



City Research Online

City St George's, University of London

Citation: Ctori, I., Gruppeta, S. & Huntjens, B. (2015). The effects of ocular magnification on Spectralis spectral domain optical coherence tomography scan length. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 253(5), pp. 733-738. doi: 10.1007/s00417-014-2915-9

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: <https://city-ref-test.eprints-hosting.org/id/eprint/5850/>

Link to published version: <https://doi.org/10.1007/s00417-014-2915-9>

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to [City Research Online policy](#).

**Title: The effects of ocular magnification on Spectralis spectral domain
optical coherence tomography scan length**

Irene Ctori (1), Stephen Gruppetta (1) and Byki Huntjens (1*),

1. Applied Vision Research Centre, The Henry Wellcome Laboratories for
Vision Sciences, City University London, Northampton Square, London,
EC1V 0HB, UK

E-Mail:

Irene.Ctori.2@city.ac.uk

Steve.Gruppetta.1@city.ac.uk

Byki.Huntjens.1@city.ac.uk;

* Corresponding author:

Byki.Huntjens.1@city.ac.uk

Tel.: +44-20-7040-0145

Fax: +44-20-7040-8355 (not private)

The final publication is available at

<http://link.springer.com/article/10.1007/s00417-014-2915-9>

Abstract (180 words)

Purpose: To assess the effects of incorporating individual ocular biometry measures of corneal curvature, refractive error and axial length on scan length obtained using Spectralis spectral domain optical coherence tomography (SD-OCT).

Methods: Two SD-OCT scans were acquired for 50 eyes of 50 healthy participants, first using the Spectralis default keratometry (K) setting, then incorporating individual mean-K values. Resulting scan lengths were compared to predicted scan lengths produced by image simulation software based on individual ocular biometry measures including axial length.

Results: Axial length varied from 21.41 to 29.04mm. Spectralis SD-OCT scan lengths obtained with default-K ranged from 5.7 to 7.3mm and with mean-K 5.6 to 7.6mm. We report a stronger correlation of simulated scan lengths incorporating the subject's mean-K value ($\rho = 0.926$, $P < 0.0005$) compared to Spectralis default settings ($\rho = 0.663$, $P < 0.0005$).

Conclusions: Ocular magnification appears to be better accounted for when individual mean-K values are incorporated into Spectralis SD-OCT scan acquisition compared to using the device's default-K setting. This must be considered when taking area measurements and lateral measurements parallel to the retinal surface.

Key Words: Optical Coherence Tomography; axial length; scan length; Spectralis; keratometry.

Introduction

Optical Coherence Tomography (OCT) allows a direct cross-sectional view of the human retina [1] correlating well with retinal histology [2]. SD-OCT provides increased acquisition speed and higher image resolution compared to older time-domain OCT techniques [3,4]. OCT technology is increasingly employed in the clinical diagnosis of ocular pathology such as age-related macular degeneration [5], macular holes [6], vitreo-macular traction [7], and glaucoma [8]. Quantitative evaluation of retinal thickness using both automatic and manual measuring techniques is used to aid clinical diagnosis and design treatment protocols [9-11]. It is known that segmentation algorithms employed by individual OCT instruments result in variability in retinal thickness measurement complicating comparison across different platforms [12,13]. In addition, ocular magnification of retinal images is affected by refractive error, corneal curvature, refractive index, axial length and anterior chamber depth [14,15]. The distance of the eye to the measuring device can also influence the magnification effect [16]. In the case of OCT scan images, ocular magnification may affect lateral measurements i.e. those made parallel to the retinal plane [17]. The optical set-up of the OCT instrument as well as the software program for calculating image size will govern image size calculation in computerized fundus imaging [18]. If lateral measurements such as drusen diameter, geographical atrophy area in dry age-related macular degeneration or foveal width measurements for example are to be used for establishing diagnosis and treatment protocols, the potential impact of ocular magnification on lateral measurements must be considered.

70 An inverse correlation between retinal nerve fibre layer thickness, optic
71 nerve head parameters and axial length has been reported [19-22]. However,
72 these correlations became negligible when corrections accounting for axial
73 length were applied to the measured values [19,22,23]. This suggests that
74 axial length should be taken into account when assessing the reliability of
75 OCT data [24]. However, not all OCT platforms account for axial length
76 induced ocular magnification, and various attempts have been made to
77 correct for the magnification of an individual nominal scan length produced by
78 the OCT instrument [22]. In a study by Wagner-Schuman et al., a ratio of the
79 individual's axial length to that assumed by the instrument was applied to
80 lateral measurements [25]. Others have addressed the issue of lateral scaling
81 by applying a correction based on the SD-OCT instrument manufacturer's
82 formula using modified Littman's method [14], which incorporates individual
83 refractive error, corneal radius and axial length [22,26]. An alternative
84 approach used in studies of retinal morphology has been to exclude subjects
85 with refractive error greater than ± 5.00 or ± 6.00 DS to minimize potential
86 errors [27,28]. In contrast to these other SD-OCT platforms, the Spectralis
87 (Heidelberg Engineering, Heidelberg, Germany) applies an automatic
88 modification process to cancel out the effect of ocular magnification,
89 generating individual scan lengths based on three parameters. It assumes a
90 non-modifiable pre-set axial length of 24.385mm based on the Gullstrand
91 schematic eye [29] (personal communication with Heidelberg Engineering,
92 Germany; July 2013). Secondly, by allowing the operator to focus the retinal
93 image, the subject's refractive error is taken into account. Thirdly, a default
94 corneal curvature i.e. keratometry (K) setting of 7.70mm equal to the K-value

of Gullstrand's model eye [29] is assumed by the device, as described in its technical specifications. Alternatively, an option to use the subject's actual mean-K is provided. The present study was carried out to investigate the effect of individual mean spherical error (MSE), mean-K and axial length on B-scan length obtained using the Spectralis SD-OCT.

Methods

Study protocol

The study was conducted from October to December 2013 at the Division of Optometry and Visual Science, City University London. A total of 50 volunteers took part; all presented Log MAR visual acuity better than 0.3 log units in the eye being tested. Exclusion criteria were: ocular pathology, medication that may affect retinal function and previous laser eye surgery. By default, measurements were taken for the right eye unless it did not meet the inclusion criteria, in which case the left eye was used. Each participant had measures of MSE (based on an average of five autorefractor readings) and mean-K (average of three horizontal and vertical K readings) taken with the Auto Kerato-Refracto-Tonometer TRK-1P instrument (Topcon, Tokyo, Japan).

The Spectralis SD-OCT was used to scan the undilated test eye of each participant in a dark room [30,31]. Two high resolution 20° x 10° volume scans (97 B-scans 30 microns apart, ART 16 frames including 1024 A scans) were acquired for each participant. The first scan was obtained using the default corneal curvature setting of 7.70mm; while the second had the subject's mean-K entered into the software prior to scan acquisition. The participant was instructed to look at the central fixation target while the

infrared fundus image was focused with a dial corresponding to their MSE. During scan acquisition, the investigator independently monitored the participant's fixation via the live fundus image. All scans had a minimum quality level of 25 decibels, as recommended by the manufacturer guidelines. The resulting "default-K" and "mean-K" scan length was recorded from the Spectralis mapping software, Heidelberg Eye Explorer (Version 1.7.0.0 © 2011). Axial length was measured using the IOLMaster (Carl Zeiss Meditec, Dublin, CA, USA). This is a well-known non-contact device based on partial coherence interferometry shown to have good axial length measurement repeatability [32,33]. Zemax optical design software (Zemax, LLC, Redmond, WA, USA) was used for simulation of an image from a 20° SD-OCT incorporating individual subject's MSE, mean-K and axial length data. The Gullstrand's exact model eye [29] was applied to the simulation since Spectralis software image size calculations are based on this model. Within the Zemax model, mean-K values and axial length were modified for each subject by changing the radius of curvature of the anterior corneal surface and the axial distance between posterior lens surface and retinal plane respectively. MSE was modelled as a paraxial lens immediately before the model eye. An object with a field of 10° (with respect to the optical axis, resulting in 20° overall field) was set and the size of the image at the retinal plane calculated by the software was used to represent the simulated scan length. This was compared to the default-K and mean-K scan lengths.

Ethical approval and consent

The study was approved by Optometry Research & Ethics Committee City University London. Written informed consent was obtained from all subjects conforming to the tenets of the Declaration of Helsinki.

Statistical analysis

All statistical analyses were performed using SPSS version 21.0 for Windows (SPSS Inc., Chicago, USA). Values in the text and tables are presented as the mean $\pm$ standard deviation (SD). Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. Since Kolmogorov-Smirnov test revealed a significant deviation from a normal distribution for scan length and MSE, Spearman's Rank Correlation Coefficient ρ was calculated to explore the correlation between default-K and mean-K with simulated scan lengths. Statistical significance was accepted at $P < 0.05$.

Results

A total of 22 males and 28 females were included in the study. The mean age was 21 ± 2.9 years. Mean, minimum and maximum values of mean-K, MSE, axial length, and scan lengths are summarised in Table 1.

[insert Table 1 approximately here]

A Wilcoxon Signed Rank Test revealed a statistically significant difference in scan lengths obtained using default-K, mean-K and from simulations (Figure 1). There was a significant correlation between mean-K ($\rho = 0.926$, $P < 0.0005$) and default-K scan length with the simulated scan length ($\rho = 0.663$, $P < 0.0005$), shown in Figure 2. We explored the effect of axial length and

MSE on these relationships and found that the correlation between mean-K and simulated scan length remained strong and significant when controlling for axial length ($\rho = 0.822$, $P < 0.0005$) and for MSE ($\rho = 0.875$, $P < 0.0005$). The correlation was weakened for default-K measurements when controlling for axial length ($\rho = 0.473$, $P < 0.001$) and became non-significant when controlling for MSE ($\rho = 0.221$, $P = 0.128$).

[insert Figure 1 and Figure 2 approximately here]

Discussion

The Spectralis SD-OCT generates individual scan lengths based on refractive error, corneal curvature and a non-modifiable pre-set axial length of 24.385mm according to the Gullstrand schematic eye. We explored the correlation of Spectralis SD-OCT scan length acquired using the instrument's default-K setting of 7.70mm versus using the subject's mean-K, when compared to Zemax software simulated scan length. The aim was to ascertain whether the effect of ocular magnification on SD-OCT scan length was represented more accurately using an individual's mean-K value as opposed to the Spectralis default-K setting in comparison to simulated output based on Gullstrand exact eye model [20]. We included individuals with axial length of 21.41mm to 29.04mm resulting in mean-K scan lengths ranging from 5.6 to 7.7mm (Figure 1). Whilst direct comparisons cannot be drawn from other studies with different subject demographics, individual scan lengths ranging from 5.3 to 7.0mm have been reported whereby the nominal 6mm scan was corrected using each subject's axial length (varying from 21.56 to 28.36mm)

based on the Cirrus eye model [20]. Of note, the most accurate model eye to calculate ocular magnification has yet to be determined [18], although differences between modified Littman's technique [14] and the Gullstrand eye model are less than 2% for axial lengths from 22 to 26.5mm [34].

While there was significant correlation of mean-K ($p = 0.926$, $P < 0.0005$) and default-K scan length with the simulated scan length ($p = 0.663$, $P < 0.0005$), the correlation was much stronger for mean-K scan length. The within-subject SD of K measurements have been shown to range from 0.05mm to 0.18mm depending on the instrument used [35]. According to the Spectralis technical guidelines, a 0.1mm error in K will result in an error in lateral measurement of 0.8%. This translates to a 0.1mm change in scan length for every 0.2mm deviation from the individual's mean-K. The TRK-1P gives repeated measurements within $\pm 0.12DS$ on test eyes (personal communication with Topcon; June 2014) that may explain the lack of perfect agreement between the mean-K and simulated scan lengths in the current study. Another consideration is that subjective refraction was not carried out to estimate MSE. However, it has been shown that using an autorefractor is an accepted method to approximate refractive error [36]. Nonetheless, accuracy of ocular biometry measurements is potentially a limitation of the study. We incorporated individual's mean-K and MSE values into Spectralis scan acquisition as well as the Zemax simulation. Any error in these values would therefore have the same effect on both occasions. We postulate that the discrepancy from perfect correlation is more likely to be caused by some other assumption built into the OCT software. Furthermore, Tan et al. explored the effect of different lens powers and varying eye-scanner distance

on image magnification while maintaining a constant axial length [37]. This was repeated keeping a constant lens power while varying eye-scanner and axial length. The results showed that even with accurate axial length measurement, in eyes not complying with standard assumptions (for example cataract) or in eyes that over-accommodate during imaging, the magnification is still not sufficiently corrected. In addition, there was no option to include separate horizontal and vertical K values in the Spectralis software. The mean-K value underestimates or overestimates the horizontal K value depending on whether the individual has with- or against-the-rule astigmatism. The latter may explain the lack of perfect agreement between the mean-K and simulated scan lengths in the current study. However, as the mean-K value has to be inserted prior to scan acquisition and cannot be changed retrospectively, using mean-K allows subsequent analyses of vertical frames or measurements of area.

There was a strong and significant correlation between scans taken with mean-K and the simulated scan length when controlling for the effect of MSE ($p = 0.875$, $P < 0.0005$) and axial length ($p = 0.822$, $P < 0.0005$). This was not the case for scans taken using the default setting of $K = 7.70\text{mm}$. A recent study aimed to address the issue of the influence of axial length on OCT data acquired from Spectralis SD-OCT scans [38]. The study involved a novel method of measuring the known distance of a sub-retinal visual implant *in vivo*. The results confirmed the accuracy of lateral measurements taken from Spectralis SD-OCT measurements of emmetropic medium (22.51 to 25.5mm) length eyes. The authors did recommend that caution should be exercised when comparing measurements obtained from very short (<

22.5mm) or very long ($> 25.51\text{mm}$) eyes. Contrary to this, when the data was examined in the current study, the largest deviation of either mean- or default-K scan length from the simulated scan length did not belong to those with the higher MSE or those with axial length that deviated most from the Gullstrand exact eye model value of 24.385mm (Figure 2). Moreover, optic nerve head area measurement from Spectralis SD-OCT scans has been found to be independent of axial length when transverse scaling is applied using measures of ocular biometry including K and axial length [39]. It therefore does not seem to be necessary to measure axial length to minimise potential lateral measurement errors resulting from not correcting for ocular magnification [20].

The simulated scan length consistently overestimated the mean-K and default-K scan length output. Nonetheless, we observed a stronger correlation between scan length obtained with mean-K compared to default-K. Scan lengths above 5.9mm produced by the default-K setting were increasingly under-estimated compared to those obtained with mean-K (Figure 2). This implies that lateral measurements of drusen size and foveal width for example are likely to be underestimated if SD-OCT scans larger than 5.9mm are obtained with the default-K setting. We recommend incorporating the individual's mean-K and MSE during lateral retinal measurements when using the Spectralis SD-OCT. In addition, it is important to consistently use the individual's mean-K value for subsequent scans of the same patient for long-term monitoring in a clinical setting, for example measuring progression of non-exudative pigment epithelial atrophy.

CONCLUSION

This study provides useful information on the effect of ocular biometry measures on Spectralis SD-OCT scan length. The effect of ocular magnification on scan length appears to be better accounted for when an individual's mean corneal curvature value is incorporated into Spectralis SD-OCT scan acquisition as opposed to using the device's default setting. We recommend performing scan acquisition incorporating a measured mean keratometry value, with the fundus image focussed according to the individual's refractive error. This should be considered when taking area measurements and lateral measurements parallel to the retinal surface. These results may be of interest for clinical trials using SD-OCT for area or lateral measurements.

Acknowledgements

The authors thank Carl Zeiss Meditec for use of the IOLMaster.

Conflict of Interest Statement

All authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest

(such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Legends

Table 1 Summary of variations in mean keratometry, axial length and mean spherical error within the study sample

Figure 1 Box and whisker plot to show scan lengths obtained from SD-OCT scans obtained with default-K settings; mean-K values; and from software simulations incorporating axial length values. The length of each box is the interquartile range and the band inside the box represents the median. The whiskers show the smallest and largest values, with outliers indicated by the circles and extreme outliers by the asterisks. The mean and median scan length for scans using the default-K was $6.04 \pm 0.28\text{mm}$, $Md = 5.95\text{mm}$; for the mean-K group $6.10 \pm 0.33\text{mm}$, $Md = 6.00$; and for the simulated-K group was $6.23 \pm 0.38\text{mm}$, $Md = 6.21\text{mm}$

Figure 2 Scatterplot of mean-K (black squares) and default-K (grey triangles) scan lengths against Zemax simulated scan length (x-axis). There is a statistically significant correlation of mean-K ($\rho = 0.926$, $P < 0.0005$) and default-K ($\rho = 0.663$, $P < 0.0005$) with the simulated scan length. Dashed grey line represents perfect agreement, $r = 1.00$

References

1. Huang D, Swanson EA, Lin CP, Schuman JS, Stinson WG, Chang W, Hee MR, Flotte T, Gregory K, Puliafito CA (1991) Optical coherence tomography. *Science* 254:1178-1181
2. Anger EM, Unterhuber A, Hermann B, Sattmann H, Schubert C, Morgan JE, Cowey A, Ahnelt PK, Drexler W (2004) Ultrahigh resolution optical coherence tomography of the monkey fovea. Identification of retinal sublayers by correlation with semithin histology sections. *Exp Eye Res* 78:1117-1125
3. Leung CK, Cheung CY, Weinreb RN, Lee G, Lin D, Pang CP, Lam DSC (2008) Comparison of macular thickness measurements between time domain and spectral domain optical coherence tomography. *Invest Ophthalmol Vis Sci* 49:4893-4897
4. Nassif N, Cense B, Hyle Park B, Yun SH, Chen TC, Bouma BE, Tearney GJ, Boer JFd (2004) *In vivo* human retinal imaging by ultrahigh-speed spectral domain optical coherence tomography. *Optics Letters* 29:480-482
5. Regatieri CV, Branchini L, Duker JS (2011) The role of spectral-domain OCT in the diagnosis and management of neovascular age-related macular degeneration. *Ophthalmol Surg Las Im* 42:S56
6. Oh J, Smiddy WE, Flynn HW, Gregori G, Lujan B (2010) Photoreceptor inner/outer segment defect imaging by spectral domain OCT and visual prognosis after macular hole surgery. *Invest Ophthalmol Vis Sci* 51:1651-1658

- 336 7. Mojana F, Cheng L, Bartsch D-UG, Silva GA, Kozak I, Nigam N, Freeman
337 WR (2008) The role of abnormal vitreomacular adhesion in age-related
338 macular degeneration: spectral optical coherence tomography and surgical
339 results. *Am J Ophthalmol* 146:218-227
- 340 8. Moreno-Montañés J, Olmo N, Alvarez A, García N, Zarranz-Ventura J
341 (2010) Cirrus high-definition optical coherence tomography compared with
342 stratus optical coherence tomography in glaucoma diagnosis. *Invest*
343 *Ophthalmol Vis Sci* 51:335-343
- 344 9. Chakravarthy U, Williams M (2013) The Royal College of Ophthalmologists
345 guidelines on AMD: Executive Summary. *Eye* 27:1429-1431
- 346 10. Lee S, Fallah N, Forooghian F, Ko A, Pakzad-Vaezi K, Merkur AB, Kirker
347 AW, Albiani DA, Young M, Sarunic MV, Beg MF (2013) Comparative analysis
348 of repeatability of manual and automated choroidal thickness measurements
349 in nonneovascular age-related macular degeneration. *Invest Ophthalmol Vis*
350 *Sci* 54:2864-2871
- 351 11. Chiu SJ, Izatt JA, O'Connell RV, Winter KP, Toth CA, Farsiu S (2012)
352 Validated automatic segmentation of AMD pathology including drusen and
353 geographic atrophy in SD-OCT images. *Invest Ophthalmol Vis Sci* 53:53-61
- 354 12. Carpineto P, Nubile M, Toto L, Aharrh Gnama A, Marcucci L,
355 Mastropasqua L, Ciancaglini M (2009) Correlation in foveal thickness
356 measurements between spectral-domain and time-domain optical coherence
357 tomography in normal individuals. *Eye* 24:251-258

- 358 13. Folgar FA, Yuan EL, Farsiu S, Toth CA (2014) Lateral and axial
359 measurement differences between spectral-domain optical coherence
360 tomography systems. *J Biomed Opt* 19:16014
- 361 14. Bennett AG, Rudnicka AR, Edgar DF (1994) Improvements on Littmann's
362 method of determining the size of retinal features by fundus photography.
363 *Graefes Arch Clin Exp Ophthalmol* 232:361-367
- 364 15. Rudnicka AR, Burk ROW, Edgar DF, Fitzke FW (1998) Magnification
365 characteristics of fundus imaging systems. *Ophthalmology* 105:2186-2192
- 366 16. Garway-Heath DF, Rudnicka AR, Lowe T, Foster PJ, Fitzke FW, Hitchings
367 RA (1998) Measurement of optic disc size: equivalence of methods to correct
368 for ocular magnification. *Br J Ophthalmol* 82:643-649
- 369 17. Sanchez-Cano A, Baraibar B, Pablo LE, Honrubia FM (2008)
370 Magnification characteristics of the optical coherence tomograph Stratus OCT
371 3000. *Ophthalmic Physiol Opt* 28:21-28
- 372 18. Almeida MS, Carvalho LA (2007) Different schematic eyes and their
373 accuracy to the in vivo eye: a quantitative comparison study. *Braz J Phys*
374 37:378-387
- 375 19. Leung CK, Cheng ACK, Chong KKL, Leung KS, Mohamed S, Lau CSL,
376 Cheung CYL, Chu GC, Lai RYK, Pang CCP, Lam DSC (2007) Optic disc
377 measurements in myopia with optical coherence tomography and confocal
378 scanning laser ophthalmoscopy. *Invest Ophthalmol Vis Sci* 48:3178-3183

- 379 20. Odell D, Dubis AM, Lever JF, Stepien KE, Carroll J (2011) Assessing
380 errors inherent in OCT-derived macular thickness maps. J Ophthalmol.
381 doi:10.1155/2011/692574
- 382 21. Rauscher FM, Sekhon N, Feuer WJ, Budenz DL (2009) Myopia affects
383 retinal nerve fiber layer measurements as determined by optical coherence
384 tomography. J Glaucoma 18:501-505
- 385 22. Savini G, Barboni P, Parisi V, Carbonelli M (2012) The influence of axial
386 length on retinal nerve fibre layer thickness and optic-disc size measurements
387 by spectral-domain OCT. Br J Ophthalmol 96:57-61
- 388 23. Bayraktar S, Bayraktar Z, Yilmaz F (2001) Influence of scan radius
389 correction for ocular magnification and relationship between scan radius with
390 retinal nerve fiber layer thickness measured by optical coherence
391 tomography. J Glaucoma 10:163-169
- 392 24. Wakitani Y, Sasoh M, Sugimoto M, Ito Y, Ido M, Uji Y (2003) Macular
393 thickness measurements in healthy subjects with different axial lengths using
394 optical coherence tomography. Retina 23:177-182
- 395 25. Wagner-Schuman M, Dubis AM, Nordgren RN, Lei Y, Odell D, Chiao H,
396 Weh E, Fischer W, Sulai Y, Dubra A, Carroll J (2011) Race- and sex-related
397 differences in retinal thickness and foveal pit morphology. Invest Ophthalmol
398 Vis Sci 52:625-634
- 399 26. Ooto S, Hangai M, Tomidokoro A, Saito H, Araie M, Otani T, Kishi S,
400 Matsushita K, Maeda N, Shirakashi M, Abe Hi, Ohkubo S, Sugiyama K, Iwase
401 A, Yoshimura N (2011) Effects of age, sex, and axial length on the three-

- 402 dimensional profile of normal macular layer structures. Invest Ophthalmol Vis
403 Sci 52:8769-8779
- 404 27. Kirby ML, Galea M, Loane E, Stack J, Beatty S, Nolan JM (2009) Foveal
405 anatomic associations with the secondary peak and the slope of the macular
406 pigment spatial profile. Invest Ophthalmol Vis Sci 50:1383-1391
- 407 28. Menke MN, Dabov S, Knecht P, Sturm V (2009) Reproducibility of retinal
408 thickness measurements in healthy subjects using spectralis optical
409 coherence tomography. Am J Ophthalmol 147:467-472
- 410 29. Atchinson DA, Smith G (2000) Schematic eyes. In: Optics of the human
411 eye. Butterworth Heinemann, Oxford:, pp 250-251
- 412 30. Paunescu LA, Schuman JS, Price LL, Stark PC, Beaton S, Ishikawa H,
413 Wollstein G, Fujimoto JG (2004) Reproducibility of nerve fiber thickness,
414 macular thickness, and optic nerve head measurements using Stratus OCT.
415 Invest Ophthalmol Vis Sci 45:1716-1724
- 416 31. Nolan JM, Stringham JM, Beatty S, Snodderly DM (2008) Spatial profile of
417 macular pigment and its relationship to foveal architecture. Invest Ophthalmol
418 Vis Sci 49:2134-2142
- 419 32. Verkicharla PK, Mallen EAH, Atchison DA (2013) Repeatability and
420 comparison of peripheral eye lengths with two instruments. Optom Vis Sci
421 90:215-222

- 422 33. Lam AKC, Chan R, Pang PCK (2001) The repeatability and accuracy of
423 axial length and anterior chamber depth measurements from the
424 IOLMaster™. *Ophthalmic Physiol Opt* 21:477-483
- 425 34. Song H, Chui TYP, Zhong Z, Elsner AE, Burns SA (2011) Variation of
426 cone photoreceptor packing density with retinal eccentricity and age. *Invest*
427 *Ophthalmol Vis Sci* 52:7376-7384
- 428 35. Visser N, Berendschot T, Verbakel F, de Brabander J, Nuijts R (2012)
429 Comparability and repeatability of corneal astigmatism measurements using
430 different measurement technologies. *J Cataract Refract Surg* 38:1764-1770
- 431 36. Pesudovs K, Weisinger HS (2004) A comparison of autorefractor
432 performance. *Optom Vis Sci* 81:554-558
- 433 37. Tan JC, Poinoosawmy D, Fitzke FW, Hitchings RA (2004) Magnification
434 changes in scanning laser tomography. *J Glaucoma* 13:137-141
- 435 38. Röck T, Wilhelm B, Bartz-Schmidt KU, Röck D (2014) The influence of
436 axial length on confocal scanning laser ophthalmoscopy and spectral-domain
437 optical coherence tomography size measurements: A pilot study. *Graefes*
438 *Arch Clin Exp Ophthalmol* 252:589-593
- 439 39. Patel NB, Wheat JL, Rodriguez A, Tran V, Harwerth RS (2012)
440 Agreement between retinal nerve fiber layer measures from Spectralis and
441 Cirrus spectral domain OCT. *Optom Vis Sci* 89:E652-666
- 442
443