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# Ultrasonic Measurement of Binocular Longitudinal Corneal Apex Movements and Their Correlation to Cardiopulmonary System

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The characteristics of binocular axial eye movements are of interest in studies of eye biomechanics and vision. Current techniques that are used to evaluate such movements were found to be of insufficient resolution. Here, synchronised measurements of binocular eye movements with custom designed high resolution ultrasound transducers, and cardiac electric cycle were considered. The mechanical and electrical signals were examined using spectral, time-frequency, and coherence analyses. The results showed that a close correlation and intricate phase relationships exist between longitudinal eye movements and cardiopulmonary signals. Understanding these relationships could provide a better insight on interactions between eye biomechanics and vision.

K e y w o r d s: longitudinal corneal apex movements, cardiopulmonary system, ultrasonic distance sensor, spectral analysis, coherence function

## 1. Introduction

Human eye is a complex dynamic opto-biomechanical system. In general, one can distinguish movements of the whole eye globe such as saccades, tremor, and drift; or micromovements of particular eye elements such as of the corneal surface, crystalline lens, and choroid. All of these movements have some influence on the visual function [1]. Rotational motions of the human eye in terms of saccades [2], gaze control [3], eye-head coordination [4], and ocular torsion [5] have been intensively studied. However, eye movements along the visual axis have not been fully described yet.

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Axial or longitudinal eye movements can be observed in terms of the corneal apex movements which, in turn, are expected to be influenced by intraocular pressure (IOP) pulsatile changes and periodical deformations of the eye globe. So far, techniques such as fast videokeratoscopy [6] and spectral optical coherence tomography [7] were used to record longitudinal displacement of the corneal apex [8–10]. In both cases, relations to pulse and respiration have been noticed. The results obtained in these studies were promising. Typical axial movements of the corneal apex that were associated with the cardiopulmonary system were about 40 μm to 50 μm [10]. However, the resolution of methods based on optical instrumentation of about 10 μm was found to be insufficient to study intricate dynamic changes in axial movements of the eye.

Encouraged by the results of previous studies, we aimed to develop a non-optical method of longitudinal corneal displacement registration that would be more accurate, more effective, and less cumbersome than its optical predecessors. To achieve this goal, we revisited the concept of measuring ocular pulse using ultrasound transducers that was original proposed by Zuckerman et al. in animal studies [11].

## 2. Materials and Methods

### 2.1. Measurements

Custom designed air-coupled composite ultrasonic distance sensors (developed by MediCom, Wrocław, Poland) were used to measure the longitudinal corneal apex movements. Zuckerman et al. [11] used similar method in 1977 to measure ocular pulse in dogs using hybrid ultrasound transducers [12].

The measurement setup consists of two ultrasonic transducer heads so that corneal apex displacements of both eyes can be registered. Transmitter signal of frequency of about 0.8 MHz is emitted through air to the anterior corneal surface from each of the transducers (see Fig. 1). Measurement of the time elapsing between sending and receiving the signal reflected from cornea allows calculating the distance between transducer and the corneal apex. The piezoelectric ultrasound transducers are of hybrid construction and consist of both transmitting and receiving segments. Unlike in [12], where the hybrid construction was concentric, the transducers we use have semicircular construction. At a working distance between 12 and 20 mm the transmitter produces a collimated ultrasonic beam of about 2 mm in diameter. The system performance was first evaluated on static and dynamic inanimate test surfaces. The accuracy of distance measurement was found to be about 2 μm.

Four subjects were used in the study aged 23 (emmetrope), 25 and 44 (myopes), and 60 (presbyope). Subjects were free of any ocular diseases and had all good general health. Both eyes of the subjects were examined. The subjects were positioned in a solid head rest with a byte bar, as shown in Fig. 2, and in some measurements their heads were additionally strapped to minimise any minute head movements.

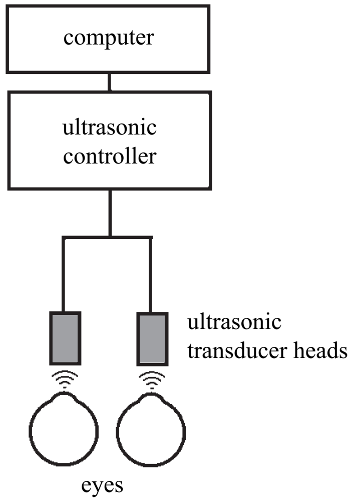


**Fig. 1.** The concept of ultrasonic measurement of binocular longitudinal movements of corneal apex

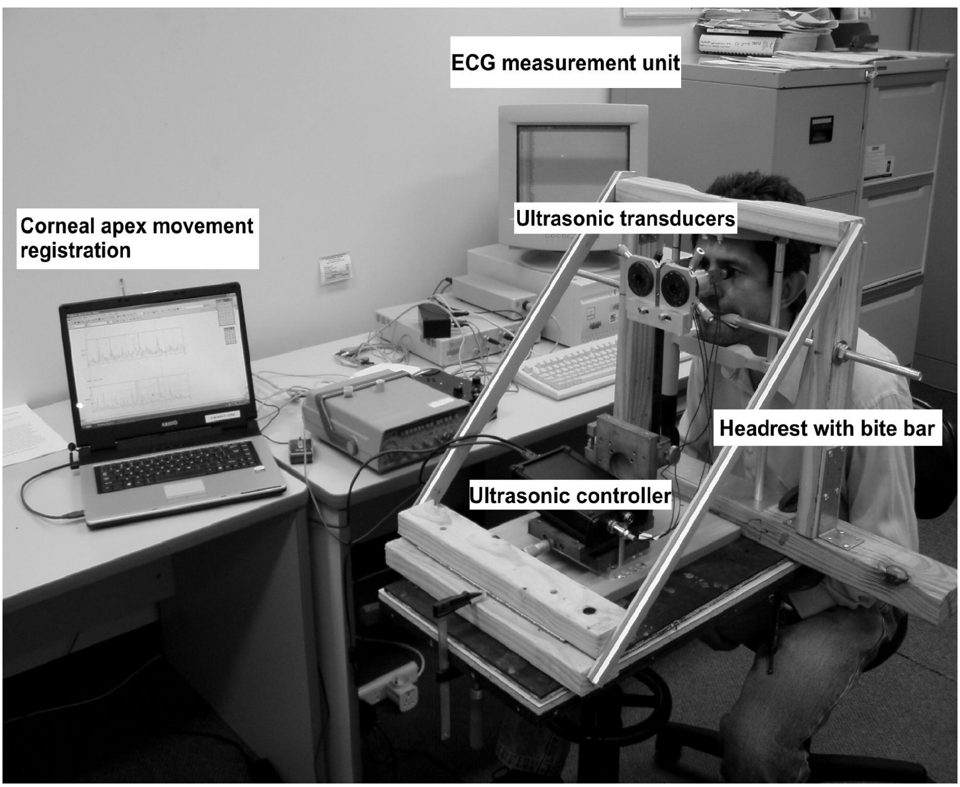


**Fig. 2.** Synchronized measurement of binocular corneal apex displacements and ECG. Subjects head is placed in a heavy headrest with bite bar

The study met the requirements of the Queensland University of Technology human ethics committee.

The longitudinal corneal apex movements were acquired at a rate of 100 Hz. Most measurements were of 20 second period providing 2000 data points available for further numerical analysis. During the measurement the subject was asked to suppress blinking. Simultaneously with measurement of the corneal apex displacement, cardiac electric signal was registered. Electrocardiogram (ECG) was recorded with three bipolar leads, connected to two wrists and the left ankle of a subject in a so-called Eindhoven triangle [13], at sampling frequency of 100 Hz.

### 2.2. Data Analysis

Time, frequency, and time-frequency analysis was performed for each of the acquired signals and their derivatives. Preliminary signals were first linearly detrended and the very low frequency components of the ECG associated with wander noise [14] were removed with a band pass filter with cut-off frequencies of 0.1 Hz and 40 Hz. To obtain the spectral characteristics of the considered signal, a spectral estimator based on the windowed (Bartlett-Priestley) periodogram was used [15]. Additionally, frequency characteristics were normalized so, that the height (pick) of the frequency component signifies average amplitude of displacement or the averaged amplitude of the apex velocity for the particular harmonic.

Spectral analysis alone does not provide full information about the signals whose frequency range varies in time. Because the acquired signals exhibit some nonstationarity, combined time-frequency analysis was used. For this purpose, the algorithm of short-time Fourier transform with a four second length Hamming window was applied. The 2D plot of time-frequency representation shows the variations of frequency components in time.

To evaluate the potential linear association between the measured signals, coherence function $C(f)$ was calculated as follows:

$$C(f) = \frac{|S_{XY}(f)|^2}{|S_X(f)| \cdot |S_Y(f)|} ,$$

where $S_X$ and $S_Y$ are the auto spectral density functions and $S_{XY}$ is the cross spectral density function of two considered signals $X$ and $Y$ [16]. In our application, signals $X$ and $Y$ denote the electrocardiogram signal and the corneal apex velocity signal of particular eye, or the corneal apex velocity signals of the left and the right corneal apex, respectively. Value of coherence function ranges from zero to one and indicates the synergy between the two signals in the frequency domain. The coherence of zero indicates that two given signal components at certain frequency are independent. If the coherence value is one signals are highly correlated (their phases change in time in the same way).

## 3. Results

For each of the subjects that participated in the study several synchronized measurements of the ECG and the corneal apex longitudinal movements were registered. In this paper, representative results obtained for the 23 years old healthy subject are shown and discussed since no substantial differences were found between the four considered subjects. In Figure 3, typical time representations of the synchronically recorded binocular longitudinal displacement of corneal apexes and ECG are shown. To make this graph clearer we have shown here only the first half of the measurement, namely the first 10 seconds. Time representations of the corneal apex displacement signals obtained from two eyes seem to be closely correlated and in phase. Maximum magnitude displacement of the corneal apex amounts to approximately 55 μm. Normalized frequency representations of the signals are presented in Fig. 4, where the average amplitude of longitudinal movement of both the corneal apexes related to respiration (around 0.2 Hz) amounts to 26 μm and 28 μm respectively, while the

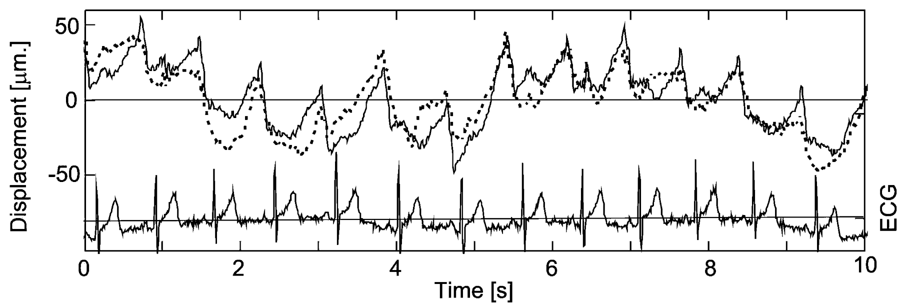


**Fig. 3.** Longitudinal displacements of corneal apexes (top plot) and synchronically registered ECG signal (bottom plot). Continuous line shows displacements of the left corneal apex and the broken line that of the right corneal apex

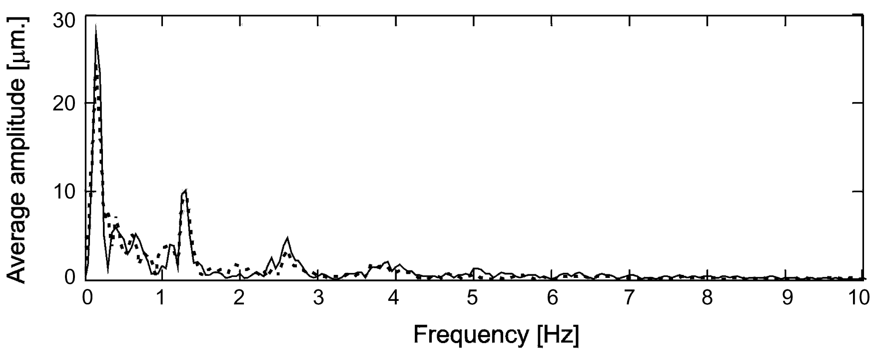


**Fig. 4.** Amplitude spectrum of displacements of the left (—) and the right (--) corneal apexes

averaged amplitude related to the principal heart rate frequency (around 1.25 Hz in this case) amounts to about 10 μm for both eyes. Spectral characteristics of the corneal apex displacements decay quite fast for higher frequencies. Figure 5 shows amplitude spectrum of the derivatives of both longitudinal displacements of the corneal apexes as well as that of the ECG signal. It is known from the Fourier Transform properties that Fourier Transform of derivatives of the function is proportional to the product of the function Fourier Transform and the Fourier Transform argument (frequency). Thus, we can see in Fig. 5 that the spectral composition of the first derivative of displacements (corneal apex velocity) is the same as that of displacements themselves but the higher harmonics are more pronounced. However, also in this case, values of velocity amplitudes for particular harmonic decrease at higher frequencies. The averaged amplitude of both apex velocities for the principal frequency of the heart rate and its first harmonics are very similar and have values in the range between 0.05 and 0.08 mm per second. Spectrum of the ECG signal closely resembles the corneal apex velocity spectra.

An example of time-frequency representations obtained for the left eye's corneal apex velocity and for the corresponding ECG signal, given in Fig. 6, shows that both signals are not stationary. The blood pulse frequency (1.25 Hz approximately) and its harmonics vary in time according to the Heart Rate Variability (HRV). It is interesting to note that the variability of spectral components in time for both signals is very similar. This effect confirms previous results based on videokeratoscopic measurements [9].

Figure 7 shows three estimates of the coherence between: the ECG signal and the corneal apex velocity of the left eye (grey, continuous line), the ECG and the corneal apex velocity of the right eye (black, dotted line) and for the corneal apex velocities of both eyes (black continuous line). There is a very strong linear dependence (coherence approximately between 0.8 and 0.9) between particular signals, even in the high

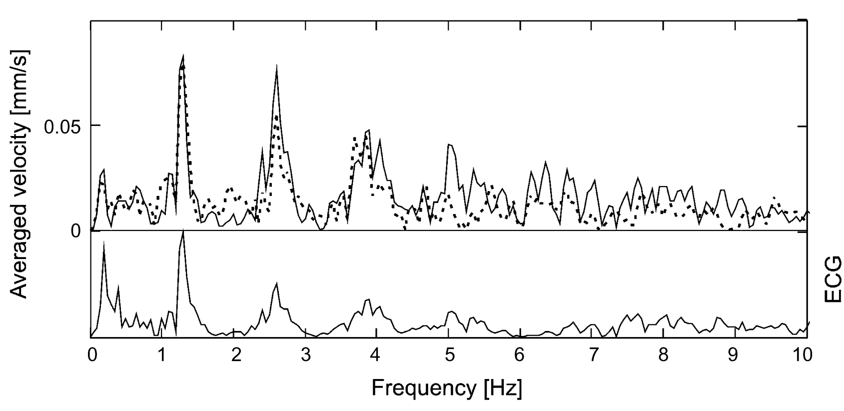


**Fig. 5.** Normalized frequency characteristics of: corneal apexes axial velocity (top plot); ECG signal (bottom plot)

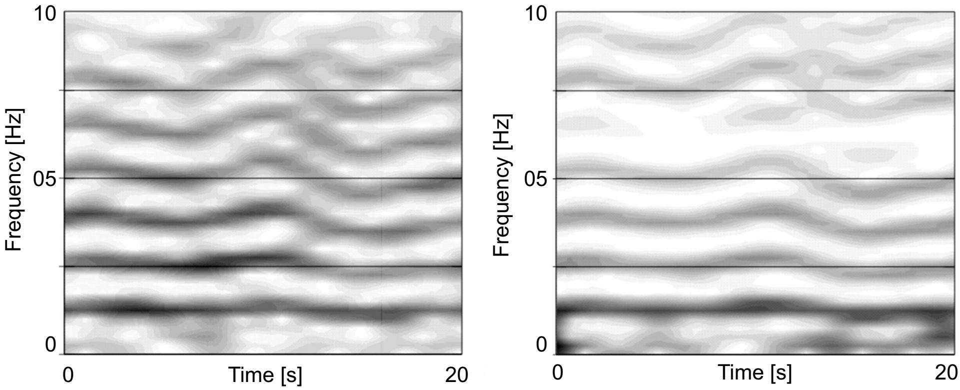


**Fig. 6.** Time-frequency representations of the left corneal apex velocity (left plot) and of the corresponding ECG signal (right plot)

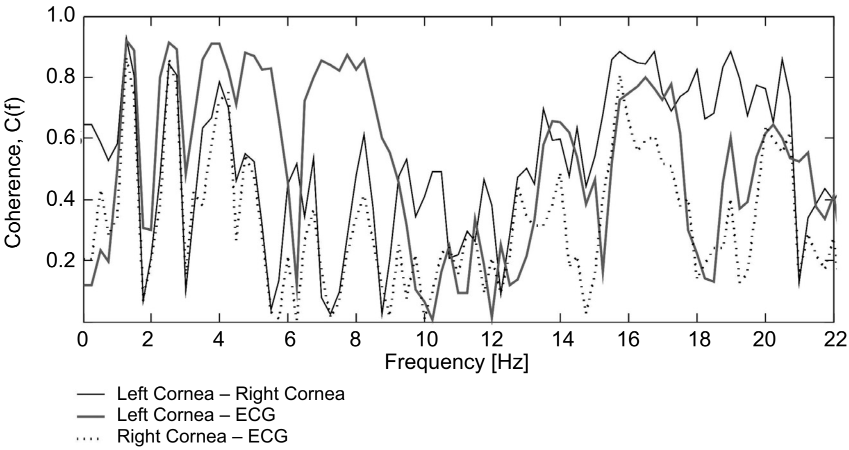


**Fig. 7.** Estimates of coherence function between the considered pairs of signals

frequency range (15 Hz to 21 Hz). This result is very interesting and not completely expected since all three signals have relatively small high frequency content. The coherence analysis clearly shows that the observed frequencies in the corneal apex velocities are very closely linked to the cardiopulmonary system. However, it is also worth to note that for frequencies in the range between 10 Hz 12 Hz all considered signals were found to correlate weakly.

## 4. Discussion and Conclusions

We have measured the longitudinal binocular corneal apex movements using two air-coupled ultrasonic transducers. For the first time the longitudinal movements of both corneas were synchronously registered. In comparison to previously presented methods of measuring of corneal apex longitudinal movements using videokeratoscopy [9, 10], our system is characterised by higher accuracy of distance measurements (2 µm approximately) and higher sampling frequency of acquired signals (100 Hz).

The aim of this work was to establish the relationships between frequency content of electrocardiogram signal and that of corneal apex movements. Presented results proved that the corneal movements of apexes of both eyes are closely related to the cardiopulmonary system. The role of these relationships has not been fully understood yet, but they may lead to better understanding of the eye hemodynamics and provide foundations for new eye diagnostic methods of measuring the ocular pulse.

The results obtained from four considered subjects show some differences in spectral characteristics of the signals. However, all of the frequency spectra showed clear correlation to pulse and respiration frequencies. Characteristic features of signals, such as amplitude and number of spectral components linked to pulse frequency can be an effect of individual biomechanical properties of cornea or intraocular pressure value and its distribution.

Understanding of the dynamics of anterior cornea and spectral contents can be of interests in several applications. For example, Evans et al. [17] used pneumatonometric continuous recording of the IOP and spectral analysis for identifying patients with glaucoma. Factors that seem to have an influence on the longitudinal corneal apex movement and its spectrum, i.e. IOP, eyes hemodynamics and elasticity of the cornea, can be at the same time parameters that we would like to measure, using a non invasive ultrasonic method. We hope that further measurements and analysis, carried out for more differentiated subjects, will lead us to create a non invasive method of IOP and eye vascular status diagnosis.

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