A Concept for the analysis of repeatability and precision of corneal shape measurements

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Abstract

We propose a framework for the analysis of the repeatability and precision of corneal elevation and the repeatability of corneal thickness data measured by clinically used topographers and tomographers. The repeatability is given by the standard deviation of different measurements of the same eye for each data point. The differences between measurements can partially be explained by different positions of the eye at each measurement. The precision is given by the standard deviation of the data after correction for displacements (decentration, tilts, rotations). The applicability is demonstrated using measurements of the Pentacam HR [1] (Oculus Optikgeräte GmbH, Wetzlar, Germany) Scheimpflug tomographer. It provides anterior corneal elevation data with a precision that was almost limited by the axial resolution of 1 μm in the central 6 mm zone. This is approximately five times better than the precision of the posterior elevation. The results can be applied to surface

Konzept zur Bestimmung der Wiederholbarkeit und statistischen Messunsicherheit der Hornhautform-Messung

Zusammenfassung

Wir stellen ein Konzept für die Bestimmung von Wiederholbarkeit und statistischer Messunsicherheit der kornealen Höhenmessung und Wiederholbarkeit der kornealen Dickenmessung von klinisch genutzten Topo- und Tomographiegeräten vor. Die Wiederholbarkeit ist durch die Standardabweichung unterschiedlicher Messungen am gleichen Auge für die jeweiligen Messpunkte charakterisiert. Die Unterschiede zwischen den Messungen können teilweise auf eine unterschiedliche Position des Auges zu den Messzeitpunkten zurückgeführt werden. Die statistische Messunsicherheit ist durch die Standardabweichung der Daten nach Korrektur der unterschiedlichen

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approximation of the exported corneal elevation data and give a measure for the goodness of the fit.

Keywords: Corneal topography, pachymetry, repeatability, precision, Pentacam HR

Positionierungen in sechs Dimensionen (Dezentrierung, Verkippungen und Rotationen) gegeben. Die Anwendung wird an Hand von Messungen der Pentacam HR [1] (Oculus Optikgeräte GmbH, Wetzlar, Deutschland) demonstriert. Sie liefert Höhendaten der vorderen Hornhautoberfläche mit einer statistischen Messunsicherheit in den zentralen 6 mm, die beinahe durch die axiale Auflösung von 1 µm limitiert ist. Dies ist etwa fünf mal besser als die statistische Messunsicherheit für die hintere Hornhautoberfläche. Die Ergebnisse können für die Oberflächenapproximation der kornealen Höhendaten genutzt werden und dienen als Maß für die Qualität derselben.

Schlüsselwörter: Hornhaut-Topographie, Pachymetrie, Wiederholbarkeit, Präzision, Pentacam HR

1 Introduction

The cornea contributes approximately $\frac{2}{3}$ to the total refractive power of the normal eye [2]. On average, its anterior surface has a central refractive power of ≈48 D while the posterior corneal surface reduces the total refractive power of the cornea by approximately 6 D. A precise representation of both surfaces is essential for optical modeling and the calculation of (customized) intraocular lenses [3–5].

Several techniques are used in clinical topographers to determine the corneal shape. While the shape of the anterior cornea can be assessed with Placido disk imaging, optical coherence tomography of the anterior segment and slit-lamp Scheimpflug imaging are capable of measuring the posterior shape as well. The Pentacam® HR [1] (Oculus Optikgeräte GmbH, Wetzlar, Germany) uses slit-lamp Scheimpflug imaging to create elevation maps for the anterior and posterior cornea. While rotating around the eye, a camera captures a series of slit-images from various angles. It can either capture 25 images in 1 s or 50 images in 2 s. The image-contrast results from volume scattering of the probe light in the cornea and the anterior chamber. The surfaces are segmented by edge detection using the difference on the grey-scale values of each picture [6].

The optical quality of the eye can be studied with the help of ray-tracing [5,7,8], if an accurate description of the refractive surfaces of the particular eye is available. The thickness of the cornea (pachymetry) is given by the perpendicular distance between these surfaces. Reliable knowledge of corneal thickness is especially important for refractive surgery planning and keratoconus diagnosis [9,10].

The surface descriptions are often obtained by approximating the elevation data with higher order polynomial representations such as Zernike or Taylor polynomials [11–13]. The validity of these approaches can only be verified if the uncertainty of the underlying data is estimated. For eyes after corneal surgery or eyes with corneal pathology such as keratoconus the Zernike method fails to represent all relevant information that influence visual performance [14]. In such cases basis splines (BSplines) or non-uniform rational basis splines (NURBS) [15] could be proper tools for surface modeling [16,3,7,17]. They can be used to interpolate or approximate corneal elevation. A good approximation has an approximation error that is of the order of the precision of the underlying data.

The repeatability of the evaluation of the resulting surface with Zernike polynomials was studied by de Jong et al. [18]. In comparison with three other topographers the Pentacam HR is found to provide the best repeatability for the anterior corneal shape. In patients with keratoconus the repeatability of the Zernike fit using the Pentacam (a different model of the tomographer with lower resolution), is found to be worse than in normal population, but the relative magnitude of the repeatability to the wavefront aberrations is comparable [19]. MacAlinden and coworkers [20] studied the repeatability of several measurements of the Pentacam HR including the front and back surface elevation and the pachymetry maps of the cornea. They provided the repeatability at three different points (2 mm, 3 mm, and 4 mm inferior to the apex) based on a study on 100 eyes. They concluded that the 50 images mode provides no significant advantage over the 25 images mode. Their results show that the precision of the anterior corneal surface elevation is better than for the posterior corneal surface, and better in the center than in the periphery. Unfortunately, they were not able to export the corneal elevation maps.

In this paper the measurement of the precision of the complete corneal elevation maps (distance of the corneal surface to the reference plane) is demonstrated using data from the Pentacam HR. A straight forward procedure for the calculation of the precision is introduced (Section 2). The repeatability of anterior and posterior corneal elevation as well as corneal thickness, and the precision of the corneal elevation for both