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The Globe's Eccentric Rotational Axis

Why Medial Rectus Surgery Is More Potent than Lateral Rectus Surgery

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Purpose: Tables typically recommend greater lateral rectus (LR) than medial rectus (MR) surgical doses for horizontal strabismus of any given magnitude, a difference unexplained by mechanical models that assume globe rotation about its center. We tested this assumption during horizontal ductions.

Design: Prospective observational study.

Participants: Eighteen adult subjects with normal binocular vision.

Methods: Surface coil magnetic resonance imaging at 390 or 430 μm resolution was obtained using 2-mm–thick contiguous axial planes while subjects fixated targets in central, right, and left gaze. Angular displacements of lines connecting the corneal apex through the minor lens axis to the retina were measured to approximate clinical ductions. Globe centers were calculated from their area centroids. Apparent lens and globe-optic nerve (ON) junction rotations around the globe center were then compared with clinical ductions.

Main Outcome Measures: Apparent angular rotations of lenses and globe-ON junctions during horizontal ductions.

Results: Globe-ON junctions appeared to rotate significantly less around globe centers than did lenses for abduction (20.6°±4.7° vs. 27.4°±7.4°, ± standard deviation (SD), $P < 0.001$) and adduction (25.3°±6.7° vs. 31.9°±8.3°, $P < 0.001$). Both rotations differed significantly from clinical adduction (27.9°±8.3°, $P < 0.007$), but only in abduction was globe-ON junction rotation significantly less than clinical abduction (28.6°±9.4°, $P < 0.001$). The true geometric globe rotational center was 2.2±0.5 mm medial and 0.8±1.0 mm posterior to the geometric globe center and was displaced farther medially and posteriorly during adduction. This eccentricity imbues each millimeter of MR recession with approximately 30% more trigonometric rotational effect than equivalent LR recession.

Conclusions: The medial and posterior eccentricities of the normal ocular rotational axis profoundly influence horizontal rectus action. The proximity of the globe's rotational axis to the MR shortens its lever arm relative to the LR, explaining why mechanical effects of smaller MR recessions are equivalent to larger LR recessions. *Ophthalmology 2018;■:1–5 © 2018 by the American Academy of Ophthalmology*

Both simple[1-3] and complex[4-8] models of the biomechanical effects of extraocular muscle (EOM) action assume that the globe rotates about its geometric center. With this assumption, mechanical factors that determine idealized globe rotation in response to applied force are limited to the lever arm of each EOM insertion with respect to globe center,[2,9] the pulling direction of the EOM relative to its pulley,[6,7,10-16] and the tangency of the EOM insertion to the globe.[17]

However, the eye is not an isolated sphere of uniform density rotating in a frictionless environment. Instead, it is a nonuniform structure constrained by and attached to orbital tissues. The sclera and cornea vary in thickness from anterior to posterior,[18] whereas the lens, ciliary body, and vitreous body all have slightly different viscosities and densities.[19] In addition, whereas the 4 rectus EOMs have a relatively balanced distribution of insertions, the superior oblique and inferior oblique insertions are asymmetrically placed relative to the globe's geometric center.[5,20] Finally, in the posterior orbit, the globe-optic nerve (ON) junction is asymmetrically medial to the globe's geometric center.

Any eccentricity of the globe's axis of rotation changes the lever arm for each EOM and thus their respective torques even at identical EOM tensions, introducing a potentially important biomechanical nuance to the contributions of each EOM to duction. Analogous to the larger and smaller gears on a bicycle, displacements in EOM insertions along the globe surface closer to the rotational axis would rotate the globe more degrees per millimeter, whereas displacements of EOM insertions along the globe surface farther from the rotational axis would have less angular effect.

If the globe rotates about its geometric center, all structures on the globe surface should appear to move the same number of degrees of arc with respect to the globe center. For this study, we compared the apparent angular rotation of the lens with that of the globe-ON junction during abduction

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and adduction to determine if the globe does indeed rotate about its geometric center.

Methods

Participants

Eighteen adult volunteers (average age 59±12 SD years; 5 male, 13 female) were prospectively recruited through advertising for this study. Each subject consented in writing to a protocol conforming to the tenets of the Declaration of Helsinki that was approved by the University of California, Los Angeles Institutional Review Board. Every subject was evaluated with a comprehensive eye examination to verify normal motility, normal binocular alignment, and normal corrected vision.

Magnetic Resonance Imaging

With the use of a 1.5-T General Electric SIGNA scanner (Milwaukee, WI) enhanced with a dual-phased surface coil array (Medical Advances, Milwaukee, WI), high-resolution T2 fast spin echo axial magnetic resonance imaging (MRI) was performed[21] as subjects fixated a fiber optic target in central gaze and various right and left gaze positions. Images were obtained in contiguous 2-mm slices over a 10-cm or 11-cm field of view, yielding 390 μm or 430 μm in plane resolution.

Analysis

Digital MRI images for each gaze position were converted into image stacks and quantified with the *ImageJ* program (W. Rasband, National Institutes of Health, Bethesda, MD). For each gaze position, the rotation of midline structures of the face away from the scanner vertical was measured to vertically align the midline for all gaze positions (Fig 1). To measure duction, the angular displacement from the scanner vertical of a line from the apex of the cornea through the minor axis of lens to the retina was measured for each gaze position; the change in angle of that line in the various gaze positions approximated clinical measurements of duction.

Then, the geometric globe center was measured by manually outlining the largest globe cross-section that did not include the cornea and using the "Area Centroid" function of *ImageJ* to define the center of that globe cross-section with sub-pixel resolution. Likewise, the largest cross-section of the lens and the breadth of the attachment of the ON onto the globe were manually outlined (Fig 2), and the "Area Centroid" function was used to define the centers of the lens and globe-ON junction, respectively.

Once the globe center, lens center, and globe-ON junction were defined for each gaze position, geometry using the globe center as the common origin allowed calculation of the apparent angular rotation of the lens and globe-ON junction for each gaze position. Paired *t* tests were then used to compare rotations of the lens and globe-ON junction with each other and with clinical ductions.

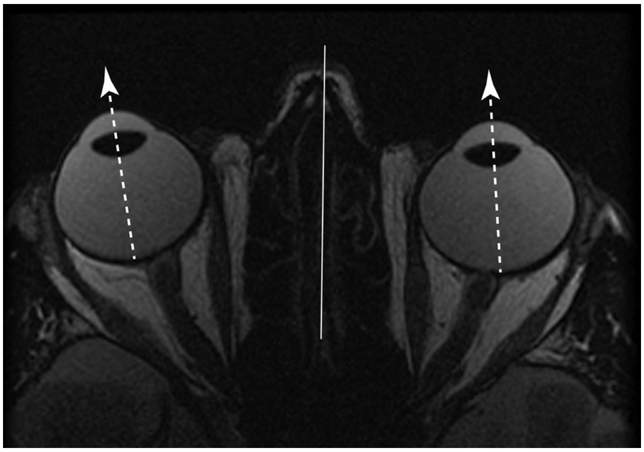

Figure 1. T2-weighted axial magnetic resonance image (MRI) of a normal subject in central gaze. *Dashed white lines* from the retina through the minor axis of the lens and corneal apex approximate the visual axes. The angular change in the *dashed lines* between gaze positions was used to measure clinical duction.

Results

Recruitment was halted after 18 subjects because there were no meaningful changes to the results after the 10th subject. Each subject completed imaging in 5 positions of gaze: central gaze, smaller and larger angles of right gaze, and smaller and larger angles of left gaze. Globe axial length averaged 24.5±1.2 mm. Table 1 summarizes the average clinical ductions and apparent lens and globe-ON junction rotations for the different gaze positions if oculocentric rotation is assumed. Overall, globe-ON junctions appeared to rotate significantly less around geometric globe centers than did the lenses in abduction (20.6°±4.7° vs. 27.4°±7.4°, $P < 0.001$) and adduction (25.3°±6.7° vs. 31.9±8.3°, $P < 0.001$). Both rotations differed significantly from clinical adduction (27.9°±8.3°, $P < 0.007$ for both), but only the globe-ON junction rotation appeared significantly less than clinical abduction (28.6°±9.4°, $P < 0.001$).

The foregoing differences imply that the globe does not rotate about its geometric center, but about a different rotational center for which computed rotations for every part of the eye are indeed equal. The intersection of lines connecting the lens center and globe-ON junction in central gaze and in eccentric gaze occurred at the true globe rotational center and represents the point about which the lens and globe-ON junction appeared to have equal rotational change (Fig 2). Table 2 summarizes the average displacements of the true globe rotational axis from geometric globe center for each of the different gaze positions studied. Overall, globe rotational axis was eccentric by 2.2±0.5 mm medial and 0.8±1.0 mm posterior to geometric globe center during horizontal gaze changes and was displaced farther medially and posteriorly during adduction than abduction. There was minimal correlation between the magnitude of the eccentricity of the axis of rotation and the axial length.

Greater proximity of the globe's rotational axis to the medial rectus (MR) insertion than the lateral rectus (LR) insertion implies a shorter lever arm for the MR than the LR. Thus, each millimeter of movement of the MR insertion in its arc along the globe surface generates a greater angular effect than a corresponding millimeter of movement of the LR insertion. Table 3 summarizes the predicted differences in globe rotation for 1 to 6 mm of surgical recession for the MR versus the LR, assuming a 24-mm diameter globe and typical EOM insertion locations.[5] The eccentric location of the globe's rotational axis imbues each millimeter of MR recession with more than 30% greater rotational effect than the equivalent LR recession.

Discussion

The commonly held assumption that the globe rotates about its geometric center must be discarded because this study