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Quantitative assessment of corneal vibrations during intraocular pressure measurement with the air-puff method in patients with keratoconus

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ABSTRACT

Background: One of the current methods for measuring intraocular pressure is the air-puff method. A tonometer which uses this method is the Corvis device. With the ultra-high-speed (UHS) Scheimpflug camera, it is also possible to observe corneal deformation during measurement. The use of modern image analysis and processing methods allows for analysis of higher harmonics of corneal deflection above 100 Hz.

Method: 493 eyes of healthy subjects and 279 eyes of patients with keratoconus were used in the measurements. For each eye, 140 corneal deformation images were recorded during intraocular pressure measurement. Each image was recorded every 230 μs and had a resolution of 200 × 576 pixels. A new, original algorithm for image analysis and processing has been proposed. It enables to separate the eyeball reaction as well as low-frequency and high-frequency corneal deformations from the eye response to an air puff. Furthermore, a method for classification of healthy subjects and patients with keratoconus based on decision trees has been proposed.

Results: The obtained results confirm the possibility to distinguish between patients with keratoconus and healthy subjects. The features used in this classification are directly related to corneal vibrations. They are only available in the proposed software and provide specificity of 98%, sensitivity-85%, and accuracy-92%. This confirms the usefulness of the proposed method in this type of classification that uses corneal vibrations during intraocular pressure measurement with the Corvis tonometer.

Discussion: With the new proposed algorithm for image analysis and processing allowing for the separation of individual features from a corneal deformation image, it is possible to: automatically measure corneal vibrations in a few characteristic points of the cornea, obtain fully repeatable measurement of vibrations for the same registered sequence of images and measure vibration parameters for large inter-individual variability in patients.

1. Introduction

Keratoconus is one of the diseases of the cornea characterized by changes in its structure [1,2]. These changes usually lead to thinning and excessive bulging of the cornea [3]. As a result, there occurs a change in the corneal curvature [4,5]. The cornea takes a conical shape, which in turn causes visual difficulties [6]. Keratoconus is the most common corneal dystrophy. It has no ethnic restrictions and is not directly related to the degree of progress of civilisation [7,8]. The disease is relatively unknown, has indeterminate etiology and its course is difficult to predict. Due to corneal thinning, it also has an impact on changes in the biomechanical properties of the cornea. It should be visible in a special way in the sequence of corneal deformation images during intraocular pressure measurement using the air-puff method, e.g. when performing measurement with the Corvis tonometer [9–11]. The methods of image analysis and processing enable to determine the position of inner and outer contours of the cornea when measuring its deformation [12]. It is also possible to separate from the eye response to an air puff: the eyeball reaction, low-frequency ($\leq$ 100 Hz) and high-frequency ($>$ 100 Hz) corneal reactions [13–18]. The eyeball reaction is dependent on the response of musculi bulbi oculi [15]. The left eye reacts differently in comparison with

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the right one [16,17]. These reactions are so characteristic that on their basis it is possible to say with almost 100% certainty which eye (left or right) is being examined [18,19]. Extremely low-frequency corneal deformations are primarily three characteristic moments: the time of the first applanation (temporary flattening of the cornea), the maximum corneal deformation, the time of the second applanation [20]. High-frequency corneal reactions (>100 Hz), hereinafter referred to as vibrations, and their relationship with diseases of the cornea are currently being addressed by ophthalmologists [1,2]. The connection between vibrations of the cornea (its parameters) with keratoconus and an attempt to classify healthy subjects and patients are presented below.

2. Material

493 eyes of healthy subjects and 279 eyes of patients with keratoconus were used in the measurements. For each eye, $I=140$ corneal deformation images were recorded during intraocular pressure measurement. Each image was recorded every 230 μs and had a resolution $M\times N=200\times 576$ pixels, which gave the pixel size of 16.5×15.7 μm. Healthy subjects gave informed consent for examinations and in the case of children the consent was obtained from their legal guardians. The examinations of ill patients were from routine medical examinations carried out at the Instituto de Olhos Renato Ambrósio, Rio de Janeiro. All tests were performed in accordance with the Declaration of Helsinki. Healthy subjects and patients ranged in age from 16 to 89 years, 58% of them were women. They had no history of any other type of condition and, above all, any other eye diseases. Diagnosis of keratoconus was made based on placido disk-based axial topography, elevation-derived anterior corneal curvature maps, [21] and according to the criteria used in the collaborative longitudinal evaluation of Keratoconus study [22]. Keratoconus cases with a history of corneal surgery or with extensive corneal scarring were excluded from the study.

3. Method

The method of image analysis and processing proposed in this paper is fully automatic and provides reproducible and quantitative results. The proposed method has been divided into 3 phases:

- image pre-processing and detection of the outer corneal contour,
- detection of corneal vibrations,
- selection of features necessary to classify patients.

Image pre-processing involved image acquisition from the Corvis tonometer, filtration, detection of the outer corneal edge and then separation of individual components: constant component, eyeball reaction and corneal deformation. In the second phase, corneal vibrations in a few specific areas in the two axes of the coordinate system (rows and columns of the image matrix) are analysed. In the final stage, characteristic features of keratoconus are selected and a classifier in the form of discriminant analysis and decision trees is proposed. The illustrative diagram of measurement and analysis is shown in Fig. 1. The phases of the proposed image analysis and processing method and the selection of features and classification are described in detail in the following sub-sections.

3.1. Image pre-processing

The algorithm proposed in this paper is designed for analysis of a sequence of images from the Corvis ST tonometer (OCULUS Optikgeräte GmbH, Germany). The sequence of images may be read from the following files: *.u12, *.avi or *.jpg. In each case, it will be a sequence of i images $L_{GRAY}(m,n)$ for $i\in(1,I)$. The first stage of analysis involves median filtering with a mask h sized $M_h\times N_h=200\times 576$ pixels. The image $L_M(m,n)$ resulting from median filtering is normalised to the image $L_W(m,n)$. Then, this image ($L_W(m,n)$) is analysed in terms of the position of maximum values for each of the columns, i.e.:

$$L_K(n)=\min_{m} L_T(m,n) \tag{1}$$

where:

$$L_T(m,n)=\begin{cases} n & \text{if} \quad (L_W(m+1,n)-L_W(m,n))>p_r \\ N & \text{other} \end{cases} \tag{2}$$

and

$$L_W(m,n)=\frac{L_M(m,n)-\min_{m,n} L_M(m,n)}{\max_{m,n}\left(L_M(m,n)-\min_{m,n} L_M(m,n)\right)} \tag{3}$$

for $m\in(1,M-1)$.

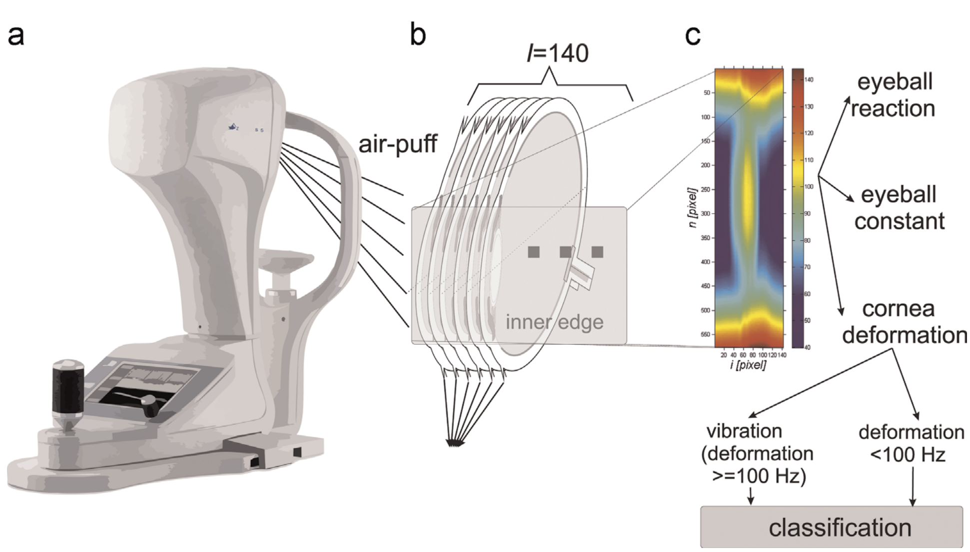

Fig. 1. Block diagram of measurement: (a) the Corvis ST tonometer; (b) a sequence of images of corneal deformation in response to an air puff; (c) the result of automatic detection of the outer corneal contour for the sequence of 140 images, and the division of the eye response into: eyeball reaction, eyeball constant and corneal deformation.