JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 30 (2014) 91–102

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Research Paper

Numerical study on human cornea and modified multiparametric correction equation for Goldmann applanation tonometer☆

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ARTICLE INFO

Article history:
Received 8 June 2013
Accepted 2 October 2013
Available online 25 October 2013

Keywords:
Cornea
Intraocular pressure
Tonometry
Glaucoma
Numerical modeling

ABSTRACT

Glaucoma, a chronic eye disease, is quoted to be a second leading cause of blindness with 66.8 million people suspected to be victimised by the same in year 2000 (Morrison, 2003), and is caused due to an elevated intraocular pressure (IOP). Goldmann Applanation tonometer (GAT), a gold standard (Organization, 2001), suffers from inefficacies to measure intra-ocular pressure (IOP) independent of the biomechanical properties of an eye. Thus, the purpose of this paper is to study the importance of wide range of corneal parameters and to propose a multiparametric correction equation for GAT based on a numerically simulated comprehensive finite element model (Dohadwala et al., 1998; Morrison, 2003; Organization, 2001). Towards this end, with the help of numerical model, the parameters considered in correction equation proposed elsewhere (Elsheikh et al., 2011) were extended to include combined influence of central corneal thickness (CCT), central anterior curvature (R), peripheral corneal thickness (PCT), corneal asphericity (Pa), age, measured IOP itself and, was separately studied for role played by corneal support orientation (θ°) in this aspect. Findings indicate that for a wide range of parameters considered, while increased age is related with gain in corneal stiffness, the maximum (average) individual effects of variations in PCT, Pa, CCT, age and θ° on IOPG were estimated at 0.25 mmHg/100 μ of PCT, 0.073 mmHg/0.1 of Pa, 1.9 mmHg/100 μ of CCT, 24.3%/decade relative of IOPT and 0.95 mmHg/5° increase in θ°. The multiparametric correction equation has been modified accordingly. The GAT correction equation can consider the combined effect of PCT, Pa, CCT, and age on IOPG. Separately the non-linear effect of θ° on IOPG cannot be ignored for reasons of precision.

1. Introduction

Glaucoma, a chronic eye disease, is caused due to an elevated intraocular pressure (IOP) of an eye and is quoted to be a second leading cause of blindness with 66.8 million people suspected to be victimised by the same in year 2000 (Morrison, 2003). Studies on glaucoma pair the level of increase in intraocular pressure with the optic nerve damage. A tonometer is a device used to

☆Financial disclosure(s): The author(s) have no proprietary or commercial interest in any materials discussed in this article.

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http://dx.doi.org/10.1016/j.jmbbm.2013.10.002

gauge the intraocular pressure of an eye. Although a number of tonometers have come into existence due to the seriousness of this disease, but Goldmann Applanation tonometer (GAT) is still considered a gold or reference standard (Dohadwala et al., 1998; Organization, 2001) despite the inventor's acknowledgment of sources of inaccuracy (Goldmann and Schmidt, 2000). Since then, various parameters have been investigated for having effect on GAT and resulted in the suggestions of correction nomograms for use in clinical practice. Considering criticality of parameters on GAT readings of IOP (i.e., IOPG), a large literature has focused the studies towards variation in CCT, age, and R, while the relevance of parameters, such as PCT, corneal asphericity and θ°, towards effecting IOPG have been largely ignored. According to (Cho and Sin Wan, 2000) the cornea is thinner at the center and increases its thickness towards periphery (i.e., cornea–sclera junction) and this variation in the human eye can be as high as 120 μm. The CCT for normal specimen is found to be 0.534 mm (Doughty and Zaman, 2000) and the thickness of the periphery (PCT) has been found to be 0.670 mm (Anderson, 2005). In addition to this, variation is found in such thickness between left and right eye. Ultrasonic techniques have been used (Reinstein et al., 1994) to obtain a central corneal thickness of 514.6 μm for the right eye and 516.2 μm for the left one. Concerned with CCT as major source of inaccuracy in IOPG (Goldmann and Schmidt, 1957; Goldmann and Schmidt, 1961; Kamiya, 1973), Ehlers et al. (1975) was first to study the effect of CCT variation on IOPG, after which several other studies (Bhan et al., 2002; Foster et al., 1998; Foster et al., 2003; Gunvant et al., 2004; Ko et al., 2005; Kotecha et al., 2005; Schneider and Grehn, 2006; Shah et al., 1999; Shimmyo et al., 2003; Stodtmeister, 1998; Tonnu et al., 2005; Whitacre et al., 1993; Wolfs et al., 1997) quantified their findings and confirmed the influence of the same on IOPG although to a lower slope of association i.e. widely ranging between 0.7 and 4.5 mm Hg as compared to that measured by Ehlers et al. (1975) of the value of 7.1 mm Hg per every 100 μm change in CCT. For this reason, the variation in CCTs between right and left eyes (around 1.6 μm) has been found of less significance for consideration in current study. Meanwhile the overall effect of CCT on IOPG has been considered such that thicker corneas led to IOP overestimation and thinner corneas led to IOP underestimation (Ehlers et al., 1975; Gunvant et al., 2004; Kotecha et al., 2005; Liu and Roberts, 2005; Orssengo and Pye, 1999; Tonnu et al., 2005; Weinreb et al., 2007). Subsequent studies (Weinreb et al., 2007) suggested that it was corneal stiffness rather than CCT itself that was responsible for error on GAT readings. With increased interest in the topic, studies led to findings that identified parameter *R* effecting the accuracy of IOP measurement (Liu and Roberts, 2005; Mark, 1973; Weinreb et al., 2007; Kanngiesser et al., 2005) ranging between 0.57 and 1.14 mmHg per 1 mm change in *R* (Gunvant et al., 2004; Liu and Roberts, 2005; Orssengo and Pye, 1999). It is noted that there are highly significant changes that occur in the shape of the cornea in the periphery itself (Read et al., 2006). Early studies relevant to cornea assumed its shape being spherical (Eghbali et al., 1995) until the beginning of the 1970s when Mandell (Mandell, 1962) described the flattening of cornea towards the periphery. Due to this the corneal radius of curvature 'R' also varies along the corneal surface, thereby leading to its assumption of being similar to an elliptical shape (Eghbali et al., 1995). Researchers (Cheung et al., 2000; Eghbali et al., 1995) have also shown concern about the variation of Pa within the cornea affected due to variation in corneal meridians and need to be fully determined. As GAT is based on Imbert–Fick Law (Goldmann and Schmidt, 1957), in which the force to applanate the anterior corneal surface is equal to the true IOP of the applanated area at the posterior corneal surface, it is concluded that due to low contact area available than the actual in case of prolate corneas, it would lead to IOP underestimation as contrary to flatter corneas (Fig. 2). Based on clinical data this error was found to grow up to 3 mmHg (Mark, 1973). Other studies (Paranhos et al., 2000; Schmidt, 1960) also provide the significant evidence of correlation of IOPG measurement and corneal curvature. With the advent of research it was identified that material properties are responsible for errors in IOPG (Hamilton et al., 2008; Liu and Roberts, 2005) with the stiffening of corneal tissue being associated with age (Elsheikh et al., 2007, 2008b; Tang et al., 2012; Knox Cartwright et al., 2011) in a way that relates IOP overestimation with increased age (Kotecha et al., 2005). Other factors responsible for influencing IOPG, such as diurnal hydration, ectasia, wound healing, and diseases such as keratoconus, need to be fully determined (Andreassen et al., 1980; Bryant et al., 1994; Meek et al., 2005; Nash et al., 1982; Radner et al., 1998; Shah et al., 2000; Daxer et al., 1997).

Researchers have made attempt to generate correction factors and nomograms addressing the effect of corneal thickness and curvature on IOPG, while current study model also incorporates the effect of material stiffness with age on measurement accuracy. More precisely, with the help of current study model it was possible to generate correction factor considering multi parameters (Elsheikh et al., 2011, 2009) unlike most recent researches addressing only single parameters with the exceptions of Shimmyo et al. (2003) and Chihara, (2008) considering no more than two parameters (CCT and R). However, within the current knowledge of author, the combined effect of parameters such as CCT, R, age, PCT, corneal asphericity and IOP itself have been completely ignored. Hence, in line with the work published elsewhere (Elsheikh and Wang, 2007; Elsheikh et al., 2006, 2011, 2009), current study intends to further address such a shortfall with the development of correction factor using numerical simulations that simultaneously combines effect of six parameters on IOPG i.e., CCT, R, age, PCT, corneal asphericity and IOP itself (keeping θ° constant=35°) and the effect of θ° was studied separately as it may experience variations based on varied reasons (Rojas et al., 2006; Hansson and Jerndal, 1971). Inspired by Orssengo and Pye (1999), Elsheikh and Wang (2007) carried out studies to find the value of $\theta^{\circ}=23^{\circ}$ to the limbal plane for present model representing whole eye model condition. Meanwhile during the process, the importance of each parameter was noted based on their respective influence(s) on IOPG.

2. Numerical model and method

The study used a non-linear finite element simulation model representative of GAT procedure (Elsheikh and Wang, 2007; Elsheikh et al., 2006) as seen in Fig. 1