Effect of Motion Artifacts and Scan Circle Displacements on Cirrus HD-OCT Retinal Nerve Fiber Layer Thickness Measurements

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Purpose. To evaluate the effect of scan circle displacements on retinal nerve fiber layer thickness (RNFLT) measurements in Cirrus HD-OCT scans with motion artifacts affecting the optic disc.

Methods. In this cross-sectional study, 70 scans from 18 healthy eyes and 100 scans from 26 glaucomatous eyes were divided into 85 pairs, each composed by a scan with one motion artifact affecting the optic disc, and a scan from the same eye without motion artifacts. En face images underwent automated realignment, and horizontal/vertical scan circle displacements were determined. Multiple regression analysis evaluated the relationship between scan circle displacements and RNFLT change.

Results. Scans with motion artifacts showed similar displacements in healthy and glaucomatous eyes (P values $\geq$ 0.08). Average RNFLT and quadrants were relatively unchanged, while clock-hours showed more changes (e.g., in glaucomatous eyes, clock-hour-7 RNFLT was lower in scans with motion artifacts, $P = 0.05$). Scan circle displacements produced average RNFLT changes above test–retest variability in 3/85 cases (3.53%). Retinal nerve fiber layer thickness tended to decrease in sectors moved away from the disc and to increase in sectors closer to the disc ($R^2 \leq 0.40$ and $R^2 \leq 0.22$ in healthy and glaucomatous eyes, respectively). In healthy eyes, horizontal displacements $\geq$ 423 and 325 μm were associated with average and quadrant RNFLT changes above test–retest variability, respectively.

Conclusions. Scan circle displacements occurred in all scans with motions artifacts affecting the optic disc. Average RNFLT and quadrants were more robust than clock-hours. Because motion artifacts may be difficult to detect, clinicians should carefully inspect en face OCT images for their presence and interpret clock-hour results cautiously.

Keywords: motion artifacts, optic disc, retinal nerve fiber layer thickness, scan circle displacement, spectral-domain OCT

Standard OCT scanning protocols for detecting glaucoma and monitoring its progression calculate the retinal nerve fiber layer (RNFL) thickness from axial scans evenly distributed along the path of a circle placed around the optic disc.[1,2] Previous studies[3–7] have shown that scan circle displacements may affect RNFL thickness measurements. However, Cirrus HD-OCT (Carl Zeiss Meditec, Dublin, CA, USA) is provided with a built-in algorithm for automated scan circle positioning.

It is generally assumed that the Cirrus HD-OCT scan circle is placed evenly around the optic disc and in the same location over repeated testing. However, no studies have been specifically designed to validate this assumption and to investigate potential sources of displacement. For example, the device lacks an eye-tracking system and, despite a relatively short acquisition time (<2 seconds), rapid eye movements during scan acquisition may generate motion artifacts. To avoid this occurrence, the system relies on patients' ability to maintain steady fixation. Unfortunately, this test is most commonly offered to an aging patient population with poor fixation and often presenting with a disease that may also affect central visual function.[8,9] Automatic detection of motion artifacts is not currently available; however, most of these artifacts produce a shift in the retinal vessels' path and may be identified when examining the en face image on the Cirrus HD-OCT Optic Disc Cube printout. Even after multiple rescans, their presence on OCT scans remains a common finding in a clinical setting, as fixation cannot be steadily maintained by many patients. In addition, some motion artifacts may be undetectable when interpreting OCT scans for the diagnosis and management of glaucoma, particularly when they are localized in the optic disc region and in areas with no retinal vessels.

It is conceivable that motion artifacts involving the optic disc may interfere with the instruments' ability to correctly identify the disc center and to place the scan circle evenly around it. Therefore, the purpose of the present study was to evaluate the effect of scan circle displacements on RNFL thickness measurements in Cirrus HD-OCT scans with motion artifacts affecting the optic disc.

Methods

This was an observational study conducted at the Department of Ophthalmology and Visual Sciences, The University of Texas

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Medical Branch (UTMB) at Galveston, Texas, United States. The study was approved by the UTMB Institutional Review Board, and all methods adhered to the tenets of the Declaration of Helsinki and the Health Insurance Portability and Accountability Act. Written informed consent to participate was obtained from all subjects after explanation of the nature and possible consequences of the study.

As part of the GLAucoma Diagnostic Imaging UTMB Study (GLADIUS), a prospective study designed to investigate modern glaucoma imaging devices, participants underwent a complete ophthalmologic examination, including review of medical history, best corrected visual acuity, slit lamp examination, gonioscopy, Goldmann applanation tonometry, dilated funduscopic examination with a 78–diopter (D) lens, spectral-domain optical coherence tomography (SD-OCT) scanning sessions, standard automated perimetry using Humphrey Field Analyzer II (Carl Zeiss Meditec), and stereoscopic optic disc photography using Topcon TRC-NW6S (Topcon Corporation, Tokyo, Japan). To be included in this study, participants had to have spherical refraction between ±5 D, cylinder between ±3 D, and open angle at gonioscopy. Subjects were excluded if they had coexisting retinal diseases, uveitis, nonglaucomatous optic neuropathy, history of intraocular surgery other than uncomplicated cataract or glaucoma surgery, or significant media opacities.

Eyes were classified as healthy or glaucomatous by two independent glaucoma specialists (MFS and GV) according to the absence or presence of structural glaucomatous damage to the optic disc or the RNFL. Typical glaucomatous damage included focal or diffuse neuroretinal rim thinning, cupping, optic disc hemorrhages, peripapillary atrophy, or wedge-shaped RNFL defects. The assessment was performed on color optic disc digital stereophotographs by using a hand-held stereoscopic viewer (Screen-Vu Stereo Viewer, Portland, OR). The two graders were masked to the participants' demographic and ophthalmic information, and to the other evaluator's results. In case of disagreement adjudication was achieved by consensus.

If eligible, both eyes of the same individual were included in this study.

Instrumentation

The Optic Disc Cube 200 × 200 protocol of Cirrus HD-OCT version 5.0.0.326 was used for scan acquisition. The protocol generates a cube of data over a 6 × 6-mm^2 area centered on the optic disc by acquiring a series of 200 horizontal scan lines (B-scans), each composed of 200 axial scans (A-scans). The instrument's axial resolution in tissue is 5 μm, with a scan acquisition rate of 27,000 A-scans/s. For analysis, a built-in automated algorithm identifies the center of the optic disc and places a scan circle of 3.46-mm diameter evenly around it. After automated RNFL segmentation, the system samples from the data cube 256 A-scans along the path of the scan circle to obtain average and sectoral (four quadrants and 12 clock-hours) RNFL thickness. Measurements are statistically compared to the normative database and color-coded classification results are displayed on the printout for clinicians to evaluate.

Cirrus HD-OCT scans with signal strength < 6 were excluded, as per manufacturer's recommendation. Additional scan exclusion criteria were the presence of any visible RNFL segmentation artifacts, multiple motion artifacts within the scan circle, media opacities, or floaters on the scan circle.

All scans were obtained by a single operator who did not modify the position of the scan circle as determined by the instrument.

Scan Selection Criteria

To replicate what might occur in a clinical scenario, motion artifacts were not purposely generated for this study. Rather, they resulted from involuntary eye movements during scan acquisition in the clinic. In fact, motion artifacts, as they appear on the en face OCT image, likely result from horizontal involuntary saccades during scan acquisition. Horizontal eye movements typically produce a shift in the retinal vessels' path and may be identified when examining the en face image on the Cirrus HD-OCT Optic Disc Cube printout.[10] The generated motion artifacts were identified and scans with motion artifacts used for further analysis. Specifically, for each eye examined, pairs of Cirrus HD-OCT scans collected as part of GLADIUS were considered for further evaluation. To be included, each pair had to be composed of one scan without motion artifacts to serve as a reference for subsequent realignment, and one scan from the same eye presenting with one motion artifact passing through the optic disc. One experienced observer (GT) reviewed all available en face images from our database for inclusion in one of these two scan categories. Specifically, the absence or presence of motion artifacts was evaluated on full-size (668 × 668 pixels) en face images exclusively displayed in *no graphic* mode. In this viewing modality, motion artifacts detection is facilitated by the absence of "superpixels," colored elements representing areas of statistically significant RNFL thinning as compared to the normative database. More importantly, in *no graphic* mode the optic disc center, disc margins, and scan circle are not visible, thus eliminating potential selection biases from knowing the position of these items.

The scans within each pair had to be signal-strength matched to account for the association between signal strength and RNFL thickness.[3,11] In turn, signal-strength matching was performed only after scan selection for motion artifacts was complete and without knowledge of the RNFL thickness measurements.

If multiple scans from the same eye met the above criteria, pairs were generated by random scan selection using IBM SPSS Statistics version 20.0.0 (IBM Corporation, Armonk, NY, USA), with scans assigned to one pair only.

Image Registration

The Optic Disc Cube 200 × 200 protocol is not provided with a scan area registration feature, that is, it is not possible to automatically rescan the same 6 × 6-mm^2 area over time. In fact, two scans from the same eye may have different "offset," a parameter displayed on the printout representing the position of the optic disc center within the scanning area. However, even same offset does not imply that the two scans share the same scan circle and optic disc center, since their position is not recorded at baseline, but systematically determined after each scan acquisition.

The presence of scan circle displacement between two scans from the same eye (Figs. 1A, 1B) can only be detected by manually aligning the correspondent anatomic structures (optic disc and retinal vessels), and assessing the position of the scan circles and optic disc centers afterward (Fig. 1C). Therefore, TurboReg[12] software for ImageJ version 1.44p (National Institutes of Health, Bethesda, MD, USA) was used to realign the image with the motion artifact to the correspondent reference without motion artifacts. By definition, motion artifacts produce horizontal scan shifts typically noticeable as partial or complete shift of the retinal vessel walls, which may significantly affect the reliability of the realignment. Thus, segments containing motion artifacts were excluded for the purpose of obtaining the most accurate

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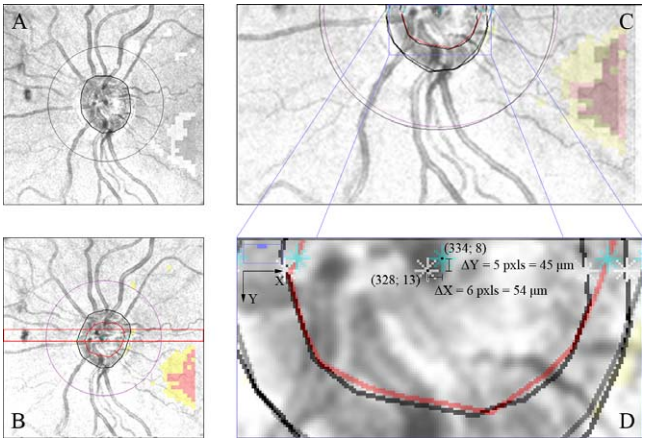

FIGURE 1. (**A**, **B**) Pair of signal-strength–matched Cirrus HD-OCT en face images from a left glaucomatous eye. A motion artifact affecting the optic disc, enclosed by the *red rectangle*, is visible in (**B**). (**C**) The image with the motion artifact (*purple scan circle*) was realigned and overlaid to the reference without motion artifacts (*black scan circle*). A magnified view of the optic disc region is presented in (**D**). After registration, disc center coordinates of the image with the motion artifact (*green disc center*) and the reference (*white disc center*) were recorded. The amount of horizontal (ΔX) and vertical (ΔY) scan circle displacement, in number of pixels, was estimated by subtracting the *x*- and *y*-coordinates of the two disc centers, respectively. ΔX and ΔY values were then converted into micrometers. In this example, the image with the motion artifact displayed a 54-μm temporal and a 45-μm superior scan circle displacement from the reference image without motion artifacts.

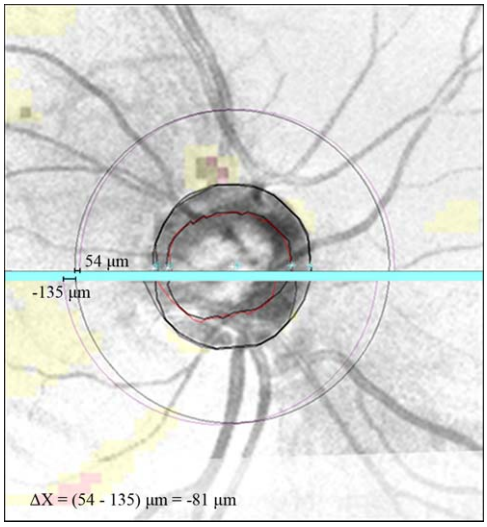

FIGURE 2. Realigned pair of Cirrus HD-OCT en face images from a right glaucomatous eye. The scan circle of the scan without motion artifacts is shown in *black*, while the scan circle of the scan with the motion artifact is shown in *purple*. In this example, the motion artifact affected clock-hours 3 (nasal quadrant) and 9 (temporal quadrant). For these sectors, the amount of horizontal scan circle displacement (ΔX) was calculated as the algebraic sum of the displacements detected in the areas above (54 μm) and below (–135 μm) the motion artifact, corresponding to –81 μm. *Negative signs* indicate temporal displacement. There was no vertical scan circle displacement in these sectors.

alignment between the two images. The performance of TurboReg was pre-assessed on a set of 20 scans randomly selected from our database: the software displayed excellent realignment accuracy (relative deviations, in absolute values, were 0.06% and 0.07% for the registration along the *x*- and *y*-axis, respectively) and perfect reproducibility (within-subject standard deviation = 0, as evaluated on 11 consecutive realignments per scan).

After registration, the presence of scan circle displacement is evidenced by a distance between the optic disc centers of the two realigned images. To estimate the amount of horizontal (ΔX) and vertical (ΔY) shift, in each pair the differences in number of pixels between the *x*- and *y*-coordinates of the two disc centers, as provided by ImageJ, were calculated and then converted into micrometers (Fig. 1D). Knowing that full-size Cirrus HD-OCT en face images are composed of 668 × 668 pixels (6 × 6-mm^2 scan area), the length of 1 pixel is equal to 9 μm of retinal surface.

For the right and left eyes, $\Delta X > 0$ indicated nasal scan circle displacement; $\Delta X < 0$, temporal displacement; $\Delta Y > 0$, superior displacement; and $\Delta Y < 0$, inferior displacement, respectively. In addition, for the sectors of the scan circle touched by the motion artifact, the displacement was calculated as the algebraic sum of the scan circle shift detected in the areas above and below the motion artifact (Fig. 2).

Statistical Analysis

Descriptive statistics included mean and standard deviation. Two-tailed *t*-tests for continuous distributions and χ^2 test for proportions were used to evaluate demographic and ophthalmologic differences between the healthy and glaucoma groups.

For average RNFL thickness, quadrants and clock-hours of the two groups, multiple regression analysis was performed to evaluate the relation between horizontal and vertical scan circle displacement (predictors), and change in RNFL thickness (outcome). Previous studies[5–7] have found that measurements of the temporal and nasal quadrants are affected by horizontal scan circle displacements, while measurements of the superior and inferior quadrants are affected by vertical displacements. Similarly, in this study, it was hypothesized that horizontal scan circle displacements could explain more variance in the nasal and temporal quadrants and that vertical scan circle displacement could explain more variance in the superior and inferior quadrants. In addition, it was hypothesized that average RNFL thickness decreased with nasal shifts and increased with temporal shifts, as previously described.[5]

A generalized estimating equation (GEE) model was used to adjust for the correlation between the two eyes of the same individual and between multiple pairs of scans from the same eye.[13]

Considering an α level = 0.05 and 80% power to detect a slope of the regression line of 0.102 for the average RNFL thickness (based on the equation provided in a previous investigation using time-domain [TD]-OCT),[3] the minimum number of pairs required for this study was 32 per group.

The α level for this study was set at 0.05. Statistical analysis was performed by using SPSS and Stata version 10.0 (StataCorp LP, College Station, TX, USA).

Results

Overall, 70 Cirrus HD-OCT optic disc scans divided in 35 pairs from 18 healthy eyes and 100 scans divided in 50 pairs from 26 glaucomatous eyes were included in the analysis. Scans within each pair were collected within a mean (SD) time interval of 0.49 (0.89) and 0.62 (0.73) weeks in healthy and glaucomatous eyes, respectively, which was similar between the two groups ($P = 0.45$).

The Table summarizes the demographic and ophthalmic characteristics of the study groups. On average, healthy eyes

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Table. Demographics of the Study Groups

	Healthy (70 Scans, 18 Eyes)	Glaucoma (100 Scans, 26 Eyes)	*P*
Male/female subjects	6/8	7/11	0.82*
Age, y	64.29 (7.15)	69.28 (10.77)	0.15†
Left/right eye	9/9	15/11	0.61*
Cirrus HD-OCT signal strength	9.00 (0.77)	8.27 (1.12)	0.01†
MD, dB	−0.94 (2.68)	−7.40 (7.52)	0.001†
PSD, dB	1.90 (0.68)	4.96 (3.41)	<0.001†
VFI, %	98.80 (1.21)	82.17 (23.47)	0.003†

MD, mean deviation; PSD, pattern standard deviation; VFI, visual field index.
* χ^2 test.
† Independent samples *t*-test. Standard deviations in parenthesis.

had greater signal strength and better perimetric indexes than glaucomatous eyes (*P* values $\leq$ 0.01).

Figure 3 shows two pairs of scans from two glaucomatous eyes. In each case, the RNFL deviation map of the reference scan (left), along with the RNFL deviation map of a scan with one motion artifact passing through the optic disc (right), is presented at the top, while at the bottom is the image resulting from the realignment process. In case 1, the slight displacement of the scan circle produces no change in average RNFL thickness (green rectangles in the center). In case 2, a more pronounced horizontal displacement of the scan circle likely produces a false increase in average RNFL thickness, from 63 μm in the reference scan to 66 μm in the scan with the motion artifact.

All pairs examined in this study showed the presence of scan circle displacement, which was within 180 μm temporally, 135 μm superiorly, 314 μm nasally, and 99 μm inferiorly. The mean horizontal and vertical displacements were similar in the two groups (*P* values $\geq$ 0.08) and were 59.89 and 32.91 μm, respectively, in healthy eyes, and 56.88 and 30.60 μm, respectively, in glaucomatous eyes.

In both groups, average and quadrant RNFL thickness were similar in scans with and without motion artifacts (*P* values > 0.05). However, in healthy eyes, scans with motion artifacts

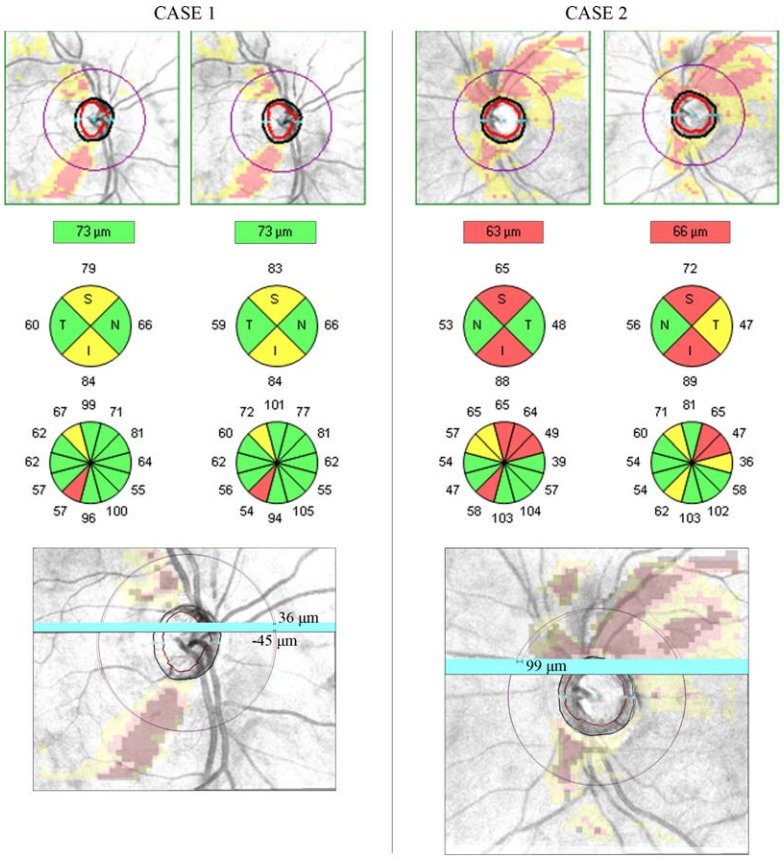

Figure 3. Pairs of signal-strength–matched Cirrus HD-OCT optic disc scans from a left (case 1) and a right (case 2) glaucomatous eye, showing the RNFL deviation maps (*top*); average, quadrant, and clock-hour RNFL thickness measurements with classification results (*middle*); and output of the automated realignment (*bottom*). The second scan of each pair presents with one motion artifact affecting the optic disc, which is not easily identifiable. Motion artifacts located outside the scan circle, instead, are more easily detected as horizontal shifts of the retinal vessel wall (e.g., case 1, *top right image*). In case 1, there are no classification changes between the two scans of the pair. In case 2, a 99-μm temporal displacement of the scan circle detected in the scan with the motion artifact is associated with a 3-μm increase in average RNFL thickness and classification changes in the temporal quadrant and clock-hours 2, 5, 9, and 12.

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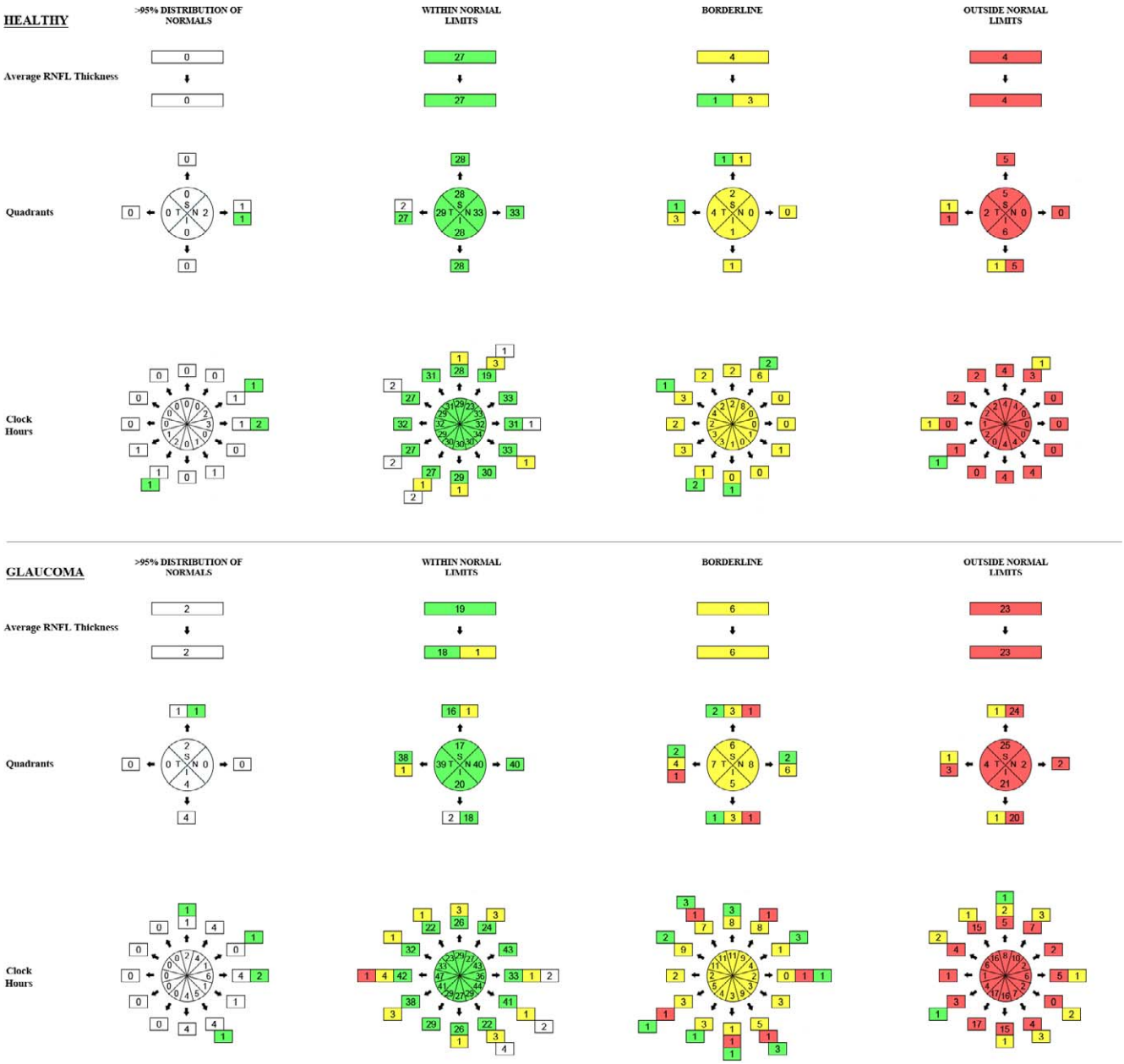

Figure 4. Frequency of classification changes, expressed as absolute number, between scans with and without motion artifacts (reference scans). For each sector, the *arrow* indicates the pattern of classification results in the scans with motion artifacts. For example, in healthy eyes, the temporal quadrant was "borderline" (i.e., *yellow*) in four scans without motion artifacts; in the corresponding scans with motion artifacts, the quadrant remained "borderline" in three cases, while it changed to "within normal limits" (i.e., *green*) in one case. Right-eye (*clockwise*) orientation was used to display quadrants and clock-hours. T, temporal; S, superior; N, nasal; I, inferior.

had greater RNFL thickness in clock-hours 4 and 5 (P values = 0.03), while in glaucomatous eyes, scans with motion artifacts had greater RNFL thickness in clock-hours 4, 5, 10, and 11 (P values $\leq$ 0.05) and lower RNFL thickness in clock-hour 7 (P = 0.05) than scans without motion artifacts.

To determine the frequency of RNFL thickness changes between scans with and without motion artifacts exceeding the test–retest variability of the instrument, mean reproducibility coefficients (RCs) from published Cirrus HD-OCT reproducibility studies were considered.[14–16] When not explicitly reported, RCs were calculated as 2.77 × within-subject standard deviation.[17] For average RNFL thickness, quadrants and clock-hours, changes above test–retest variability occurred in 2.86%, 3.57%, and 3.57% of cases, respectively, in healthy eyes, and in 4.00%, 3.00%, and 9.67% of cases, respectively, in glaucomatous eyes. We also determined the frequency of classification changes. When including "borderline," "within normal limits," and ">95th percentile of the normative distribution" results in the same category, in the two groups combined, average RNFL thickness, quadrant and clock-hour classification changes occurred in 0%, 2.35%, and 2.65% of cases, respectively. The number and type of classification changes that occurred in the scans with motion artifacts are presented in Figure 4.

The regression plots with R^2 and P values for average RNFL thickness and quadrants are presented in Figure 5. In general, although the trends were similar in the two groups, results were statistically significant in healthy eyes but not in

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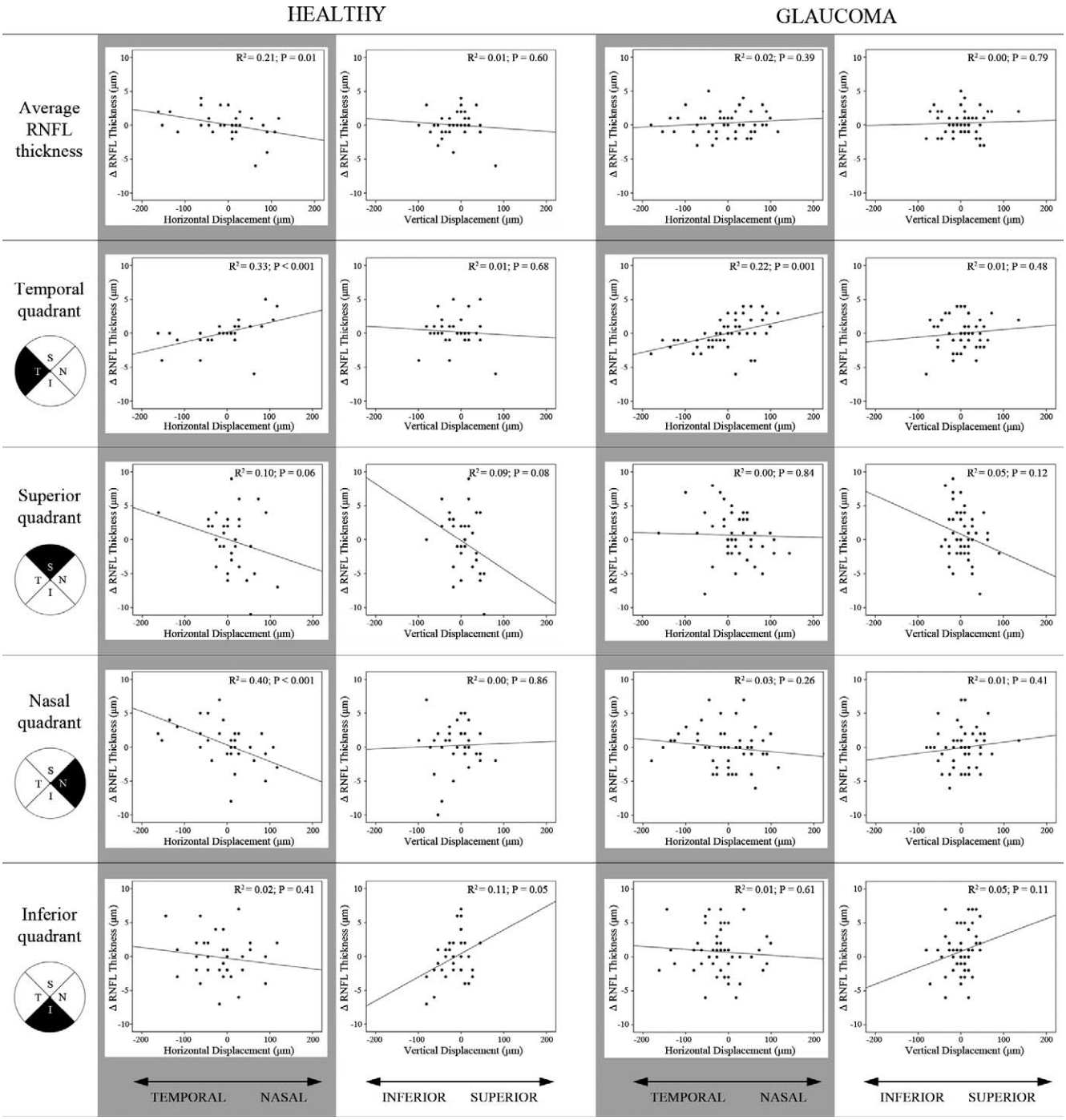

Figure 5. Regression plots of horizontal (*grey background*) and vertical (*white background*) scan circle displacement against change in RNFL thickness. *Arrows* (*bottom*) indicate the direction of the displacement.

glaucomatous eyes. As previously hypothesized, average RNFL thickness tended to increase with temporal displacements and decrease with nasal displacements (in healthy eyes, $R^2 = 0.21$, $P = 0.01$), while it did not appear to be affected by vertical displacements (in healthy eyes, $R^2 = 0.01$, $P = 0.60$). Results also indicated that displacements toward the optic disc margin were associated with increased RNFL thickness in the sector closer to the disc, while measurements were decreased in the sector displaced further away from the disc. These findings were confirmed by a GEE model that adjusted for the correlation between the two eyes of the same individual and between multiple pairs of scans from the same eye (data not shown).

The obtained regression equations allowed determining the minimum amount of scan circle displacements associated with RNFL thickness changes above test–retest variability. In the sectors where the model reached statistical significance, the outcome (RNFL thickness change) was replaced by the RC to derive the correspondent minimum displacement in micrometers. In healthy eyes, horizontal scan circle shifts of 423 and 325 μm corresponded to changes in average and quadrants RNFL thickness above test–retest variability, respectively. On

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average, horizontal scan circle displacements of 277 and 216 μm corresponded to changes in clock-hour RNFL thickness above test–retest variability in healthy and glaucomatous eyes, respectively.

Discussion

In this study, scan circle displacements occurred in all Cirrus HD-OCT scans with one motion artifact passing through the optic disc. There were no statistically significant changes in average and quadrant RNFL thickness between scans with and without motion artifacts. However, in some cases the magnitude of scan circle displacement detected in either direction produced RNFL thickness changes above test–retest variability and/or changes in classification results, which were more frequent in clock-hours than quadrants (see Fig. 4). A systematic analysis conducted in healthy and glaucomatous eyes also revealed that horizontal and vertical displacements were associated with RNFL thickness changes. In healthy eyes, a decrease in average RNFL thickness, compared to the reference scan, was associated with nasal scan circle displacements. In general, measurements for a given sector of the scan circle tended to increase for displacements occurring toward the optic disc margin, while they tended to decrease when the displacement occurred away from the disc margin.

These findings are in agreement with previous studies conducted with TD-OCT with the scan circle manually displaced up to 700 μm away from its original position.[4–6] In the present investigation, scan circle displacements did occur but they were more limited even in the presence of a motion artifact passing through the optic disc. However, it is possible that larger displacements may be found in a clinical setting in the presence of multiple motion artifacts or other artifacts significantly impacting image quality and the ability of the instrument to correctly identify the optic disc center. Therefore, it should be emphasized that the present findings may not apply to scans with multiple motion artifacts for which the soundness of the data is not known. Additional factors, such as those possibly related to inaccurate RNFL segmentation induced by the motion artifacts but not visibly noticeable, and/or factors unknown at the present time, may account for the amount of measurement variability not explained in this study and they may warrant further research.

The model used in our study to predict RFNL thickness changes due to scan circle displacements appeared to be more suitable in healthy eyes, where statistical significance was reached in average RNFL thickness and quadrants. In glaucomatous eyes with a larger sample size, although the trends were similar, scan circle displacements were not significantly associated with RNFL thickness changes in most sectors, including average RNFL thickness. This can be explained by the fact that our study was powered on the basis of a previous investigation conducted in healthy eyes. Higher variability that is usually observed in glaucomatous eyes may have negatively affected the strength of the association between scan circle displacement and RNFL thickness changes. It is also possible that in our subset of advanced glaucoma cases characterized by severe RNFL loss, changes might have been minimized owing to a "floor effect" (i.e., further RNFL thinning may not occur even for major displacements away from the disc margin).[18] These results suggest that the impact of scan circle displacement may be more profound in healthy eyes or eyes suspected of having glaucoma than in eyes with advanced disease.

From the obtained regression equations, we calculated the minimum scan circle displacements associated with RNFL thickness changes above the instrument's variability. The minimum amount of horizontal displacement necessary to produce such changes progressively decreased from average RNFL thickness to quadrants and clock-hours, suggesting that clock-hour measurements might be more susceptible to shifts of the scan circle along the horizontal axis than quadrant and average RNFL thickness measurements. To our knowledge, this is the first study to systematically evaluate scan circle displacements by using Cirrus HD-OCT. Because the device is provided with a built-in automated algorithm for scan circle placement, it is generally assumed that the same data points along the path of the scan circle are sampled over time. Previous studies[14–16] reported excellent reproducibility in healthy and glaucomatous eyes under optimal scan quality conditions. However, motion artifacts are common in clinical practice and they are often undetected when examining the Cirrus HD-OCT printout, particularly when they affect the optic disc region (Fig. 3). In our database composed of 2002 Cirrus HD-OCT optic disc scans, for example, motion artifacts occurred in 1180 (59%) cases. Considering only those scans with motion artifacts affecting the scan circle and/or the optic disc ($n = 921$), 55% had one single motion artifact, while the remaining 45% had more than one motion artifact. Although it is generally recommended that scans with visible motion artifacts should be excluded, the effects of motion artifacts on RNFL thickness measurement variability remain unclear. A previous investigation[19] did not find any significant differences in average and quadrants RNFL thickness between scans with and without motion artifacts. It is possible that the study lacked adequate power to detect changes in RNFL thickness. Based on the results of our study, motion artifacts involving the optic disc may affect Cirrus HD-OCT measurements and normative database classification results, particularly clock-hour RNFL thickness. Different mechanisms, not mutually exclusive, may be implicated. On one hand, motion artifacts may interfere with the instrument's ability to identify the RNFL boundaries. However, only one pair of scans with evidence of RNFL segmentation artifacts was excluded from this study. On the other hand, the scan shift produced by motion artifacts implies that different RNFL data points are sampled upon placement of the scan circle, even without significant scan circle displacement. Finally, motion artifacts may alter the shape and center of gravity of the optic disc, thus changing the position of the disc center with subsequent scan circle displacement.

Cirrus HD-OCT has developed specific software for glaucoma progression ("Guided Progression Analysis" or GPA), which includes automated registration/realignment of the scan area and automated scan circle placement. This software is used to detect significant changes in RNFL thickness over time. It is possible that GPA registration may fail, or be less reliable, in follow-up scans with motion artifacts. In addition, the current GPA report does not include RNFL thickness trends and classification results for quadrants and clock-hours. Thus, serial evaluation of the Optic Disc Cube 200 × 200 printouts still remains a widely used tool in clinical practice, further raising the clinical relevance of the present investigation.

Our study showed that displacements of a large magnitude may affect average RNFL thickness along with quadrant and clock-hour results. Therefore, it is important that clinicians identify motion artifacts passing through the optic disc and verify the position of the scan circle. Magnification of the en face image on the Cirrus HD-OCT screen may facilitate these tasks and it may allow for the detection of motion artifacts otherwise not visible on the Cirrus HD-OCT printout. Scans with motion artifacts passing through the optic disc should be excluded and clinicians should always interpret clock-hour measurements and classification results more cautiously.

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Our study has limitations. Although we were able to estimate the amount of horizontal and vertical scan circle displacement between two scans, differences in image rotation due to head tilt could not be objectively determined and were not considered in this study. Future research will determine the contribution of scan rotations to RNFL thickness changes, since head tilt has been suggested as a source of measurement variability for Cirrus HD-OCT.[20]

Scan circle displacement in scans with multiple motion artifacts was not evaluated owing to the technical complexity in realigning these images. It is conceivable that multiple motion artifacts passing through the optic disc involving the scan circle, or other artifacts not identified in this study, may represent an additional source of measurement variability.

It should be emphasized that this study was not designed to investigate the accuracy of the scan circle placement, since the position of the "true" optic disc center remains unknown to clinicians. Our models were built to predict changes in RNFL thickness as a result of *changes* in the position of the scan circle and not *errors*, intended as deviations from a true value. In fact, it was not assumed that the position of the scan circle was more accurate in the scans without motion artifacts. Rather, these scans were subjectively evaluated to be used as reference based on their optimal image quality. Longitudinal studies are necessary to further investigate the impact of scan circle displacements on the ability of the instrument to detect RNFL thickness changes over time.

In conclusion, this study evaluated the effects of scan circle displacements in Cirrus HD-OCT scans with motion artifacts passing through the optic disc, which appeared to be generally more pronounced in healthy than in glaucomatous eyes. The results confirmed previous findings with TD-OCT, in which measurements for a given sector of the scan circle tended to increase for displacement toward the optic disc margin and to decrease when the displacement occurred in the opposite direction. In some cases, such displacements produced RNFL thickness changes above the test–retest variability of the instrument and/or classification changes. However, average RNFL thickness and quadrants appeared to be more robust than clock-hours to scan circle displacements resulting from the presence of motion artifacts passing through the optic disc. Because these artifacts may be often difficult to detect, clinicians should be aware of these findings and carefully review the OCT en face images when interpreting Cirrus HD-OCT scans for glaucoma diagnosis and management.

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