LCAD of the left eye and the ECG signal for the first five harmonics corresponding to the highest *CW* coherence coefficient value for Subject I and Subject II

4. Discussion and Conclusions

Longitudinal corneal apex displacement (LCAD) and ECG signal are strongly correlated. Therefore, it was interesting to examine using the coherence function how the phase relationship between these two signals changes. The time delays for obtained first five harmonics of two considered signals are different. For increasing number of signal harmonic the time shift between LCAD and ECG signals, for which particular harmonic achieves the maximum of coherence function – decreases. This tendency is noticed for seven of examined subjects, but the range of received time shifts for them differs. This discrepancy could have been related to many factors, such as: the IOP variations, biomechanical properties of the cornea, ocular blood flow, variation of the heart rate, vascular system state, concentration and comfort of the subject during the measurement, as well as subject's age.

After clinical tests carrying out for more subjects and introduction of statistical tests the proposed noninvasive method might be helpful in the future for measuring the IOP pulse and estimating hemodynamic status of the eye. Additionally, the application of other calculation method such as correlation function can be interesting way to assess and compare obtained data.

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