INTRODUCTION

Central corneal thickness (CCT) is a variable that significantly affects intraocular pressure (IOP) measurements on indentation and applanation tonometry, and accounting for CCT during IOP measurement remains a challenge in glaucoma. In addition, most available tonometers measure the “force” needed to deform or applanate the cornea, and hence indirectly provide the intraocular pressure. Dynamic contour tonometry (DCT) may solve both these problems. DCT measures IOP after contour-matching between the human cornea and the pressure-sensitive transducer tip of the tonometer occurs. This allows the measurement of an IOP that is less dependent, or perhaps independent of CCT. Theoretically, this tonometer measures “pressure” rather than force, and hence directly measures IOP. In addition, the device incorporates the measurement of the ocular pulse amplitude (OPA), a variable that has controversial significance in the diagnosis and management of glaucoma. Many centers have studied its use in glaucoma with varying results; however, this new technique may hold promise for IOP measurement in glaucoma management.

The human sclera and cornea are neither uniformly elastic nor thin and flexible, and hence most tonometers, including the widely accepted gold standard Goldmann applanation tonometer (GAT),1,2 approximate the intraocular pressure using averaged values of tissue properties, such as corneal elasticity and central corneal thickness (CCT).

However, CCT seems to vary considerably between healthy individuals and groups at risk for or diagnosed with glaucoma, as shown by multicenter studies. The Ocular Hypertension Treatment Study reported a mean (+/− SD) CCT of 573 (+/− 39.0) µm,3 and the Rotterdam Study described a mean (+/− 2SD) CCT of 537.4 (+/− 3.6) µm, with a range of 193 µm, and a maximal difference between eyes of 42 µm.4 Corneas tend to be thicker in patients with ocular hypertension, which may be explained, in part at least, by the fact that some of these eyes are misclassified owing to IOP overestimation.5 Argus5 described a mean ± SD CCT in his ocular hypertension group of 610 ± 33 µm. Patients having primary open-angle glaucoma (POAG) show slightly thinner corneas than those of control subjects.4,5 Most strikingly, normal-tension glaucoma (NTG) is associated with CCT in the low 500-µm range.6

These inter-individual/inter-group variations in CCT may serve as a source of error for GAT and other methods of IOP measurement.7 Thicker corneas require greater applanation forces compared to thinner corneas, and hence result in IOP overestimation. Conversely, very thin corneas may cause an underestimation of the IOP. Different studies have shown variations from 0.11 mm Hg7 to 0.71 mm Hg8 (with an average of 0.25 mm Hg) for every 10 µm of CCT change.

Established methods of measuring intraocular pressure use indirect methods of measuring the IOP. The Goldmann, Schiotz, Perkins, Mackay-Marg, Draeger and all non-contact (“air-puff”) tonometers might be classified as “force tonometers” as they measure the force required to generate a defined amount of deformation of the cornea. They then indirectly estimate the IOP after taking into consideration a set of material constants which are assumed to be uniform for all eyes.

A tonometer which could measure the true “pressure” directly and continuously, without being affected by CCT or corneal elasticity would be useful in clinical practice. Manometry would be able to measure the true IOP directly, but is invasive and impractical for routine use. The pneumotonometer according to Langham, another type of indirect device, allows a continuous measurement of IOP, displaying a pressure curve that reveals pulsatile short-term fluctuations in IOP. Dynamic contour tonometry (DCT) may solve some of these problems, and its principle and practical use are described in this article and accompanying video.

Dynamic Contour Tonometry (DCT)

Let us assume a hypothetical contour that resembles that of most human corneal centers. A tonometer tip that is equipped with this hypothetical contour and that touches the cornea alters the corneal shape into the desired contour. The force distribution that is needed to gently fit the corneal surface to that hypothetical contour counterbalances the force distribution generated by the intraocular pressure. The distribution of interface forces between the tip and the cornea equals the force...
distribution generated by the IOP. Hence, a pressure sensor that is centrally and concavely embedded into the tonometer tip precisely measures the pressure of the eye transcorneally. As the name suggests, DCT is based on “contour matching”, i.e. when the contour of the tonometer tip matches that of the human cornea, a surface-independent measurement of IOP can be achieved.

Three theoretical steps guide the development of a functioning DCT device. First, we assume that the cornea is a spherical shell made of a material that resists stretching and is fairly flexible to bending deformations, although, rigidity forces (i.e., due to bending and buckling) are not totally without effect (however, they are negligible for practical purposes). To build an ideal device for transcorneal pressure measurement, we need to imagine a container that is filled with casting resin surrounding an entire globe. In this closed system, the resin around the eye is under a pressure “p” that exactly equals the pressure inside the eye. The forces “F” that are generated by the intraocular pressure “p” act perpendicularly through the cornea and sclera and uniformly on the bulbar-resin interface and are counterbalanced by the external forces caused by the pressure in the resin. The eye floats in the resin in total relaxation. If the resin cures homogeneously under constant conditions without shrinking, it forms a hollow space matching exactly the size and shape of the relaxed globe. The eye holds its shape almost irrespectively of the IOP and equals both the size and shape under living conditions in its “unloaded” state. The forces “F” act in the same manner as before, but now on the wall of the hollow space. If we replace a small part of the wall by a pressure sensor with identical surface shape, the sensor measures a pressure “p” that exactly corresponds to the true intraocular pressure “P.” The same concept applies if the surrounding sphere is only partial.

Therefore, if we take a cylindrical tip that duplicates for a part of the sphere, with a surface contour identical to the one of the whole sphere, the force distribution and area will also be identical, and therefore, we presume the same.

The cornea that served for the hypothetical models is idealized and does not exist in vivo. However, as the experimental part will show, the contour adapted to the ideal cornea sufficiently matches the physiologically relevant range of human corneal shapes. Kanngiesser, et al designed and built an actual DCT head that consists of a cylindrical tip with a surface contour that closely resembles the contour of the human cornea when the pressure on both sides is equal. The centrally located piezoresistive pressure sensor has the same surface contour as the surrounding tip. Its sensitive element has an active diameter of less than 0.25 mm². The resolution is better than 0.1 mm Hg over a range of more than 300 mm Hg. This type of sensitive element is commercially available as silicon pressure dice. Applying a constant appositional force, the cornea and the tip will be in direct contact across a circular area of diameter d. Within the contact area, the shape of the cornea is matched to the contour of the concave tip (“contact area = area of contour matching”, Aₜ). The distribution of the external interface forces between the tip and the cornea equals the distribution of the internal forces that are generated by the IOP. Changes in the appositional force, the corneal radius and thickness, or other corneal properties alter the diameter d, but do not affect the force distribution, provided that the diameter of the tip is larger than d and the diameter of the pressure sensor (1.7 mm) is smaller than d. The appositional force is freely selectable over a range defined in the experimental part.

DCT allows for non-invasive and direct IOP measurement, and has been proposed to accurately measure the IOP irrespective of the CCT or corneal elasticity. It also provides a continuous measurement of the IOP and is based on the direct trans-corneal pressure detection. The pressure sensing device is embedded within a contact tonometer that closely matches the corneal contour, thus minimizing the amount of corneal deformation. Even though conclusive proof that DCT is independent of corneal thickness can only be obtained by comparing DCT to manometric readings in living, normal eyes—a study that would be difficult to perform—evidence has been gathered from studies which compare DCT with GAT, suggesting that the DCT measurements are independent of corneal characteristics, as explained in the next section.

An additional feature of the commercial version of the DCT (Swiss Microtechnology AG, a Ziemer Ophthalmic Systems Group Company) is that it allows the simultaneous measurement of the ocular pulse amplitude (OPA). The OPA, which may play a role in the clinical course of glaucoma, is an indirect indicator of the choroidal perfusion and reflects the ocular blood flow corresponding to the heart pulse as a function of time. A reduction of the blood flow to the retinal layers may be related to hypoxia and further cell death and therefore may also contribute to diseases such as glaucoma. In various studies the effect of local glaucoma therapy on ocular hemodynamics have been determined using different instruments for IOP- and OPA-measurements. DCT, which is mounted on a slit lamp device, has a wireless sensor which picks up the signal each time the IOP and OPA are measured.

In a recent study, OPA readings obtained with dynamic contour tonometry in healthy subjects was not influenced by the structure of the anterior segment of the eye but was affected by intraocular pressure and axial length. A high degree of agreement was found within and between observers.

**Do Corneal Properties affect DCT Measurements?**

Our recent study showed that DCT measures an IOP that is significantly higher than GAT in glaucoma and control subjects but not in ocular hypertensives. Furthermore, DCT was found to measure an IOP that was not dependent on the CCT, which was not true for GAT.

An experimental laboratory investigation compared IOP
measurements obtained by DCT, GAT and pneumotonometry (PTG) with intracameral manometry on human cadaver corneas of different hydration conditions. In this in vitro study, DCT values for IOP were significantly closer to the manometric reference pressure than those obtained using GAT and PTG, independent of the state of corneal hydration. The IOP values were obtained by the above-mentioned tonometers at varying stages of corneal hydration. DCT measurements were performed on maximally hydrated and dehydrated eyes and DCT was found to be independent of corneal thickness changes produced by altering corneal hydration. Other studies conducted on cadaver eyes and eyes of patients after laser in situ keratomileusis (LASIK) showed a significantly lower correlation of CCT with DCT than with GAT.

That DCT may be independent of corneal thickness was also suggested by a recently completed clinical study using DCT and applanation tonometry, in which no correlation between corneal thickness and DCT readings was found, whereas applanation tonometry according to Goldmann was correlated with CCT. Similar results were found by Kampter et al. Studies have also found the DCT to have a good correlation with GAT, although IOP values are significantly higher.

A recent study evaluated the use of DCT in patients having keratoconus (some of whom had penetratingkeratoplasty-PK) and pellucid marginal degeneration, and IOP results were significantly higher in the DCT group compared to GAT and tonopen groups, and were found to be less dependent on CCT compared to those on GAT and tonopen measurements. The IOP difference between the PK and non-PK groups was not statistically significant on DCT. Another study also found DCT to be significantly greater than GAT in patients having keratoconus, but DCT readings in keratoconus patients to be significantly lower than in control subjects.

DCT has also been found to have excellent reproducibility in a cross-sectional study involving 323 normal, consecutive eyes.

However, conclusive evidence of the independence of DCT measurements to corneal characteristics can only be obtained by comparing the IOP values with manometric results in living eyes, a study which may be difficult to perform. Future clinical studies that include manometric reference pressures would be useful to address these questions appropriately.

DCT appears to be a promising technology that could potentially improve the management of ocular hypertension and glaucoma. However, further research is warranted to determine whether IOP measurements by DCT remain reliable when used on abnormally shaped corneas (e.g., after LASIK), differently hydrated corneas (e.g., in the case of stromal edema), and corneas with irregular surfaces.

References


