The cause of increased outflow resistance leading to ocular hypertension in glaucoma remains unknown. However, several intriguing studies suggest that human trabecular meshwork (hTM) stiffness may differ in glaucomatous versus unaffected eyes. These studies raise the possibility that TM stiffness might be involved in the pathogenesis of ocular hypertension in glaucoma. Last et al., in an important early study, used atomic force microscopy (AFM) in dissected TM samples from postmortem eyes to show that TM stiffness was markedly elevated in glaucomatous versus normal eyes. Subsequently, Camras et al. examined the tensile stiffness of dissected human TM via uniaxial testing. This study found that the glaucomatous TM was softer than normal TM, contrary to the results of the AFM testing. This discrepancy might be in part due to different testing modes used (tension versus compression). Johnson et al. (IOVS 2015;56:ARVO E-Abstract 3541) estimated hTM stiffness in vivo in normal eyes using OCT imaging and an indirect method based on changes in TM geometry. In all of the above studies, there were methodologic concerns, including dissection that may have damaged/alked the TM; different mechanical loading conditions that in some cases did not replicate the loads that occur in vivo; and/or oversimplified modeling assumptions. In view of the limitations of the above studies, it is important to explore alternate approaches for TM stiffness estimation to determine whether TM stiffness is truly altered in eyes with ocular hypertension.

Optical coherence tomography (OCT) is a cross-sectional, three-dimensional imaging technique with high spatial resolution (<20 μm). Recent studies have used OCT for characterization of tissue structure and movement inside the eye. Specifically, spectral domain OCT (SD-OCT) was used to image radial limbal segments in ex vivo primate eyes. A cannula was inserted into Schlemm’s canal (SC) to control pressure inside SC lumen. A pressure gradient was introduced across the TM that differed from the gradient expected due to standing, sitting, supine, or prone positions. Instead, pressure gradients were typical of those encountered during body inversion (e.g., gymnastics and yoga) and the spectrum of partial inversions.
that occur in daily life, SD-OCT was able to capture the dynamic motion of the TM, SC, and collector channels (CCs) as SC luminal pressure was changed.

The inverse finite element method (FEM) is a computer modeling technique that has been widely used to estimate tissue biomechanical properties. The basic idea behind inverse FEM is to select input parameters for computational simulations that minimize the difference(s) between simulated and measured outcomes (e.g., tissue displacement and strain), thereby allowing indirect determination of such parameter values from experimental data. 12–14

The goal of this paper was to determine human TM stiffness in normal and glaucomatous eyes using a novel approach combining OCT and the inverse FEM. We reasoned that this technique would be less disruptive to TM structure than previous approaches. Additionally, we carried out en face AFM stiffness measurements on the same hTM samples to compare with results obtained from the OCT/inverse FEM approach. Finally, stiffness data were correlated with outflow facility in some eyes.

METHODS

In brief, human eyes were obtained from eye banks, and anterior segments were perfused in Portland at Oregon Health & Science University under organ culture conditions 15 to measure outflow facility and identify high- and low-flow (HF, LF) regions of the TM. Anterior segment HF and LF wedges in culture medium were then sent on ice to Seattle by overnight express for 1 hour prior to termination of flow experiments. HF and LF wedges approximately 4 mm wide were cut, based on relative CellMask staining intensity, and sent to Seattle for OCT scanning. OCT scanning was performed the following day using the same formulation of culture media used at Oregon Health & Science University.

OCT

Anterior segment wedges encompassing the cornea, limbal region with TM, SC, and approximately 5 mm of sclera were mounted in a petri dish with pins, with the inner TM surface facing upward. The entire wedge was submerged in a saline bath, eliminating possible surface tension effects on the open end of SC. This uniform and stable saline bath surface also helped to eliminate surface motion artifacts when dynamic TM motion occurred (Fig. 1). A crucial factor in the protocol was a previously described custom-made steeply tapered and flexible insertion cannula fashioned from PE 60 tubing with an outside diameter of 1.22 mm, a taper length of 4.5 mm, and an outside diameter at the tip of 130 to 150 μm that provided a tight fit when inserted into the SC.

The cannula was inserted into SC with the help of a dissecting microscope and a micromanipulator while the other end remained free (open). The tip of the cannula slid into, and made a tight contact with, the canal lumen. The other end of the cannula was connected to a reservoir filled with saline, so that SC lumen pressure could be controlled by changing the height of the reservoir. To capture the dynamic movement of tissues along the SC lumen at high resolution, the SD-OCT imaging probe was adjusted to face the TM. A series of cross-sectional scans of the wedge were captured at multiple locations for different reservoir pressures (e.g., 0, 5, 10, 20, 30, and 50 mm Hg). The distance between two adjacent scans was about 10 μm. The central wavelength of the SD-OCT system was 1310 nm, and the spatial resolution in each scan was 5.75 μm in the axial and lateral dimensions, respectively. The imaging was performed through air without the OCT probe touching the sample. The system was capable of an imaging speed of 92 kHz (i.e., 92,000 A-scans/s). At this speed, a system sensitivity (or dynamic range) of 105 dB was measured when the light power on the sample was 5 mW. Thus, for each location along TM/SC (typically one to three random locations were scanned for each wedge), a set of images were obtained for assessment of tissue configuration at several pressure levels (Fig. 1).

Inverse FEM

For two to three wedges per eye and one to three cross-sectional locations per wedge, we created a pseudo–two-dimensional (2D) FEM geometry in Abaqus (version 6.16; Simulia Corp., Providence, RI, USA). This pseudo-2D model was formed by “extruding” the 2D cross section for a distance of 10 μm from a single OCT scan at a low SC pressure (Fig. 2). OCT scans were used only if a clear, open SC lumen could be identified.

In more detail, tissue components including TM, SC, sclera/cornea, and ciliary body (CB) were first delineated from the OCT scan and verified by one coauthor (MAJ) by carefully looking at the relative deformation of outflow tissues from the 3D OCT videos of SC lumen during the pressurization interval. The model was then meshed with eight-node hexahedral
CB contains the ciliary muscle, vessels, and fibrous connective tissue. Poisson’s ratio was assumed to be 0.5. Fortunately, a sensitivity analysis (see Supplementary Materials) demonstrated that the assumed CB stiffness value had a limited impact on the resulting estimated TM stiffness. Unlike the rest of the tissue components, the stiffness of the TM (E) was allowed to vary over a range of values, typically from 18 to 300 kPa.

Loading conditions were specified based on those that were imposed experimentally. The plane strain assumption was made when imposing boundary conditions, suitable for the case in which SC cross-sectional shape changed slowly over axial distances comparable to the characteristic dimensions of the SC cross section. The bottom surface of sclera was fixed in all three directions, and one of the two side faces containing TM and SC was fixed in its normal direction. A pressure load was applied to the walls of SC lumen, carefully corrected for losses in the delivery tubing, the cannula, and the distance from the tip of cannula to the OCT scan location (see Supplementary Materials). Due to the small cross-sectional area of the SC lumen, most of the computed pressure drop typically occurred within SC. Young’s modulus for TM was allowed to vary over a certain range in steps of 6 kPa, and tissue deformations were computed for each TM stiffness using the open source FEBio package (version 2.2.2; Musculoskeletal Research Lab at the University of Utah, Salt Lake City, UT, USA). Differences in SC lumen size (area) between simulations and experiments were then calculated as

$$\text{Area difference} = \sqrt{(\text{Area}_{\text{OCT}} - \text{Area}_{\text{FEM}})^2}$$ (2)

where subscripts “OCT” and “FEM” refer to experimentally measured and numerically simulated cross-sectional areas, respectively. The TM stiffness value that gave the minimum difference in SC cross-sectional area was then taken as the estimated local TM stiffness for that model/cross section (Fig. 5).

As a quality control step, SC lumen contours were compared between OCT images and simulations at the corresponding elevated pressure (Fig. 3, left). We excluded a total of two quadrants when the match in contour shape was poor even if the SC cross-sectional area agreed well between the numerical simulation and the experimental data (Fig. 4).

Finally, the average value of estimated TM stiffness over all modeled quadrants in one eye was taken as the TM stiffness of that eye.

Figure 2. (Upper) Representative OCT image at a low SC luminal pressure (here, 0 mm Hg) with delineated tissue structures superimposed. (Bottom) Geometry created in ABAQUS with mesh superimposed. The total number of hexahedral elements for this mesh was 55,358, with typical edge lengths from 5 to 10 \(\mu\text{m}\). Scale bar: 250 \(\mu\text{m}\). Sample: inferior temporal quadrant of eye 77R.

Figure 3. Comparison between SC contours as measured by OCT and as computed for a range of TM stiffnesses. (Left) SC contours at reservoir pressures of 0 mm Hg and 20 mm Hg are shown in red and black, respectively. The trabecular meshwork lies above SC lumen, with sclera immediately below. The blue dots represent a set of computed SC contours from simulations at 20 mm Hg over a range of TM stiffnesses. Blue dots are not visible along the lower portion of the figure because there was essentially no computed deformation of the SC outer wall (i.e., blue dots are overlain by the red dots in this region). (Right) Quantification of SC lumen area difference, as computed from equation 2, at a reservoir pressure of 20 mm Hg for different numerically specified Young’s moduli for the TM (x-axis). A minimum difference was observed at 48 kPa, which was therefore taken as the best estimate of Young’s modulus for the TM at this location. Scale bar: 50 \(\mu\text{m}\). Sample: inferior temporal quadrant of eye 77R.
AFM

The wedges, immersed into centrifuge tubes containing organ culture media, were then shipped overnight from Seattle to Atlanta on wet ice (typical postmortem time on receipt: 15 days). Upon receipt, each wedge was glued (Super glue; Loctite, Düsseldorf, Germany) onto a Petri dish with the same orientation as in the OCT experiment (glue was applied at the three corners of the wedge which were far from the limbal region). Samples were transferred to an MFD-3D AFM (Asylum Research, Santa Barbara, CA, USA) and immersed into the same organ culture media. Silicon nitride cantilevers with an attached borosilicate sphere (radius, 5 μm; nominal spring constant, 0.1 N/m; Novascan Technologies, Inc., Ames, IA, USA) were used. Cantilevers were calibrated by measuring the thermally induced motion of the unloaded cantilever before measurements. A series of forcemaps were obtained in regions located along a line starting on the cornea and ending on the sclera. The starting location for this line was determined visually with the aid of markers on the Petri dish. Specifically, the markers were several grids which were drawn on the bottom of the Petri dishes using a permanent marker that could be seen through the transparent cornea. Even with marker’s help, there was still some uncertainty in measurement location due to the thickness of the samples. When observed from the bottom camera, the cantilever tip and tissue were usually not focused on the same plane. Thus, the desired measurement location and the cantilever tip may not have been in the same spot. To estimate the uncertainty in measurement location, the cantilever tip was first moved to barely touch the surface of a glass slide and the bottom camera was focused on that surface. Then the cantilever tip was raised by 0.8 mm (typical wedge thickness at the limbus) and the camera was refocused on the cantilever tip. The distance between cantilever tip before and after the refocusing was used to estimate the uncertainty of the measurement location.

Each forcemap region consisted of 16 force curves in a 4 × 4 grid covering a scan region of 20 × 20 μm. The center-to-center distance between adjacent forcemap regions was 20 to 80 μm. Each force curve was taken at a rate of 8 μm/s, and a typical indentation depth was 0.5 to 1 μm. For the 16 force curves in each forcemap region, those lacking either linear behavior or a clear cantilever contact point were discarded from the analysis. The remaining force curves were fit to a Hertz model (Equation 3) for a sphere in contact with a flat surface to determine the local compressive modulus (version 6.34A; Igor Pro software, Portland, OR, USA) (Fig. 5).

\[ E = \frac{3(1 - \nu^2)F}{4R^3/2\delta^{3/2}} \]  

In Equation 3, E is Young’s modulus, F is the force applied by cantilever bending, R is the radius of the sphere on the cantilever tip, \( \delta \) is the actual sample indentation, and \( \nu \) is the sample’s Poisson’s ratio, taken as 0.5. In Figure 5, the force experienced by the cantilever tip is zero when the cantilever is far from the sample surface. The force increases as the cantilever tip touches and indents the sample surface. The cantilever starts to retract once it reaches a maximum force, leading to a decreasing force.

The average modulus from the valid measurement points within a forcemap region was taken as the compressive modulus of that region. These moduli from all forcemap regions in one sample were then plotted as a function of region location along the measurement line (cornea to sclera). The TM region was putatively defined as the anterior-most pigmented area that was adjacent to the cornea plus the narrow white band, representing the scleral spur (shown as the region between the two dashed lines in Fig. 6). The mean of the modulus values along the measurement line traversing the TM region was taken as the TM stiffness of that location. Typically, two to three such locations were measured for each sample.
TABLE 1. TM Stiffness in Normal and Glaucmatous Human Eyes Obtained by Inverse FEM and AFM

<table>
<thead>
<tr>
<th>Identifiers</th>
<th>E, Young’s modulus; IN, inferior nasal; IT, inferior temple; ND, not determined; PT, postmortem time from death to stationary culture in Portland; SN, superior nasal; ST, superior temple; ( ), discarded value.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye No.</td>
<td>Age, y</td>
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<tr>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>Normal Eyes</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>77R</td>
</tr>
<tr>
<td>2</td>
<td>80R</td>
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<tr>
<td>3</td>
<td>111</td>
</tr>
<tr>
<td>4</td>
<td>115</td>
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<tr>
<td>5</td>
<td>116</td>
</tr>
<tr>
<td>6</td>
<td>124</td>
</tr>
<tr>
<td>Glaucmatous eyes</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>118</td>
</tr>
<tr>
<td>2</td>
<td>121</td>
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<tr>
<td>3</td>
<td>122</td>
</tr>
<tr>
<td>4</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>126</td>
</tr>
</tbody>
</table>

* Eyes from the same individual.

Results

TM stiffnesses for six normal and four glaucomatous human eyes were successfully estimated using the inverse FEM method (Table 1). We were unable to use this approach for one eye (121), as it was discarded due to the lack of a clear and open SC lumen at the OCT scan locations. Elastic modulus determined in this way in normal hTM ranged from 42 to 102 kPa (mean, 70 ± 20 kPa; Table 1), whereas glaucomatous hTM samples had slightly larger elastic moduli, ranging from 79 to 123 kPa (mean, 98 ± 19 kPa; Table 1).

This trend of a slightly stiffer glaucomatous TM was consistent with TM stiffness measured by AFM, where hTM stiffness in normal eyes (mean, 1.57 ± 0.56 kPa) was lower than that in glaucomatous eyes (mean, 2.75 ± 1.19 kPa). AFM measurements were performed on a total of four normal and five glaucomatous human eyes. We were unable to make stiffness measurements on two of the six normal eyes due to logistical issues. None of the above differences between normal and glaucomatous TM stiffness reached statistical significance (Mann-Whitney U test: FEM, P = 0.051; AFM, P = 0.127); however, we suggest it is reasonable to call the P value of 0.051 associated with the difference in TM stiffness estimated by inverse FEM a “borderline significant” result.

TM stiffness measured by AFM was approximately 1/40 of that estimated by inverse FEM. This difference is almost certainly due, at least in part, to different modes of testing (compressive in AFM versus primarily tensile by SC luminal pressurization), because it is known that the type of mechanical load applied to a tissue can result in very different mechanical behavior. Specifically, soft tissues are usually much stiffer in tension, consistent with our results. Further, the length scales of the two measurement techniques were quite different, which could contribute to the discrepancy. The FEM involved deformation of the entire TM, whereas AFM measurements were very local. It has been reported that elastic properties of soft tissues can strongly depend on the length scale of the measurement technique, because different tissue structural components can be involved at different length scales.11 We examined the correlation between TM stiffnesses determined by inverse FEM and that determined by AFM (Fig. 7). Interestingly, there was a strong positive correlation (P = 0.0099) between TM stiffness measured by AFM and that estimated by inverse FEM (n = 8: 4 normal and 4 glaucomatous eyes were both measured by FEM and AFM). From the above evidence, it appears that combining numerical modeling and OCT has the potential to provide an alternative indirect approach to assess hTM stiffness, which does not require excision of the TM.

Outflow facility (Cpf) was measured for four normal and five glaucomatous eyes (Table 1). We excluded Cpf values for two
eyes (eyes 125 and 126) from further analysis because, although they were documented as glaucomatous eyes, they had abnormally high facilities (0.54 and 0.46 μL/min mm Hg, respectively).22,23 After excluding these eyes, Cpf of normal eyes was higher (0.24 ± 0.15 μL/min mm Hg) compared with that in glaucomatous eyes (0.15 ± 0.02 μL/min mm Hg), but this difference did not reach statistical significance. We then plotted Cpf versus TM stiffness as estimated by inverse FEM (Fig. 8). Despite the limited number of eyes (n = 6), the Cpf and TM stiffness were significantly correlated (P = 0.018; r² = 0.79), suggesting that nearly 80% of the variation in Cpf was associated with variation in TM stiffness. None of the two eyes were from the same individual, so that the statistical confounding effect of nonindependence of paired eyes was avoided.

TM stiffness in HF and LF regions was also compared for both normal and glaucomatous eyes (Fig. 9). TM stiffness determined by inverse FEM was higher in LF wedges than that in HF wedges, both in normal and glaucomatous eyes. However, AFM measurements did not show the same trend. In fact, on average, AFM measurements of TM stiffness in HF wedges were close or even higher than those in LF wedges.

**DISCUSSION**

This study estimated the stiffness of hTM in normal and glaucomatous eyes using an inverse FEM approach while also performing AFM on the same tissues. Our results indicated that TM stiffness is slightly greater in glaucomatous eyes compared with that in normal eyes, which is qualitatively consistent with the previous study of Last et al.2 However, it is extremely important to note that stiffness differences that we observed did not reach statistical significance, and the TM stiffnesses of glaucomatous eyes measured by AFM were of much smaller magnitude than those observed by Last et al.2 Thus, our results were not quantitatively consistent with those of Last et al.2 This is most likely due to methodological differences: Last et al.2 dissected the TM and measured the stiffness of the outermost part of the tissue, whereas we used intact wedges and measured the stiffness of the innermost aspects of the tissue.

It is also important to point out that differences in Cpf between the normal and glaucomatous eyes did not reach statistical significance. In fact, some of the “glaucomatous” eyes had facilities that were much higher than that in “normal” eyes. This may indicate an inaccurate classification of the donated eyes; all patients that the eye bank reported as having glaucoma were included in our study as glaucomatous eyes. Some “glaucoma” eyes may have been from patients with normal tension glaucoma without an outflow system abnormality, and/or the facility may have been affected by long-term use of antiglaucoma medication (e.g., prostaglandin analogs).24–28 However, it is of interest that we did observe a statistically significant correlation between Cpf and hTM stiffness when the data were pooled from all eyes. This suggests that these factors are highly associated in both normal and glaucomatous eyes, although perhaps to a lesser extent than originally suggested by the study of Last et al.2

We also point out that the hTM stiffness determined by the inverse FEM method cannot be directly quantitatively compared with that measured by AFM, even though the two were correlated. This is because several factors differ between the two methods, including how the load is applied to the tissue. In the OCT experiments the TM was primarily in tension, whereas in the AFM studies, the TM was primarily in compression. Soft tissues, such as the TM, can be orders of magnitude softer when loaded in compression versus when they are loaded in tension. Thus, in our study, the Young’s modulus deduced by inverse FEM can be interpreted as a general indication of the TM tensile stiffness, whereas the modulus obtained by AFM tends to reveal the local compressive stiffness of the inner uveal meshwork. However, comparison of differences between normal and glaucoma hTM stiffness within a measurement method should remain valid.

Compared with other data in the literature for hTM (Table 2), our estimated FEM mean hTM stiffness value is close to that measured by Johnson et al. (IOVS 2015;56:ARVO E-Abstract 3541). Instead of direct measurement on TM, Johnson et al. used a beam-bending model to predict TM stiffness based on in vivo changes in TM and SC thickness which were visualized by OCT as intraocular pressure (IOP) was elevated. In that study, the pressure load was applied from the anterior chamber side.
not the SC side in our FEM approach. However, in both studies, the TM was in tension along a direction which is perpendicular to SC lumen. For AFM results, our measured TM stiffness of normal eyes was on the same scale but slightly lower than that measured by Last et al., and much less than that measured by Camras et al. In Camras’ study, the whole dissected TM were stretched in a direction parallel to SC with elastic connections disrupted, whereas in our studies and those of Last et al., the TM was compressed locally from different side of TM. However, our measurements were done on an intact wedge where elastic connections to scleral spur should be well preserved, as well as any interactions with cornea and to the outer all of SC.

There are several limitations of our study. First, steady-state IOP is usually greater than steady-state SC luminal pressure (i.e., IOP normally ranges from 10 to 20 mm Hg and episcleral venous pressure [EVP] is 7.6 to 11.4 mm Hg). The experimental pressurization of SC lumen created a pressure gradient in the opposite direction. However, it must be recalled that EVP and SC pressure are both highly dynamic. For example, activities such as gymnastics and yoga frequently involve body inversion, and a spectrum of partial inversions is present in many activities. With full inversion, EVP rises with a resultant increase in SC pressure and entry of blood into SC. An IOP increase occurs within seconds with IOP increasing to as much as 43 mm Hg. Syndromes that cause SC to be disrupted, whereas in our studies and those of Last et al., the TM was compressed locally from different side of TM. However, our measurements were done on an intact wedge where elastic connections to scleral spur should be well preserved, as well as any interactions with cornea and to the outer all of SC.

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there is a clear need to improve access to well-documented human eye tissue. For example, there may be eyes with normal-tension glaucoma that simply appear with the diagnosis of glaucoma on medical records. Such patients have normal IOPs and thus ostensibly normal TM function, and thus should not be included in the glaucoma group in our study.

In conclusion, our data suggest that differences in perfusion outflow facility in both normal and glaucomatous human eyes are correlated with differences in TM stiffness. These data provide a motivation for initiating further studies to identify mechanisms responsible for varying TM stiffness, particularly the altered stiffness in glaucomatous eyes.

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