Effect of image quality on tissue thickness measurements obtained with spectral-domain optical coherence tomography

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Abstract

The purpose of this study was to investigate the effect of image quality on retinal nerve fiber layer (RNFL) and retinal thickness measurements obtained using three commercially available spectral-domain optical coherence tomographs (SD-OCT). Subjectively determined good, medium and poor quality images were obtained from four healthy and one glaucoma suspect eyes. RNFL and retinal thickness measurements were compared as a function of image quality. Results indicate that when image quality is within the range specified as acceptable by SD-OCT manufacturers, RNFL and retinal thickness measurements are comparable.

1. Introduction

The recent development and commercialization of Spectral Domain Optical Coherence Tomography (SD-OCT) has brought a significant improvement in our ability to visualize and measure the retina in-vivo. With scanning speeds between 25,000–40,000 A-scans/second, this technology, also known as Fourier-domain OCT, or high speed, high resolution OCT, provides excellent depth resolution (up to 5 microns) and transverse resolution (up to 14 microns) [1−7]. Reproducible, three-dimensional representations of the human eye are now possible using OCT during a routine undilated clinical examination [7−11].

RTVue Fourier Domain (FD)-OCT (Optovue Inc, Fremont, CA), Spectralis OCT (Heidelberg Engineering, GmbH, Heidelberg, Germany), and Cirrus High Density (HD)-OCT (Carl Zeiss Meditec, Dublin, CA) are three of several commercially available SD-OCT instruments. Each instrument provides numerous options to acquire scans of different sizes and densities. For example, the Cirrus SD-OCT “Optic Disc Cube” can consist of 200 A-scans × 200 B-scans or 512 A-scans × 128 B-scans centered on the optic disc. The RTVue NHM4 scan is a composite of 12 radial B-scans (452 A-scans each), and two types of circular scans (3 concentric circular B-scans of diameter 2.5mm, 2.8mm, and 3.1mm respectively by 587 A-scans and 3 concentric circular B-scans of diameter 3.4mm, 3.7mm, and 4.0mm respectively by 775 A-scans). The Spectralis “volume scan” has the flexibility of acquiring between 12 and 96 B-scans and 256 A-scans (high-speed mode) or 512 A-scans (high-resolution mode) per 10° field of view. In addition, an automatic retinal tracking (ART) mode is available in Spectralis to ensure that all B-scans required to cover the imaging area of interest are acquired coherently despite any eye movements. In ART mode, Spectralis acquires 9 B-scans per retinal location (each B-scan per
retinal location is referred to as a frame) by default and can be manually adjusted from 2 to 100 frames. The type of scan preferred represents a compromise between the time required to obtain the scan, the field of view included, and the density of the A- and B-scans. These scans generate large datasets that are analyzed and interpreted using sophisticated algorithms. In addition, the clinician can subjectively review the scans to identify specific pathologic features or conditions.

We know from other imaging instruments, such as confocal scanning laser ophthalmoscopy [12], scanning laser polarimetry [13,14] and time domain OCT [15], that poor quality scans can provide inaccurate information about the status of the optic disc and RNFL [16]. For example, it has been documented that time domain OCT signal strength is positively associated with RNFL thickness measurements (i.e., poor quality scans with low signal strength lead to underestimates of RNFL thickness) [17]. It can be assumed that interpretation of the scans is most accurate when images are of good quality. Fortunately, the SD-OCT instruments provide automated feedback to the operator about the quality of the acquired scan.

The objective of this manuscript is to examine and provide examples of how the quality of SD-OCT three-dimensional scans effects the qualitative and quantitative information available to the clinician.

2. Methods

2.1 Study Participants

Four healthy individuals (average age = 35 years, range 30 to 43 years, with healthy appearing optic discs on examination, standard automated perimetry within normal limits on all global indices, IOP ≤ 22 mmHg with no history of elevation) and one glaucoma suspect (49 years, untreated IOP > 24 mmHg and glaucomatous appearing optic discs on examination and masked stereophotograph assessment OU) from the UCSD Diagnostic Innovations in Glaucoma Study (DIGS) were included in this observational case series. Volumetric optic disk scans (details below) were acquired using three commercially available SD-OCT instruments: RTVue (Model RT100, software version 2.0.4.0), Spectralis (Model Spectralis HRA+OCT, software version 3.2a), and Cirrus (Model 4000, software version 3.0.0.64). A set of 4 volumetric scans were acquired from one randomly selected eye of each of the study participants at 3 subjective-scan-quality (SSQ) levels and at +2 diopter defocus (to simulate plausible user error in a busy clinic) using each of the SD-OCT instruments. The SSQ levels used were: 1. best quality, 2. medium quality, and 3. low quality. Table 1 provides a brief summary of the SD-OCT specifications. For Spectralis, all scans were acquired in the ART mode with the number of frames reduced to 2 (instead of the default 9 frames in the ART mode) to acquire all 4 scans in a reasonable time frame (i.e., the manufacturer imposed maximum laser exposure per day per eye to ensure patient safety) from each study participant.

For each instrument, the SSQ levels were derived based on the range of the quality scores assigned by the respective instrument (referred to as the Instrument Quality Score – IQS). For RTVue, IQS varies from 0–100; therefore, scans with IQS 60 or above were considered best quality, IQS between 40 and 60 were considered medium quality and IQS below 40 were considered low quality. Spectralis uses a signal-to-noise (SNR in dB) estimate for IQS. Scans with SNR 20 dB or above were considered best quality, SNR of approximately 15 dB were considered medium quality and SNR of approximately 10 dB were considered low quality. For Cirrus, IQS varies from 0–10; therefore, scans with IQS 8 or above were considered best quality, IQS of approximately 6 were considered medium quality and IQS of approximately 3 were considered low quality. A trained operator adjusted SSQ levels manually to achieve desired scan quality by changing the amount of instrument defocus prior to image acquisition.
2.2 Data Preparation

Raw voxel measurements of volumetric OCT scans acquired using RTVue, Spectralis, and Cirrus were exported using their respective analysis software. For RTVue, voxel measurement exports from each scan are stored in a .OCT file and detailed scan information (such as, coordinates of A- and B-scans in the .OCT file, number of A- and B-scans, and resolution along an A-Scan, between A-Scans and between B-Scans) are available in a .txt file. Using the Spectralis software module (ver. 3.2a), voxel measurements from each scan and the scan information required to correctly arrange the voxel measurements as a 3D cube were both exported in a single .vol file. Cirrus voxel measurement exports from each scan are stored in a single .IMG file. The raw exports from RTVue, Spectralis, and Cirrus were read using MATLAB (The Mathworks, Inc., Natick, MA) and generic data files were created for each scan using VTK libraries (The Visualization Toolkit, Kitware Inc., Clifton Park, New York). A VTK wrapper was used to access VTK libraries from the MATLAB environment.

To optimize volumetric visualization in OSA ISP, the floating point type raw measurements from Spectralis and RTVue were normalized to a range of values between 0 and 255 and converted to unsigned char data types. Raw exports from Cirrus are in unsigned char precision and therefore no additional data normalization was applied. Generic binary volumetric data files (.VTI) were created from the normalized volumetric measurements using the \texttt{vtkStructuredPointsWriter} class available in VTK. Volumetric measures from Spectralis were normalized as,

\[
\text{Spectralis normalized voxel (i) } = 255 \cdot \sqrt{\text{voxel (i)}}
\]

and volumetric measures from RTVue were normalized as,

\[
\text{Normalized voxel (i) } = 255 \cdot \frac{\text{voxel (i)}}{\max (\text{voxel (i)})}
\]

3. Results

Table 2 shows the IQS values from each instrument for all the study participants. Results indicate that the SSQ goals were met for all conditions.

3.1 Qualitative Assessment of Scan Quality

Figures 1–3 illustrate the effect of change in scan quality on two-dimensional cross-sections through the optic nerve head of participant H1 (chosen arbitrarily) for RTVue, Spectralis, and Cirrus respectively. Results from the +2 diopter defocus condition also are shown. In general, introduction of +2 diopter defocus had little effect on image appearance. For further details, navigable three-dimensional volume scans (OSA ISP format) can be accessed by clicking on the links in the captions.

3.2 Quantitative Assessment of Scan Quality

Table 3 shows average RNFL thickness at each SSQ and at +2 diopters defocus for each participant for RTVue, Spectralis (RNFL thickness estimates are currently not available for Spectralis, therefore retinal thickness estimates are shown), and Cirrus, respectively.

For RTVue, RNFL thickness measurements in most eyes remained stable across the range of SSQ (changes in RNFL thickness of \( \approx 3 \) μm, however see results from participant H3). These results suggest that, changes in SSQ from best to lowest quality images resulted in minimal,
clinically irrelevant, changes in measured RNFL thickness. Although we were able to vary the signal strength to a large extent (from approximately 80 to approximately 36), all RTVue images were obtained within the manufacturers suggested range for reliable images (signal strength ≥ 30). The RTVue instrument software would not save (and therefore would not analyze) images with signal strength of approximately ≤ 35. This situation likely reduced the range of observable change as a function of SSQ. Introduction of 2 diopters of optical defocus had a negligible effect on RTVue RNFL thickness measurements.

For Spectralis, retinal thickness measurements increased, rather than decreased, as a function of decreasing SSQ in all examined eyes, with changes ranging from approximately 20 μm to approximately 40 μm. However, the magnitude of change in retinal thickness is not comparable to the magnitude of change in RNFL thickness reported for Cirrus and RTVue because of differences in baseline thickness. In the current study, our medium SSQ definition was chosen to approximate the manufacturers suggested borderline image quality (15 dB signal strength). Compared to the best SSQ condition, increases in retinal thickness recorded at medium SSQ were ≤ 20 μm; an increase of approximately 6% or less of total retinal thickness. Introduction of 2 diopters of optical defocus had a minimal effect on retinal thickness measurements. These results suggest that, similar to RTVue, when Spectralis images are obtained within manufacturer specified signal strength, the variability of repeat measurements likely is clinically irrelevant. Finally, upon inspection of Spectralis images, it appeared that any increased retinal thickness associated with decreased signal strength might be attributable at least in part to a decreased ability of the retinal thickness algorithm to define reflectance differences at Bruch's membrane, in the presence of increased image noise (see Figure 4). In addition, if the Spectralis scans were acquired using the manufacturer's default setting of 9 frames in ART mode, a high SNR is likely even at the poor SSQ level.

For Cirrus, RNFL thickness measurements from healthy and suspect eyes decreased as signal strength decreased in most (but not all, see results from participant H2) eyes examined. According to manufacturer protocol, images with signal strength ≥ 6 are considered acceptable and we used this value to define our medium SSQ scans. Decreases in RNFL thickness between subjectively defined best quality images (with signal strength ≥ 8) and subjectively defined medium quality images (with signal strength ≈ 6) were ≤ 5 μm in all cases, suggesting that RNFL thickness measurement changes within the range of acceptable quality images are probably not clinically relevant. When signal strength was decreased to ≈ 3, changes in RNFL thickness measurements ranged from −10 μm to +5 μm. Introduction of 2 diopters of optical defocus decreased RNFL thickness measurements as much as 10 μm.

Figures 5–9 show within-subject (i.e., one figure per study participant) temporal-superior-nasal-inferior-temporal (i.e., “TSNIT”) plots for RNFL thickness at each SSQ level and at +2 diopters defocus for RTVue, Spectralis (retinal thickness, not RNFL thickness), and Cirrus. For all instruments, thickness values that compose the TSNIT plot were obtained using a scan circle with diameter 3.45 mm centered on the optic disc. For RTVue, RNFL thickness measurements were obtained using the NHM4 scan protocol (see [8] for description of this protocol), not the volumetric scan described in the data preparation section above. IQSs were somewhat different for volumetric and NHM4 images and are shown in Table 2. TSNIT plots reinforce the mean RNFL and retinal thickness results reported above.

4. Discussion

It is important that the clinician understand the specific strengths and weaknesses of any instrument so that the best quality information can be used for glaucoma management decisions. Fortunately, the SD-OCT instruments provide real-time automated assessment of the quality of an exam. This feedback to the operator during image acquisition improves the
likelihood that a good quality image will be available. With each instrument, deliberate effort was required to obtain a poor quality image of all eyes examined. With the RTVue very poor quality images could not be saved and with Spectralis acquiring poor quality images was made difficult by the laser time-out safety feature described in the Methods section. It should be noted that the range of the quality measures and the basis for the image quality assessment are not necessarily comparable across instruments. Therefore, a “medium” or “low” quality scan on one instrument may not be comparable to a “medium” or “low” quality scan on another. For example, the lowest quality scan obtainable with the RTVue was within the manufacturer’s suggested acceptable range. In contrast, the low quality scans acquired using Cirrus and Spectralis were well outside the manufacturer’s suggestion for a good quality scan. Moreover, for Spectralis scans, only 2 frames were acquired in the ART mode as opposed to the default value of 9 frames. For these reasons, it is not appropriate to compare differences in measurements across instruments.

During the initial study design, we attempted several approaches to systematically acquire scans at known quality level from each of the instruments so that the relationship between the retinal thickness estimates and the corresponding scan quality levels could be quantitatively described. For example, we identified the best scan quality setting for each study eye in a given instrument and attempted to incrementally and consistently degrade the scan quality in all the 3 instruments by adding external defocus in steps of 2 diopters so that scans could be acquired at 4 known defocus levels of 1) best possible quality for a given eye from each of the instruments, 2) +2 diopters focus error, 3) +4 diopters focus error, and 4) +6 diopters focus error. However, acquiring scans with an external focus > +4 diopters was very challenging and it was sometimes not possible to complete an exam due to built in features designed to ensure that good quality scans are used (Spectralis and RTVue) and that overall scan time per eye does not exceed a specified safety limit (Spectralis). Specifically, the scans acquired at higher defocus levels using Spectralis in the default ART mode did not meet the minimum required scan quality recommended by the manufacturer and therefore the instrument could not acquire scans at this setting; RTVue does not permit saving such poor quality scans. In addition, because it became harder to fixate on the scanning target at higher defocus levels and because ART mode in Spectralis requires at least 2 B-scans per retinal location, it took longer to complete a scan and some study participants could not complete all the scans due to the laser time-out safety feature. Therefore, we determined that defining scan quality levels subjectively within each instrument was the most reliable method of acquiring scans at various scan quality levels from all of the study participants, even though the quality levels are not comparable across instruments.

It is important to emphasize that automated image quality assessment is not fool-proof and can miss some types of poor quality images. Moreover, as software and hardware improves, some issues that adversely affect the quality of the scan may no longer be relevant. It is therefore essential that images be assessed subjectively for quality before they are utilized for clinical decision-making.

In this small case series, the RNFL and retinal measurements of each eye were relatively stable despite differences in the quality of the SD-OCT images, particularly among the “best”, “medium” and “+2dp level” scans. These results suggest that the measurements are robust to differences in image quality, at least in the small number of cases included. A larger sample is needed to fully investigate this issue, and to provide estimates of the range of differences in measurements that are likely to occur due to variability in scan quality.

The TSNIT plots for all the participants at “best” and “+2dp” SSQ levels are very similar indicating that small defocus errors that are plausible in a busy clinical setting do not deteriorate
the quality of the scans and do not introduce large measurements errors in the parameter estimates.

There are several possible explanations for how quality of scans influences RNFL and retinal measurements. One important issue likely is increased noise in lower quality images. More noise increases the likelihood that segmentation algorithms used to calculate thickness measurements will not accurately identify junctions of retinal layers. Increased noise also may adversely affect algorithms used for centering and aligning images for location-specific monitoring of change over time. In this study, RNFL thickness was estimated along a ~3.45mm diameter circle at temporal, superior, nasal and Inferior locations. RTVue and Cirrus software version used in our current study (software version 2.0.4.0 and 3.0.0.64 respectively) uses a semi-automatic algorithm to identify the center of the optic disk to mark the 3.45mm circular region while Spectralis requires the operator to identify the center of the optic disk to place a 3.45mm circle. However, software is improving rapidly to include features such as automatic delineation of the optic disc without operator intervention. Therefore, other components of the SD-OCT such as the SD-OCT software (especially the robustness of the segmentation algorithm to segment retinal layers) and the level of operator intervention required to ensure the scan quality may also influence the overall scan quality and repeatability of an exam. Previous studies on time-domain OCTs indicate that the RNFL thickness estimates are influenced by the centering of the 3.45mm circle [11,18]. Inconsistent centering might contribute to the explanation of regional thickness variations observed among scans obtained at different SSQs [19]. Consideration of image noise levels may be particularly important for SD-OCT because it has been suggested that SD (e.g., Fourier Domain) technology compensates less effectively for classical sources of noise than time-domain OCT because of reliance on low-pass rather than band-pass filtering, thus theoretically decreasing the effective SNR. (see [20] for a detailed description of these issues).

In summary, this case series provides examples of 3D volume scans at various subjective scan quality levels from the 3 commercially available SD-OCT instruments. These results suggest that image acquisition protocols and analysis software are relatively robust even in situations of suboptimal image quality.

Acknowledgments

The authors thank Ali Tafreshi, Hamilton Glaucoma Center, Department of Ophthalmology, University of California San Diego for acquiring the scans for this case series study. This research was supported in part by NIH EY 11008 (LMZ), and a financial support from Heidelberg Engineering, GmbH, Heidelberg, Germany.

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Fig. 1. RTVue volume and cross-sectional scans (single B-scans) through the approximate center of the optic disc of the participant H1 at various subjective scan quality (SSQ) levels and at +2 diopters refractive error. Instrument quality scores (IQS) also are listed. (a) SSQ = “Best”; IQS = 73.2 (View 1), (b) SSQ = “Medium”; IQS = 47.2 (View 2), (c) SSQ = “Low”; IQS = 36.1 (View 3), (d) At +2 dp refractive error; IQS = 62.3 (View 4).
Fig. 2.
Spectralis volume and cross-sectional scans (single B-scans) through the approximate center of the optic disc of the participant H1 at various subjective scan quality (SSQ) levels and at +2 diopters refractive error. Instrument quality scores (IQS) also are listed. (a) SSQ = “Best”; IQS = 30 dB (View 5), (b) SSQ = “Medium”; IQS = 17 dB (View 6), (c) SSQ = “Low”; IQS = 10 dB (View 7), (d) At +2 dp refractive error; IQS = 27 dB (View 8).
Fig. 3.
Cirrus volume and cross-sectional scans (single B-scans) through the approximate center of the optic disc of the participant H1 at various subjective scan quality (SSQ) levels and at +2 diopters refractive error. Instrument quality scores (IQS) also are listed. (a) SSQ = “Best”; IQS = 10 (View 9), (b) SSQ = “Medium”; IQS = 6 (View 10), (c) SSQ = “Low”; IQS = 3 (View 11), (d) At +2 dp refractive error; IQS = 6 (View 12).
Fig. 4.
Spectralis cross-sectional scans (single B-scans) through the superior parapapillary region of participant H4 obtained at “best” (View 41) and “low” SSQ (View 43). Segmentation failure along Bruch's membrane (shown in (b) is likely due to the reduced SNR at the low SSQ level. Fundus images to the left of each figure illustrate the respective B-scan placement.
Fig. 5.
TSNIT (temporal-superior-nasal-inferior-temporal) plots describing circumpapillary tissue thickness in participant H1 obtained using RTVue (top), Spectralis (middle), and Cirrus (bottom).
Fig. 6. TSNIT (temporal-superior-nasal-inferior-temporal) plots describing circumpapillary tissue thickness in participant H2 obtained using RTVue (top), Spectralis (middle), and Cirrus (bottom).
Fig. 7.
TSNIT (temporal-superior-nasal-inferior-temporal) plots describing circumpapillary tissue thickness in participant H3 obtained using RTVue (top), Spectralis (middle), and Cirrus (bottom).
Fig. 8.
TSNIT (temporal-superior-nasal-inferior-temporal) plots describing circumpapillary tissue thickness in participant H4 obtained using RTVue (top), Spectralis (middle), and Cirrus (bottom).
Fig. 9.
TSNIT (temporal-superior-nasal-inferior-temporal) plots describing circumpapillary tissue thickness in participant GS obtained using RTVue (top), Spectralis (middle), and Cirrus (bottom). Exam with +2 diopters refractive error using Spectralis could not be completed due to time constraints.
### Table 1

Volumetric scan specifications of the commercial SD-OCT instruments

|                         | RTVue  | Spectralis | Cirrus  |
|-------------------------|--------|------------|---------|
| **Scan speed (A-scans per second)** | 26,000 | 40,000     | 27,000  |
| **Axial resolution (μm)**     | 5      | 7          | 5       |
| **Transverse resolution (μm)**  | 15     | 14         | 20      |
| **Volume scan specification** | 3D Disc: 4 mm × 4mm (513 A-scans × 101 B-scans) | Volume scan: 4.5mm × 4.5mm (768 A-scans × 145 B-scans) | Optic Disc Cube 200 × 200: 6mm × 6mm (200 A-scans × 200 B-scans) |
| **Instrument quality score (IQS) for volume scans (minimum manufacturer suggested IQS representing acceptable quality)** | 0–100 (30) | SNR in dB (15 dB) | 0–10 (6) |
| **Subjective-scan-quality (SSQ) for volume scans** | Best: IQS > 60  Medium: 60 > IQS > 40  Low: IQS < 40 | Best: IQS > 20 dB  Medium: IQS ≥ 15 dB  Low: IQS ≥ 10 dB | Best: IQS ≥ 8  Medium: IQS ≥ 6  Low: IQS ≥ 3 |
Table 2

Scan quality scores of 3D volume scans acquired at various experimentally controlled subjective-scan-quality levels using RTVue, Spectralis, and Cirrus SD-OCT instruments. Healthy eyes are labeled $H1$–$H4$, and the glaucoma suspect eye is labeled $GS$. Navigable three-dimensional volume scans (Views 1–59) can be accessed by clicking on each SSQ cell.

| ID | Subjective scan quality | RTVue (Instrument quality score 0–100) | Spectralis (Instrument quality score in dB) | Cirrus (Instrument quality score 0–10) |
|----|-------------------------|---------------------------------------|------------------------------------------|---------------------------------------|
|    | Best                    | Medium                                | Low                                      | +2 dp                                 |
| $H1$| 75.0 (72.3) *           | 55.4 (47.2) *                         | 37.2 (36.1) *                            | 47.4 (62.3) *                         |
|    |                         | Best                                  | 23                                       | Medium                                |
|    |                         |                                       | 18                                       | Low                                   |
|    |                         |                                       | 15                                       | +2 dp                                 |
| $H2$| 82.5 (73.1) *           | 66.3 (47.5) *                         | 36.3 (37.5) *                            | 48.2 (66.1) *                         |
|    |                         | Best                                  | 30                                       | Medium                                |
|    |                         |                                       | 17                                       | Low                                   |
|    |                         |                                       | 10                                       | +2 dp                                 |
| $H3$| 76 (64.0) *             | 51.6 (47.0) *                         | 37.0 (35.4) *                            | 52.6 (67.2) *                         |
|    |                         | Best                                  | 22                                       | Medium                                |
|    |                         |                                       | 17                                       | Low                                   |
|    |                         |                                       | 9                                        | +2 dp                                 |
| $H4$| 82.1 (76.9) *           | 64.7 (47.9) *                         | 35.9 (35.4) *                            | 46.0 (54.8) *                         |
|    |                         | Best                                  | 25                                       | Medium                                |
|    |                         |                                       | 16                                       | Low                                   |
|    |                         |                                       | 13                                       | +2 dp                                 |
| $GS$| 57.7 (57.6) *           | 45.0 (44.5) *                         | 36.5 (35.5) *                            | 59.8 (48.1) *                         |
|    |                         | Best                                  | 19                                       | Medium                                |
|    |                         |                                       | 18                                       | Low                                   |
|    |                         |                                       | 10                                       | +2 dp                                 |

* instrument quality score of NHM4 scan obtained to record RNFL thickness measurements provided below (see Quantitative Assessment of Scan Quality section).

** Spectralis image at 2 diopters defocus was not obtained for participant GS due to time constraints.
Table 3

Average RNFL thickness (microns) of scans acquired at various experimentally controlled subjective-scan-quality levels using RTVue, Spectralis (retinal thickness, not RNFL thickness), and Cirrus SD-OCT instruments. Healthy eyes are labeled $H1$–$H4$, and the glaucoma suspect eye is labeled $GS$. Navigable three-dimensional volume scans (Views 1–59) can be accessed by clicking on each thickness measurement cell.

| ID   | Subjective scan quality | RTVue Average RNFL thickness (microns) | Spectralis Average retinal thickness (microns) | Cirrus Average RNFL thickness (microns) |
|------|-------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|
|      | Best        | Medium       | Low     | +2 dp | Best   | Medium   | Low     | +2 dp | Best   | Medium   | Low     | +2 dp |
| $H1$ | 96.9       | 97.5         | 98.6    | 97.1  | 318.5  | 336.2    | 341.7   | 319.0 | 83     | 81       | 76      | 79     |
| $H2$ | 119.6      | 118.2        | 119.3   | 118.0 | 346.7  | 361.5    | 372.0   | 343.7 | 110    | 104      | 115     | 100    |
| $H3$ | 113.3      | 109.3        | 105.9   | 111.09| 339.25 | 348.5    | 360.2   | 333.25| 101    | 97       | 95      | 95     |
| $H4$ | 126.5      | 128.4        | 124.9   | 128.2 | 378.5  | 398.0    | 420.5   | 373.5 | 115    | 111      | 104     | 106    |
| $GS$ | 104.9      | 104.6        | 101.9   | 100.4 | 318.2  | 325.7    | 354.0   | N/A   | 105    | 96       | 92      | 98     |

* Spectralis image at 2 diopters defocus was not obtained for participant $GS$ due to time constraints.