Changes in corneal biomechanics and intraocular pressure following cataract surgery

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Abstract

Purpose: The purpose of this study was to investigate the effects of cataract surgery on corneal biomechanics and intraocular pressure (IOP) measured with the updated CorvisST tonometer (CST).

Design: Prospective, interventional case series study.

Methods: This study included 39 eyes of 39 cataract patients. CST measurements were performed on pre-surgery (Pre) as well as 1 week (1W), 1 month (1M), and 3 months (3M) post-surgery. The following CST parameters were recorded: deformation amplitude max (DA max), DA ratio max 1mm and 2mm, integrated radius, stiffness parameter at applanation 1 (SP A1), Ambrosio relational thickness to the horizontal profile (ARTh), Corvis biomechanical index (CBI), central corneal thickness (CCT), non-corrected intraocular pressure (IOPnct), and biomechanically-corrected IOP (bIOP). IOP was also measured with Goldmann applanation tonometry and the non-contact tonometer CT-90A. All measurements were compared at each period using the linear mixed model, with and without adjustment for bIOP and CCT.

Results: All IOP measurements decreased over time (p<0.01). CCT was increased at 1W and 3M (p<0.01), whereas ARTh was decreased at 1W and 1M (p<0.01), but returned to its Pre level at 3M. DA max and Integrated radius were increased at 3M (p<0.01), whereas SP A1 was decreased at 3M (p<0.01). CBI was increased at 1W (p <0.01), but returned to its Pre level at 1M.

Conclusions: IOP and Corneal biomechanical properties are changed after cataract surgery. In particular, SP A1 decreases while DA max and integrated radius increase, even at 3M, suggesting a less stiff cornea.
Changes in corneal biomechanics and intraocular pressure following cataract surgery

Short title: Changes in corneal biomechanics and IOP after cataract surgery

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Introduction

Cataract is an ocular disease characterised by clouding to the lens, which causes a decrease in visual acuity. Cataract is usually treated with ultrasound phacoemulsification surgery followed by implantation of an intraocular lens (IOL). Cataract surgery recovers a person’s visual acuity, but also affects various biomechanical properties of the eye. For instance, following surgery, intraocular pressure (IOP) decreases in eyes with cataract\textsuperscript{1, 2} and also in eyes with cataract and open angle glaucoma.\textsuperscript{3, 4} In addition, central corneal thickness (CCT) increases.\textsuperscript{5-10} The advent of novel devices, such as the Ocular Response Analyser (ORA, Reichert Ophthalmic Instruments, Depew, NY, USA)\textsuperscript{11-17} and the Corneal Visualization Scheimpflug Technology tonometer (CorvisST tonometer: CST),\textsuperscript{6, 18} has revealed that several other corneal biomechanical properties are altered following cataract surgery.

The CST is a non-contact tonometer capturing corneal deformation during the application of an air puff, using a sequence of images from a high-speed camera. We have recently reported that various biomechanical corneal properties measured with CST (ver.1.02.r1092) are significantly different before and after cataract surgery. In particular, the cornea appears to deform more quickly (as suggested by an increase in CST-measured ‘A1 Velocity’) and deeply (as suggest by an increase in CST-measured ‘maximum deformation amplitude’) after cataract surgery compared to before surgery.\textsuperscript{6} Further, at the time of maximum corneal deformation (‘HC Time’), the cornea is deformed more widely (increased peak distance) and more steeply (decreased ‘radius’) while the cornea’s velocity during recovery is increased (increased ‘A2 Velocity’).\textsuperscript{6} A separate study also observed a significant difference in maximum deformation amplitude following phacoemulsification and femtosecond laser-assisted cataract surgery.\textsuperscript{19}

The software in the CST has recently been updated (version 1.3r1538) and several new measurements have been introduced (total number of parameters measured has increased to 35). Further, a number of new summary parameters, most of which are related to corneal stiffness, are now available. Several recent research papers have investigated the usefulness of these new summary parameters in evaluating the corneal stiffness in various corneal conditions; the stiffness parameter applanation 1 (‘SP A1’) measurement in keratoconic eyes,\textsuperscript{7} deformation amplitude (‘DA’) ratio max 1mm and 2mm in eyes with transepithelial photorefractive keratectomy and transepithelial photorefractive keratectomy with corneal crosslinking,\textsuperscript{20} and the Corvis biomechanical index (‘CBI’) in keratoconic eyes.\textsuperscript{21} In addition, a new biomechanically-corrected IOP (‘bIOP’) is now calculated.\textsuperscript{22}

The aim of the present study is to investigate the effects of cataract surgery on corneal biomechanics and IOP using the newly-introduced CST measurements (software version 1.3r1538).
Methods
This study followed the tenets of the Declaration of Helsinki and was approved by the ethics committee of Faculty of Medicine at The University of Tokyo (Tokyo, Japan), Saneikai Tsukazaki Hospital (Hyogo, Japan), and Hiroshima University Hospital (Hiroshima, Japan) the Graduate School of Medicine. All participants provided written informed consent.

This prospective, interventional case series study included 39 eyes of 39 patients who had uneventful cataract surgery at Saneikai Tsukazaki Hospital or Hiroshima University Hospital between June 2014 and November 2015. Full inclusion criteria are described elsewhere, but, in short, only eyes without ocular disease (except cataract) and no prior ocular surgical history were included. When both eyes of a patient met the inclusion criteria, one eye was randomly chosen. Patients who experienced complications after cataract surgery, including secondary high IOP elevation or severe inflammation were carefully excluded. Patients with incomplete data or a low quality index for the CST data were also excluded.

Cataract surgery
As detailed in our previous report, cataract surgeries were performed with phacoemulsification cataract extraction with posterior chamber IOL implantation through a 2.8 mm temporal corneal incision or a 2.8mm superior sclera-corneal incision. After surgery, steroidal (0.1% Flumetholon, fluorometholone ophthalmic solution; Santen, Osaka, Japan) and antibiotic (1.5% Cravit, levofloxacin; Santen, Osaka, Japan) medications were topically administered 4 times a day for 1 month, and nonsteroidal anti-inflammatory (0.1% Nevanac, nepafenac ophthalmic solution; Alcon, Tokyo, Japan) medication was also topically administered 3 times a day for 1 month in all cases. All data investigated were inherited from our previous report.

CST measurement
Corneal biomechanical properties were measured with CST (Oculus Optikgeräte GmbH, Wetzlar, Germany) and the results were analysed using software version 1.3r1538. The principles of CST are described in detail elsewhere. Briefly, the instrument’s camera records a sequence of images (capable of capturing 4,330 images per second) that capture corneal deformation following application of a rapid air puff; see Figure 1A. In the latest CST software (ver. 1.3r1538), the following parameters are recorded:

i. ‘CCT’: central corneal thickness
ii. ‘non-corrected IOP (IOPnct)’: IOP with no correction made for corneal stiffness.
iii. ‘bIOP’: IOP corrected for corneal stiffness, CCT, and age. An updated formula is used in the latest version of the software (personal communication with Oculus):

\[ bIOP = C_{cct1} \times C_{AP1} \times C_{age1} + C_{cct2} \times C_{age2} + C_{DCR} + a_{19} \]
where $C_{CCT1}$ and $C_{CCT2}$ are parameters representing the effect of variation in CCT (mm) and $C_{age}$ denotes effect of variation in age;

$$C_{CCT1} = a_1 \times CCT^3 + a_2 \times CCT^2 + a_3 \times CCT + a_4$$

$$C_{AP1} = a_5 \times AP1 + a_6$$

$$C_{age1} = a_7 \times \ln(\text{beta1})^2 + a_8 \times \ln(\text{beta1}) + a_9$$

Beta1 = 0.5852 * exp(0.0111 * age)

$$C_{CCT2} = a_{10} \times CCT^3 + a_{11} \times CCT^2 + a_{12} \times CCT + a_{13}$$

$$C_{age2} = a_{14} \times \ln(\text{beta1})^2 + a_{15} \times \ln(\text{beta1}) + a_{16}$$

$$C_{DCR} = a_{17} \times \text{highest concavity radius} + a_{18}$$

where the highest concavity radius is a CST parameter which represents the curvature radius when the cornea is at the point of highest concavity.

iv. ‘Deformation Amplitude Ratio max 1mm and 2mm (DA Ratio max 1mm and 2mm)’: the ratios between deformation amplitude at corneal apex and that at 1mm or 2mm (Figure 1A)

v. ‘Integrated radius’: integrated area under the curve of the Inverse Concave Radius (Figure 1B),

vi. ‘Ambrosio Relational Thickness to the horizontal profile (ARTh)’: the quotient of corneal thickness at the thinnest point of the horizontal meridian and the thickness changes (Figure 1C),

vii. ‘SP A1’: the difference between the strength of the air puff at the corneal surface and bIOP divided by deflection amplitude at the time of first applanation. The formula is:

$$SP\ A1 = (adjAP1 - bIOP) / (A1DeflAmp)$$

where \(adjAP1\) represents an adjusted air pressure impinging on the cornea at first applanation and \(A1DeflAmp\) represents Deflection Amplitude at first applanation.

viii. ‘CBI’: a parameter specifically developed for the purpose of screening keratoconus; the value is calculated using logistic regression with DA ratio max 1mm, DA ratio max 2mm, Applanation 1 velocity, the standard deviation of deformation amplitude at highest concavity, ARTh, and SP A1. The formula is as follows:

$$CBI = \exp(Beta2) / (1 + \exp(Beta2))$$

where

$$Beta2 = -59.487 \times A1\ velocity - 0.027 \times ARTh - 0.092 \times SP\ A1 - 27.169$$

$$\times DA\ ratio\ max\ 1mm + 5.472 \times DA\ ratio\ max\ 2mm - 0.599$$

$$\times SD\ Deflection\ amplitude + 46.576$$

Figure 1 illustrates the corneal movement following a rapid air puff, with a description of the CST-measured parameters. All CST measurements were repeated three times with a one minute interval between tests. Data were converted from an older software.
version (ver.1.02.r1092) to the newest software version (ver. 1.3r1538). Data from 20 eyes out of 59 eyes included in our previous study could not be converted (due to insufficient quality, required for calculating the new CST parameters). Eyes where data were unavailable three times or more for any given parameter (on any measurement day) were excluded from the current analysis.

**IOP, axial length and corneal curvature measurements**

IOP was also measured using Goldmann applanation tonometry (GAT) and the non-contact tonometer CT-90A (Topcon, Tokyo, Japan) at each visit. Axial length and corneal curvature was measured with IOLMaster, ver. 5.02 (Carl Zeiss Meditec, Jena, Germany) at each visit. The average of five repeated measurements was used in the analysis.

Data were obtained at pre-surgery (Pre) as well as 1 week (1W), 1 month (1M), and 3 months (3M) post-surgery. All measurements were conducted between 1 and 4 o’clock in the afternoon to reduce the impact of circadian changes in IOP and ocular biomechanical properties on the study results.\(^24,25\)

**Statistical Analysis**

The changes in IOP and CST measurements over time was investigated using linear mixed models. Since CST parameters are closely related to IOP,\(^8,18,26\) comparisons of CST parameters were carried out with and without adjustment for bIOP in the model. All p values were adjusted for multiple comparisons using Holm’s method.\(^27\) Many previous studies have reported that CCT is significantly altered by cataract surgery.\(^16,19,28-30\) We previously concluded that many CST parameters in the older software (ver.1.02.r1092) were not significantly related to CCT,\(^26\) however, this has not been investigated with the newer software, hence comparisons of CST parameters were also carried out with adjustment for both bIOP and CCT in the linear mixed model.

The statistical programming language ‘R’ (R version 3.4.0; The foundation for Statistical Computing, Vienna, Austria) was used for all statistical analyses.

**Results**

Demographic data of patients is summarised in [Table 1](#). [Table 2](#) and [Figure 2](#) summarise the various ocular measurements before and after cataract surgery.

All IOP measurements including GAT, CT-90A, IOPnct, and bIOP significantly decreased over time, following cataract surgery (p<0.01). This trend remained significant after adjustment for CCT (p<0.05).

CCT was significantly increased at 1W compared to Pre (p<0.001). CCT at 3M was also slightly thicker than that at Pre (p=0.003). Changes in CCT remained significant regardless of changes in bIOP (p<0.05).
DA max increased throughout the period and remained significant after adjustments for bIOP and CCT (p<0.01).

DA ratio max 1mm was significantly decreased at 1W compared to Pre (p=0.008), but returned to Pre levels by 1M. The change at 1W remained significant regardless of changes in bIOP (p<0.05), however, a significant difference was not observed after adjusting for both bIOP and CCT. DA ratio max 2mm was significantly increased at 3M compared to Pre (p<0.001). A significant difference was not observed, however, after adjusting for bIOP.

Integrated radius was significantly increased after 1M (p<0.001) and this change remained significant after adjusting for changes in bIOP and CCT (p<0.05).

ARTh was significantly decreased at 1W compared to Pre (p<0.05) and at 3M compared to Pre (p=0.028). These changes remained significant after adjustments for bIOP and CCT (p<0.05)

SP A1 was significantly decreased after 1W (p<0.01). The difference was not significant after adjusting for bIOP, however, it was significant after adjusting for both bIOP and CCT (p<0.05).

CBI was significantly increased at 1W compared to Pre (p=0.008), and was still significant after adjusting for both bIOP and CCT (p<0.05). CBI returned to Pre levels at 1M and 3M.

Discussion
In the current study, the effects of cataract surgery on CST-measured (ver. 1.3r1538) biomechanical parameters, displayed on the Vinciguerra screening report, were investigated. As expected, we observed that IOP and CCT were significantly different after cataract surgery compared to their Pre values. Other CST-measured biomechanical parameters including DA max, DA ratio max, integrated radius, ARTh, SP A1 and CBI were also significantly influenced by cataract surgery. Most of these changes remained significant after adjusting for bIOP and CCT.

CCT was significantly increased at 1W compared to its Pre value; this difference remained significant after adjusting for changes in bIOP. Previous studies have reported similar findings. The increase in CCT at 1W is a result of corneal edema induced by the application of ultrasound energy or mechanical trauma from the phacoemulsification procedure. At 3M, CCT was still slightly thicker than that at Pre, which agrees with a previous report, however, other research contradicts this result. Differences in surgical procedures, race, and age across studies may explain the contradiction. The current results suggest that clinicians should be careful when evaluating IOP in the days and weeks following cataract surgery since increased CCT induces an over-estimation of IOP, especially with GAT and traditional non-contact tonometers.

All IOP measurements decreased over time after cataract surgery, even after an
adjustment for CCT. In the study by Wei et al., non-contact IOP measured with CST was significantly elevated at 1W but returned to its Pre level after 1M.\textsuperscript{19} It is difficult to directly compare the current results with this previous study because of a lack of IOP measurements measured with GAT and non-contact tonometry in the previous study; however, the results appear inconsistent since GAT, CT-90A, IOPnct and biOP were all significantly decreased up to 3M after surgery in the current study. The effect of cataract surgery is also controversial. Yang et al. reported that IOP was significantly decreased at 3M.\textsuperscript{1} Cetinkaya et al. reported that IOP was significantly decreased at 1 year after a surgery.\textsuperscript{2} These scatter results would be attributed to the difference of the details of the investigation. For instance, IOP change is influenced by the postoperative usage of eye drops. In the current study, steroidal (0.1\% Flumetholon, fluorometholone ophthalmic solution; Santen, Osaka, Japan) medications were topically administered 4 times a day for 1M, and nonsteroidal anti-inflammatory (0.1\% Nevanac, nepafenac ophthalmic solution; Alcon, Tokyo, Japan) medication was also topically administered 3 times a day for 1M in all cases, which may be different from the previous study by Wei et al.,\textsuperscript{19} although it is unclear because this information was not given in the previous paper. In addition, differences in surgical procedures, race, and age may also be associated with difference of IOP changes.

There were differences in the magnitude of reduction in IOP values between tonometers in the current study, probably due to inherent methodological differences between devices. Many explanations for a reduction in measured-IOP, following cataract surgery, have been postulated. Reasons include an increase in the depth and volume of the anterior chamber and an increase in the angle between the cornea and iris (due to a thin IOL);\textsuperscript{1-3} other possible explanations are a stress response in trabecular meshwork cells by ultrasound phacoemulsification\textsuperscript{36} and elevation of aqueous monocyte chemoattractant protein-1 levels.\textsuperscript{37} Results from the current study suggest that changes in corneal biomechanics may also be associated with the decline in IOPs measured with GAT, CT-90A and IOPnct.

In our prior study,\textsuperscript{6} it was suggested that any measured decrease in IOP (observed using GAT or CT-90A) might actually result from a change in corneal biomechanics, however, it was not possible to determine whether IOP measured with GAT decreased after cataract surgery was because of a change in corneal biomechanics, a real change in IOP, or a combination of both. In the current study, all IOPs measured with GAT, CT-90A and CST significantly decreased over time, however, the magnitude of reduction was much lower with biOP (from 11.8 to 10.6 mmHg at 3M) than with GAT (from 16.5 to 12.6 mmHg at 3M). On the other hand, the new corneal stiffness parameters, including SPA1, integrated radius, and DA max, suggest corneal stiffness all decreased after cataract surgery. These findings imply that the reduction of IOP, measured with GAT, following cataract surgery is – in part – explained by a reduction in corneal stiffness. However, this reduction in IOP cannot be
entirely explained by a change in corneal stiffness, since bIOP also decreased at 3M. GAT measures IOP using the Imbert-Fick law, and hence GAT is affected by CCT and corneal biomechanical properties, such as stiffness. bIOP is adjusted for these factors, and our results suggest there is a change in corneal biomechanical properties after cataract surgery; in particular, the cornea becomes less stiff (as suggested by the decrease in SP A1, and increases in DA max and integrated radius). With this change in corneal stiffness, GAT measured IOP will be decreased, and this partially explains why GAT measured IOP was largely decreased at 3M. GAT and non-contact tonometer are commonly used to measure IOP in the clinical setting. As the results of the current study demonstrate, IOPs measured after cataract surgery should be considered alongside the mode of measurement because very different reductions will be observed (the magnitude of reduction is relatively small with bIOP compared to GAT).

ARTh was significantly decreased at 1W compared to Pre, returning to Pre levels at 3M. ARTh is related to CCT, but measures a different aspect of corneal thickness; ARTh is defined as the quotient of corneal thickness at the thinnest point of the horizontal meridian. In contrast to changes in CCT, ARTh assumes a small value when corneal thickness is thick in the peripheral region, or, CCT is thin in the direction of the horizontal meridian. While CCT at 1W was much thicker than that at Pre, ARTh at 1W was lower than that at Pre, even after adjusting for bIOP and CCT. This suggests that decreased ARTh following cataract surgery is a result of increased peripheral corneal thickness (peripheral corneal thickness was thicker than CCT). This phenomenon may be a consequence of the temporal incision made during cataract surgery, which will distend peripheral corneal thickness.

DA max, DA ratio max 1mm and 2mm, and integrated radius increased after cataract surgery while SP A1 decreased after cataract surgery. These parameters reflect corneal stiffness. Changes in DA max, integrated radius and SP A1 remained significant after adjusting for bIOP and CCT. The cornea has a dome-like shape, which is altered by cataract surgery, especially when a corneal tunnel incision is made. Consequently, corneal biomechanical properties may also be affected. In the peripheral cornea, the collagen lamellae are aligned circumpherentially, whereas they tend to fuse orthogonal to the nasal-temporal and superior-inferior directions in the centre of the cornea. Hon et al. investigated the corneal tangent modulus at center and also temporal quadrant (periphery) of the cornea in young (between 21 and 26 years old) and healthy eyes. Because of the differences of this collagen alignment and also the number of stromal lamellae (approximately 300 at the central cornea and 500 near the limbus), the corneal tangent modulus in the temporal quadrant (periphery) of the cornea was reduced by an average of 13.7 %. The corneal incision induces structural changes of peripheral cornea, including loss of epithelium, stromal fibre shrinkage, and Descemet membrane and endothelial cell loss, which would weaken the structures that stiffen the cornea. A previous study
compared corneal stiffness parameters following phacoemulsification or femtosecond laser-assisted cataract surgery, and reported no significant changes in DA max in the femtosecond laser-assisted cataract surgery group. In contrast, in the phacoemulsification cataract surgery group, DA max increased at 1W (returning to Pre levels at 1M).\textsuperscript{19}

CBI significantly increased at 1W compared to Pre, but returned to Pre levels at 1M and 3M. The CBI parameter was developed specifically for the purpose of screening keratoconus.\textsuperscript{21} According to the Vincigurra et al.,\textsuperscript{21} keratoconic eyes may be discriminated from normal eyes using a CBI value equal to 0.5. The average CBI value observed in our study was 0.24 at 1W (standard deviation was 0.33), however, 14 eyes (35.9\%) had a CBI value greater than 0.5 and 7 eyes (17.9\%) had a CBI value between 0.25 and 0.5. These results suggest that careful attention is needed when evaluating the CBI measurement after cataract surgery, since a high value may not be indicative of keratoconus. CBI is calculated using CST parameters representing the biomechanical properties of the cornea (SP A1, DA ration max 1mm and 2mm, and DA max, and ARTh). A recent report – based on a comparison between CCT- and IOP-matched keratoconic eyes and normal eyes – suggested that it may be useful to calculate CBI (aCBI) only with the biomechanical parameters, excluding ARTh.\textsuperscript{47} However, in a real world clinic, CCT and IOP (reading) are changed in keratoconic eyes, and adjusting for these variables may not be clinically relevant.\textsuperscript{48} Hence a further investigation was carried out and the usefulnesses of CBI and aCBI unmatched keratoconic and normal eyes. As a result, it was suggested that CBI was more useful than aCBI. Our results suggest there is no concern in using CBI to diagnose keratoconus at 1M, since CBI returned to its Pre level at this time, although ARTh was still significantly different 3M.

As described above, changes in DA max, Integrated radius, and SP A1 remained significant at 3M. Kucumen et al. investigated corneal biomechanical properties before and after cataract surgery using ORA.\textsuperscript{15} They observed significant decreases in the corneal hysteresis and corneal resistant factor ORA parameters post-surgery, however, in contrast to the current study, these changes were no longer observed at 3M. Both ORA and CST measure corneal biomechanical properties, and hence their measurements are correlated.\textsuperscript{26} However the mechanisms of the measurements are very different; ORA measures the difference of pressure at the first (inward ) and second (outward) applanations, whereas CST measures the shape of corneal deformation at different timepoints, including the first (inward) and second (outward) applanation. Reflecting this, the correlations between the measurements of ORA and CST are significant, but relatively weak.\textsuperscript{26} The current results possibly suggest that corneal biomechanical changes after cataract surgery are more accurately captured with CST than with ORA.\textsuperscript{15}

The newest CST software (1.3r1538) outputs summary parameters, in addition to 35 raw parameters: DA ratio max 1 mm and 2mm, integrated radius, ARTh, SP A1, CBI and
bIOP. Previous studies have confirmed the clinical usefulness of these summary parameters. For instance, SP A1 for the assessment of corneal stiffness measurement in keratoconic eyes,\textsuperscript{7} DA ratio max 1mm and 2mm for diagnosing eyes with transepithelial photorefractive keratectomy and transepithelial photorefractive keratectomy with corneal crosslinking,\textsuperscript{20} and the CBI to diagnose keratoconic eyes.\textsuperscript{21} Our results suggest that some of these parameters, such as DA max, integrated radius, and SP A1 were significantly affected by cataract surgery, even at 3M. This suggests careful consideration is needed when clinicians use these parameters in keratoconic eyes, eyes with transepithelial photorefractive keratectomy, and transepithelial photorefractive keratectomy with corneal crosslinking. In particular, as shown in Table 2, ARTh was significantly decreased after cataract surgery compared to Pre, whereas CBI was significantly increased at 1W, but returned to its Pre level at 1M. CBI is a parameter developed to discriminate keratoconus eyes from normal eyes, suggesting clinicians should be cautious when diagnosing keratoconic eyes at 1W, however the effect of a cataract surgery is no longer apparent after 1M.

This study has a number of limitations. Participants were not followed beyond three months and some corneal stiffness parameters and IOPs remained significantly different to their Pre values at 3M. A further limitation is the lack of data in the days immediately following surgery (1 or 2 days post-surgery). Previous studies have demonstrated that post-operative IOP is increased in the days following cataract surgery.\textsuperscript{49-51} Thus, corneal biomechanical characteristics may also be significantly different in this timeframe. It would also be interesting to investigate CST measurements taking into account the incision wound (corneal incision or sclero-corneal incision) because healing time is slightly different. Previous studies have investigated IOP differences between the two groups, with one study suggesting no significant difference,\textsuperscript{52} while a different study suggested higher IOP reduction in the corneal incision group.\textsuperscript{50} We were unable to conduct comparisons in the current study because there were only 6 eyes in the sclero-corneal incision group. In the current study, all patients were instilled the topical fluoroquinolone after cataract surgery. To the best of our knowledge, there has been no report about the effects of topical fluoroquinolone on corneal stiffness, however, this medication could affect the corneal stiffness parameters. All data analysed in the current study were inherited from our prior study\textsuperscript{6} in which 59 eyes of 59 patients were investigated. In the current study, data from the original version of the CST software (ver.1.02.r1092) were transformed to the newest software (version 1.3r1538), however, data from 20 eyes of 20 patients could not be transformed.

Careful consideration should be given when interpreting the current results because the measurement area of CST is the apex of the cornea and the apical movement is also a result of the peripheral cornea and sclera. Thus, the current results may be attributed to the corneal edema, peripheral corneal or scleral wound, and general (material) corneal stiffness.
Unfortunately, it is not possible to separate out these effects. However, the corneal edema would be much less influential on the CST measurements at 3M after cataract surgery compared to 1W and 1M, and the change at 3M would not be predominantly explained by the corneal edema. As a result, the changes observed at 3M (increased DA max and integrated radius and decreased SP A1) are probably not explained by the corneal edema. Nonetheless, it is still impossible to fully discriminate the influences of the peripheral corneal or scleral wound and general (material) corneal stiffness, even at this time. This does not deny the clinical implications of our study because changes in corneal stiffness (irrespective of the causes) can have an effect on measured-IOP.

In conclusion, corneal biomechanical properties are changed after cataract surgery. In particular, SP A1 is decreased while DA max and integrated radius are increased, even 3M after surgery, which suggest the cornea becomes less stiff. These changes in corneal biomechanical properties may be one of the reasons for a decrease in GAT measured IOP after cataract surgery. Nonetheless, these changes in corneal stiffness cannot entirely explain the reduction in IOP since bIOP, which is adjusted for corneal biomechanical properties, was also decreased.
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Figure legends

Figure 1. Corneal movement during CorvisST (CST) tonometer air puff and description of CST parameters.
(A) corneal movement during CST air puff (I to V) and description of each CST parameter including deformation amplitude (DA) max and DA ratio max 1mm and 2mm. (B) description of Integrated radius which represents the area under the curve of the Inverse Concave Radius. (C) calculation method for Ambrosio Relational Thickness to the horizontal profile (ARTh).21

Figure 2. Changes in ocular measurements following cataract surgery.
DA: Deformation amplitude, ARTh: Ambrosio Relational Thickness to the horizontal profile, SP A1: Stiffness parameter at applanation 1, CBI: Corvis biomechanical index, CCT: Central corneal thickness, GAT: Goldmann applanation tonometer, IOP: intraocular pressure, IOPnct: non-corrected IOP, and bIOP: biomechanically corrected IOP. Each bar graph show the results from linear mixed modelling with adjustment for both bIOP and CCT. CCT and IOPs were adjusted with only bIOP and CCT, respectively. *: p value less than 0.05, **: p value less than 0.01.
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<tr>
<td>Age (years)</td>
<td>73.3 ± 6.6</td>
<td>60 to 90</td>
</tr>
<tr>
<td>Corneal radius (mm)</td>
<td>7.52 ± 0.23</td>
<td>7.05 to 7.93</td>
</tr>
<tr>
<td>Axial length (mm)</td>
<td>23.55 ± 1.22</td>
<td>21.57 to 26.41</td>
</tr>
<tr>
<td>GAT (mmHg)</td>
<td>16.5 ± 4.0</td>
<td>8.0 to 25.0</td>
</tr>
</tbody>
</table>

GAT: Goldmann applanation tonometer.
Table 2. Ocular measurements before and after cataract surgery.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pre</th>
<th>1W</th>
<th>1M</th>
<th>3M</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-1W</td>
<td>Pre-1M</td>
<td>Pre-3M</td>
<td>1W-1M</td>
<td>1W-3M</td>
</tr>
<tr>
<td>DA max (mm)</td>
<td>1.14±0.11</td>
<td>1.15±0.10</td>
<td>1.18±0.10</td>
<td>1.21±0.11</td>
<td>&lt;0.05†</td>
</tr>
<tr>
<td>DA ratio max 2mm</td>
<td>4.42±0.33</td>
<td>4.48±0.90</td>
<td>4.57±0.93</td>
<td>4.52±0.34</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>DA ratio max 1mm</td>
<td>1.57±0.04</td>
<td>1.56±0.04</td>
<td>1.57±0.04</td>
<td>1.57±0.04</td>
<td>&lt;0.01†</td>
</tr>
<tr>
<td>Integrated radius (mm⁻¹)</td>
<td>8.52±0.86</td>
<td>8.62±0.85</td>
<td>8.76±0.85</td>
<td>8.88±0.85</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>ART_h</td>
<td>552.5±160.0</td>
<td>485.9±130.5</td>
<td>490.2±118.6</td>
<td>524.1±125.5</td>
<td>&lt;0.01†</td>
</tr>
<tr>
<td>SP A1</td>
<td>98.4±22.5</td>
<td>92.2±19.1</td>
<td>91.1±18.9</td>
<td>90.0±18.3</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>CBI</td>
<td>0.15±0.29</td>
<td>0.24±0.33</td>
<td>0.21±0.30</td>
<td>0.15±0.23</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>CCT (µm)</td>
<td>555.6±30.0</td>
<td>565.8±33.4</td>
<td>559.2±31.9</td>
<td>559.5±31.2</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>GAT (mmHg)</td>
<td>16.5±4.0</td>
<td>15.8±3.4</td>
<td>15.5±2.8</td>
<td>12.6±2.8</td>
<td>&lt;0.05†</td>
</tr>
<tr>
<td>CT-90A (mmHg)</td>
<td>14.3±3.0</td>
<td>13.9±2.9</td>
<td>12.8±2.2</td>
<td>12.2±2.3</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>IOPnct (mmHg)</td>
<td>13.7±3.4</td>
<td>13.0±3.1</td>
<td>12.5±2.8</td>
<td>12.4±2.7</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>bIOP (mmHg)</td>
<td>11.8±3.0</td>
<td>10.9±2.7</td>
<td>10.7±2.4</td>
<td>10.6±2.5</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

DA: Deformation amplitude, ART_h: Ambrosio Relational Thickness to the horizontal profile, SP A1: Stiffness parameter at applanation 1, CBI: Corvis biomechanical index, CCT: Central corneal thickness, GAT: Goldmann applanation tonometer, IOP: intraocular pressure, IOPnct: non-corrected IOP, and bIOP: biomechanically corrected IOP.

Data are expressed as mean ± standard deviation, and p values less than 0.05 are written in bold and italics.

† unadjusted linear mixed model.

† linear mixed model with adjustment for bIOP.

§ linear mixed model with adjustment for bIOP and CCT.

¶ linear mixed model with adjustment for CCT.
A. General movement during air puff

1. Point to air puff application
2. Puff application: A1
3. 1 frame before puff arrival
4. Post application: A1
5. Post application: A2
6. Imminent to air puff application

B. Integrated radius

C. ART1

1. Calculate: multiplying value (PI) at le to AA
2. Calculate: ratio of eccentric value at peak
3. ANOVA: on 'highest point (PI)' / averages of 2
- Corvis ST measured corneal biomechanical properties change after cataract surgery.
- SP A1 decreases while DA max and integrated radius increase after cataract surgery.
- These changes suggest a less stiff cornea after cataract surgery.
- Goldmann applanation tonometry measured intraocular pressure was deceased.
- Corvis ST’s bIOP was also decreased.
Corvis ST measured corneal biomechanical properties change after cataract surgery; SP A1 decreases while DA max and integrated radius increase after cataract surgery, suggesting a less stiff cornea after cataract surgery. Goldmann applanation tonometry measured intraocular pressure was deceased. Corvis ST's bIOP was also decreased.
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