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Application of the Cylindrical-Gaussian Form Factor for Collagen Fiber Assessment

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1. Introduction

Myopia, also known as near-sightedness is one of the common eye disorders. While myopia is not often a significant cause for concern when mild, eyes with high myopia (HM, defined as more than -6.0 diopters (D) of near sightedness) can progress to pathologic myopia, with up to 70% of patients threatened with blindness or visual impairment. As myopia progresses, posterior eye elongation is caused by changes in the microstructural properties of the sclera including decreased collagen and fibril diameters. High-frequency quantitative ultrasound (QUS) allows non-invasive measures of biomechanical parameters associated with changes in tissue microstructure.

In a previous study, QUS parameters were obtained by applying a spherical Gaussian scattering model. However, this model did not appropriately model the elongated collagen fiber geometry. Present study applies a cylindrical Gaussian scattering model to data acquired from guinea pig (GP) eyes.

2. Materials and Methods

2.1. Animals

Form-deprivation myopia (FDM) was induced in young GPs by diffusers worn over the right eye from 6 days of age for 1, 2 or 3 weeks (n = 3, 5 and 4 animals respectively). Untreated paired left eyes were used as controls. On the last day of treatment, cycloplegic spherical equivalent refractive error (SERE) and axial length (AxL) were measured. Within minutes after the eye enucleation, the eye was flash-frozen and stored at -80C until thawed immediately prior to ultrasound measurement. All procedures were approved under Australian animal ethics legislative requirements and adhered to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.

2.2. Procedures

The eye was immersed in PBS with posterior pole facing up to minimize ultrasound attenuation. To mimic *in-vivo* conditions, the eye was suspended with partial thickness corneal sutures to orient the eye with near zero-tension. Three-dimensional radio-frequency (RF) data was acquired with an 80-MHz single element transducer. The transducer had a focal length of 2.2 mm, an F-number of 2, and a -6-dB bandwidth extending from 41 to 109 MHz.

The RF data set was separated into 3-D rectangular regions-of-interest (ROIs) having lengths of 232 μm (i.e. x 7 beamwidth) in lateral x 232 μm in the slice x 120 μm (i.e. x 6.5 wavelength) in the depth directions. Parameter estimations were performed within the segmented sclerarl region. To evaluate myopia effects on QUS parameters, statistical tests were performed (i.e., paired t-test, and Kruskal-Wallis test).

2.3. Cylindrical-Gaussian model

This study introduces the cylindrical-Gaussian scattering model assuming the collagen fibers, the main scattering source, shapes the infinitely long cylinders. Measured back scattered coefficient (BSC_{meas}) was obtained following to the normalization with the reference phantom method [1]. The theoretical BSC (BSC_{theo}) is formulated as the product of the BSC in the Rayleigh limit and the backscatter form factor [2]. Because of the infinity-long cylindrical shape, this model only considers the scattering within the unit-cross sectional area. Estimated QUS parameters (Effective scatterer diameter (ESD) and effective acoustic concentration (EAC)) were obtained by the linear fitting approach [3]. The ESD and EAC parameters using a standard spherical-Gaussian model were also computed for comparison.

3. Results

Fig. 1 depicts the representative linear fitting plot of the BSC_{theo} and BSC_{meas}. The estimated ESD with the cylindrical-Guassian model was 6.42 μm and 5.59 μm with the spherical-Gaussian model. Root-mean-square error within the frequency band was 1.42 (cylindrical) and 1.25 (spherical), which yields a comparable fitting result with the proposed model. **Fig. 2** illustrates the representative ESD of

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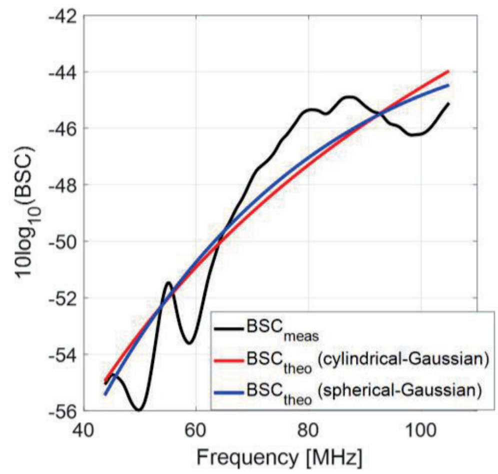

Fig. 1 Representative measured backscattered coefficient (black) fitting with the proposed cylindrical-Gaussian model (red) and the conventional spherical-Gaussian model (blue).

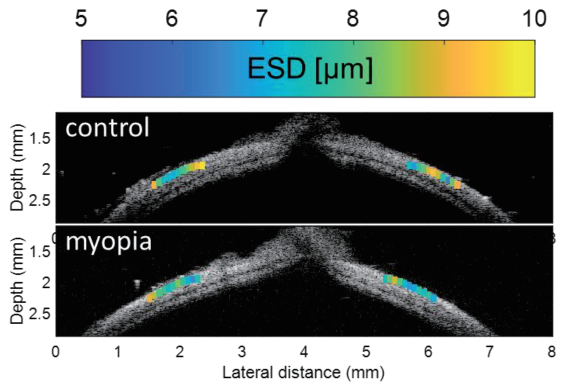

Fig. 2 Representative parametric images of the effective scatter diameter (ESD) images from the three weeks of form-deprived myopia model (bottom) and paired control eye (top) overlayed on the ultrasound B-scan.

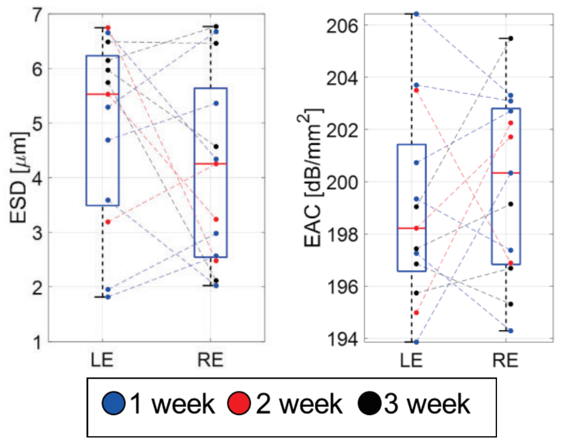

Fig. 3 Boxplot of the averaged ESD and EAC values. Each dot represents each eye, color means the treatment duration, and the dashed line represents the changes in the paired control eyes.

three-week treated paired individual calculated with the cylindrical-Gaussian model. Estimated BSC was decreased with the myopia treatment with the increasing variance of the parameter. **Fig.3** summarizes the changes in the parameters between paired eyes. The interocular difference did not reach statistical significance with the collapsed dataset ($p = 0.17$ for ESD, $p = 0.47$ for EAC). However, the ESD in two weeks and three weeks significantly decreased compared to the control eyes, which is likely to relate to the reported decreased collagen fibril diameters and greater fiber bundle dissociations.

4. Conclusions

This study introduces the cylindrical-Gaussian model for the QUS parameter analysis to characterize the collagen-rich scleral tissue in myopic eyes. The results shows the proposed model yields a comparable estimation with the conventional spherical-Gaussian model. More importantly, the cylindrical-Gaussian model is more biologically reasonable for the application to the fiber-rich structure, and could be a valuable alternative for the assessment of the changes in the scleral collagen fiber in myopic eyes. In conclusion, the proposed cylindrical-Gaussian model has the potential to quantitatively characterize microstructural changes that occur in the posterior sclera during myopia development and/or progression.

Acknowledgments

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