Rectus Extraocular Muscle Paths and Decompression Surgery for Graves Orbitopathy: Mechanism of Motility Disturbances

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PURPOSE. To study possible causes of motility disturbances that may result from orbital decompression surgery in patients with Graves orbitopathy and especially the role of rectus extraocular muscle paths.

METHODS. Sixteen patients with Graves orbitopathy were studied before and 3 to 6 months after translid (6 patients) and coronal (10 patients) orbital decompression surgery for disfiguring proptosis. Ocular motility changes were measured by comparing maximum ductions and severity of diplopia, and the positions and the displacements of the anterior rectus muscle paths were objectively measured using cine magnetic resonance imaging (MRI).

RESULTS. Averaged preoperative rectus muscle path positions were not different from those in normal subjects. Averaged postoperative muscle path positions were generally the same as preoperative paths. The only significant exceptions were centrifugal (outward from the orbital axis) displacements of the inferior rectus (IR) muscle path after translid surgery, and of the medial rectus (MR) muscle path after coronal surgery. The amount of IR path displacement with translid surgery was directly correlated with range of depression and with severity of vertical diplopia. The amount of MR path displacement with coronal surgery was inversely correlated with range of abduction and directly correlated with severity of horizontal diplopia.

CONCLUSIONS. The anterior orbital connective tissue seems to form a "functional skeleton" that is usually (except as noted for IR and MR) capable of keeping the rectus muscle paths aligned after decompression surgery and preserving the normal functions of rectus muscle pulleys. The centrifugal displacement of the IR and MR may increase the elastic component of the muscle force, leading to the specific patterns of motility disturbance that may occur in some patients after translid and coronal surgery. These findings suggest that standard surgical management of Graves orbitopathy should be supplemented. (*Invest Ophthalmol Vis Sci.* 2002;43:300–307)

Graves orbitopathy can lead to disfiguring proptosis, motility disturbances, and optic neuropathy. Orbital decompression surgery plays an important role in the rehabilitation of patients who have Graves orbitopathy.[1,2] and has been shown to be effective in restoring vision and reducing proptosis.[3] However, decompression surgery also induces or aggravates ocular motility imbalances in 10% to 80% of cases.[4–6] To date, explanations of this complication have been mostly speculative.

In 1989, Miller[7] introduced the rectus muscle pulley concept. The pulleys are musculofibrous structures in the anterior orbit that constrain the paths of the rectus muscles, relative to the orbital wall, similar to the way the trochlea constrains the path of the superior oblique muscle. They thus form the functional origin of these muscles[8] and have been demonstrated to lie a few mm posterior to the equator of the globe and to keep their position as gaze varies.[9] In the first experimental test of the pulley concept, Miller et al.[9] imaged muscle paths before and after transposition surgery and found that positions of muscle bellies relative to the orbital walls were little affected. Other studies have suggested that precise pulley location is critical to normal three-dimensional ocular kinematics.[10–12]

Most forms of decompression surgery involve extensive dissection of the periorbita, including the pulley insertions in the orbital wall; the creation of large osteotomies from orbital rim to apex; and incisions of the periorbita. If pulley stability relative to the orbital wall were due only to their direct insertions in the wall, such procedures would be expected to greatly influence ocular motility. From this viewpoint, it is surprising that motility disturbances occur in only a minority of patients after orbital decompression.

Our purpose is to study possible causes of motility disturbances as a result of orbital decompression surgery in patients with Graves orbitopathy. Rectus muscle paths were measured before and after the translid and coronal approach to decompression surgery, and the relationship of path displacements to ocular motility parameters— changes in maximum duction and diplopia—was determined.

METHODS

Sixteen patients were included in a prospective, nonrandomized cohort study conducted over 2 years. Included patients were between 18 and 65 years of age, with diagnosed Graves orbitopathy, who were candidates for either translid or coronal decompression surgery (described in the following sections) and were available for preoperative magnetic resonance imaging (MRI). Severity and activity of orbitopathy, the need for decompression surgery, and the approach were determined by a single surgeon in all cases (MPM). Criteria favoring translid surgery included unilateral proptosis or the possibility of a receding hairline (especially in males), because coronal surgery may

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leave a visible scar, whereas criteria favoring coronal surgery included severe or bilateral proptosis.[3] Patients were excluded from the study if they were ineligible for MRI because of the presence of any metallic material in the skull (except for dental fillings), a history of psychosis or claustrophobia, or near visual acuity less than 0.3, the minimum required to see the fixation marks in the scanner bore. Four patients were excluded because they did not complete the study: Two had claustrophobic symptoms during the first (preoperative) MRI scan, and two did not show up for the postoperative scan. None of these four patients had decompression-induced duction changes and all had diplopia classified as 'not worse' (defined later).

The study protocol involved three-dimensional cine MRI scanning and orthoptic examination (both to be described later) less than 1 week before decompression surgery and 3 to 6 months after surgery. Of the 16 patients, 6 (n = 10 orbits) underwent translid surgery (translid group) and 10 (n = 20 orbits) underwent coronal surgery (coronal group).

All subjects were treated in accordance with the tenets of the Declaration of Helsinki, and prior written informed consent was obtained after the nature of the study had been explained. The approval of the institutional review board of our hospital was granted for the research protocol and the informed consent form.

Ocular Motility

Ocular motility was always assessed by the same researcher. It consisted of cover test, cover prism test, Lancaster-Hess chart, and measurement (in degrees) of monocular maximum ductions (abduction, adduction, elevation, and depression) for both eyes, with the forehead and chin fixated in a modified Goldmann perimeter, as described previously.[13] Ocular motility was assessed 1 week before and 3 to 6 months after surgery. Horizontal and vertical diplopia changes as a result of decompression surgery were classified separately as follows: not worse, unchanged or less diplopia; 'worse,' a shift from no diplopia in any gaze to diplopia in the extremes of gaze or a shift of diplopia in the extremes of gaze to diplopia in primary or reading position; or 'much worse,' a shift of no diplopia to diplopia in primary or reading position.

Rectus Muscle Paths

MR gradient-echo, T_1-weighted, three-dimensional cine sequences were acquired in a stop–shoot manner on a 1.5-T MR scanner (Gyroscan NT, version 6.0; Philips Medical Systems, Best, The Netherlands). A head coil was used in turbo field echo (TFE) mode with the following settings: echo time (TE), 4.598 ms; repetition time (TR), 9.36 ms; flip angle, 20°; and matrix, 256 × 256 × 20, resulting in an acquisition time of 15 seconds per volume and a voxel size of 0.8 × 0.8 × 2.0 mm. The patients sequentially fixated on three rows of numbered marks placed on the inside of the scanner bore. After the acquisition of a volume (shoot), the patient fixated the next fixation mark (stop), and then the next volume was acquired, and so on. One row was horizontal relative to the head of the patient in the scanner and had nine fixation marks placed at intervals corresponding to approximately an 8° gaze angle difference (from −32° over 0° to +32°). Two rows were vertical relative to the head of the patient. Each of these two rows had seven fixation marks placed at 8° intervals (from −24° over 0° to +24°), one row straight ahead of the right eye (with the left eye abducted 20°), and one row straight ahead of the left eye (with the right eye abducted 20°). Thus, one sequence of nine MR volumes corresponding to nine different horizontal gaze positions (from 24° abduction to 40° adduction for each eye in the vertical 0° position), and two sequences of seven MR volumes corresponding to seven different vertical gaze positions each (from 24° elevation to 24° depression for each eye in 20° abduction, and the other eye in the horizontal 0° position) were obtained (Fig. 1). Actual gaze angles were corrected for parallax, taking into account interpupillary distance and distance of lateral orbital rim to the fixation marks.[14,15] Motion of the head of the patient was restrained by a flexible headband. The T_1 TRs were coded as 12-bit signal intensities, and the resultant volume sequences were stored on computer (Digital Imaging Communications in Medicine; DICOM 3.0 format; available at http://medical.nema.org/dicom.html) as series of separate consecutive images. The volume dimensions were calibrated in mm by the scanner software. To minimize postprocessing, the patient's head was aligned in the scanner to have the interhemispheric fissure aligned with the scanner's y-axis, and the long axis of the lateral rectus muscles with the z-axis (see Fig. 2 for an explanation of the axes).

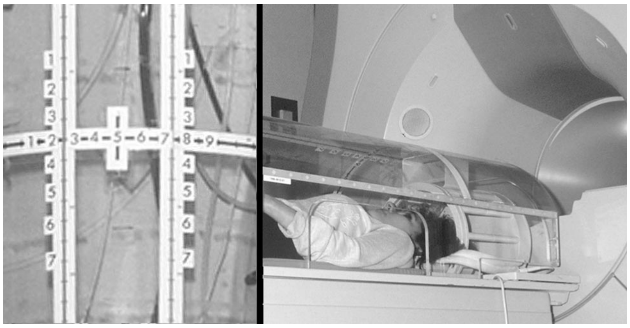

Figure 1. *Left*: detail of fixation device with numbered fixation marks; *Right*: subject on dolly in front of MR scanner bore, with fixation device in place and adjusted to proper distance from globes.

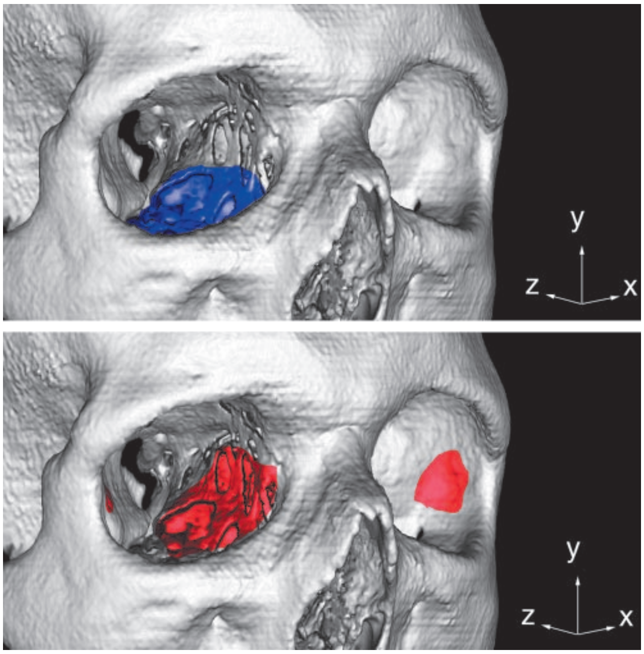

Figure 2. Osteotomies for (*top*) translid (two-wall) and (*bottom*) coronal (three-wall) decompression. Translid osteotomies are shown in *blue* and coronal osteotomies in *red*. The orbital walls and the anterior skull were volume rendered (http://www.isi.uu.nl/people/michael) from preoperative high-resolution computed tomography (CT) data. The medial orbit is very thin, and in some areas the bone is inaccurately absent. *Arrows*: orientations of the x-, y-, and z-axes.

Rectus muscle paths were defined as the line connecting the centroids (the digitally computed center of gravity of the muscle boundary) of muscles in consecutive planes perpendicular to the orbital axis. They were located according to the methods set forward by Clark et al.[16,17] Our method for determining rectus muscle paths from the volume data is very similar to theirs. In brief, image analysis was performed using the ImageJ program developed by Wayne Rasband (National Institutes of Health, Bethesda, MD; available at http://www.rsb.info.nih.gov/ij) and additional programs developed by the first author (available at http://www.isi.uu.nl/people/michael; please observe the copyright and disclaimer notices). The MRI volume data were normalized by a single (trilinear) interpolation to minimize data loss. For this interpolation, the interhemispheric fissure of the brain was aligned with the *y*-axis of the volume (approximately chin to crown), the line connecting both optic nerves in the coronal plane was aligned with the *x*-axis of the volume (approximately ear to ear), and the anteroposterior axis of the orbit was aligned with the *z*-axis of the volume (approximately nose to nape of neck). This last normalization was necessary because left and right orbits were scanned in a single volume sequence with the *z*-axis of the volume along the anteroposterior axis of the skull.[18] Normalizations of more than 5° were never needed. The gaze angle was checked using the position of the optic nerve–globe junction.

After enlarging the orbital volume data four times, the *x*-(mediolateral) and *y*-(superoinferior) coordinates of the area centroids of the extraocular rectus muscles and of the orbital soft tissue were measured (in mm) in the coronal plane by tracing their boundaries (see Fig. 3). The area centroid of the orbital wall circumference was used as the origin to normalize the muscle path positions to a semiorbitocentric coordinate system as shown in Figure 3. In this coordinate system, the *x*- and *y*-coordinates are measured relative to this origin, and the *z*-coordinates (referred to hereafter as the 'planes') are measured relative to the position of the globe–optic nerve junction.[9] Because the thin bony orbital walls are not visible in MRIs, the boundary of orbital soft tissue in that volume was used to trace the orbital wall circumference. This implies that the plane in which the orbital circumference and the orbital center were measured can differ before and after decompression surgery. In other words, no regard was paid to preoperative location of the orbital center or orbital walls in determining the origin of the postoperative coordinate system. The MR slice thickness (the *z*-dimension of the voxel) was 2.0 mm, and in the *x*- and *y*-dimension, 0.8 mm, making measurements in the *z*-dimension less accurate. Planes perpendicular to the orbital axis were defined relative to the globe–optic nerve junction. The rectus muscle paths were determined in plane 1, which lies between 2 and 4 mm anterior to the globe–optic nerve junction, the most anterior plane in which the rectus muscles paths have been shown to be stable as gaze varies.[16] This plane is located just a few millimeters posterior to the region where the sharp inflection (as gaze varies) of the rectus muscles was found in the studies by Clark et al.,[16,17] which is thought be the functional location of the pulleys. Because decompression surgery results in a posterior shift of the globe and the anterior orbital tissues, the anteroposterior location of plane 1 relative to the orbital bony walls was usually not the same before and after surgery. The position of the globe center was measured relative to the semiorbitocentric coordinate system, in the plane corresponding to the center of the globe on the *z*-axis, usually plane 6 or 7—that is, between 12 and 14 mm anterior to the junction. Rectus muscle cross-sectional areas (almost perpendicular to the long axis of the muscle) were determined in plane +1, between 2 and 4 mm posterior to the junction.

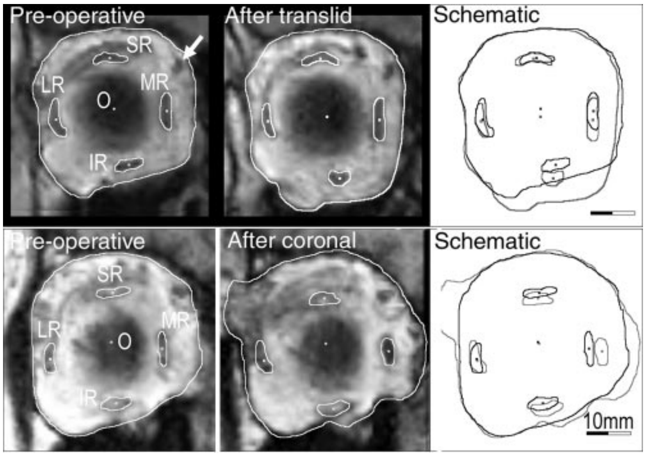

FIGURE 3. Determination of rectus muscle path centroids and displacement of orbital center and muscle paths in normalized MRI scan perpendicular to the orbital axis approximately 3 mm before the globe–optic nerve junction. *Top*: right orbit of typical translid surgical patient. *Bottom*: right orbit of typical coronal group patient. *Top*: muscle paths and orbital circumference before (*left*) and after (*middle*) translid two-wall surgery; schematic drawing (*right*) of circumference of orbital soft tissue and rectus muscle paths of same patient before (*black*) and after (*light gray*) surgery. The orbital tissue expands downward as a result of the decompression surgery. The inferior rectus muscle path shows the largest (downward) displacement relative to the orbital center, in this case 0.8 mm. The orbital center is also displaced downward, causing a relative upward displacement of the superior rectus path. *Bottom*: muscle paths and orbital circumference before (*left*) and after (*middle*) coronal three-wall surgery; schematic drawing (*right*) of circumference of orbital soft tissue and rectus muscle paths. The orbital tissue expands medially and laterally as a result of the decompression surgery. The medial rectus path is displaced the most, in this case 0.7 mm. The orbital center moves only slightly. The bony orbital walls are not visible. SR, superior rectus muscle path; IR, inferior rectus muscle path; LR, lateral rectus muscle path; MR, medial rectus muscle path; O, centroid of orbital circumference. *Top left*, *arrow*: superior oblique muscle tendon.

To validate this method, rectus muscle paths were measured in four control subjects (eight orbits) without ocular disease. No significant differences (two-tailed *t*-test according to Satterthwaite,[19] $P > 0.1$) were found between the *x*- and *y*-positions of the muscle paths determined according to our method and the results in the study by Clarke et al.[16]

Muscle paths were determined in primary position using the described method. To study the stability of muscle paths as a function of gaze, their motion as a function of gaze position was studied. Two-dimensional MRI dynamic color mapping (MRI-DCM) can objectively measure the motion in two-dimensional (2-D) sequences of MR images, using a gradient optical-flow algorithm,[15] and has been validated on phantoms.[14] 2-D image sequences were extracted from the horizontal and vertical gaze volume sequences in plane 1 and carefully registered, because motion estimation can be confused by head movements.[20] MRI-DCM was then used to determine the motion (in millimeters/degree of gaze change) of the muscle paths (relative to primary position) perpendicular to the orbital axis in the sequences. The motion estimates within the boundaries of the muscle tracings (described earlier) were averaged, so that two (one horizontal and one vertical) averages (in millimeters/degree of gaze change) were calculated for the motion of each muscle path, as a function of gaze.

Decompression Surgery

The different surgical techniques for decompression surgery have been described extensively.[1,3,21] Only those details pertinent to an understanding of their potential effect on rectus extraocular muscle paths are described in this report. During translid (two-wall) decompression surgery, the periorbita is dissected from the orbital floor and the medial wall. Large osteotomies are then created in the bony orbital floor from the orbital rim as far as the posterior wall of the antral cavity and approximately halfway up the bony medial wall, from the lacrimal bone to the posterior ethmoidal artery (see Fig. 2, top). During coronal (bilateral three-wall) decompression surgery, the periorbita is dissected from all four orbital walls up to the apex. Large osteotomies are then created in the bony lateral wall, in the medial wall from the lacrimal bone to the posterior ethmoidal artery, and in the medial part of the bony floor from the lower edge of the lacrimal bone approximately up to the infraorbital nerve (see Fig. 2, bottom). The bony strut between the inferior and medial walls is usually preserved, except in cases of extreme proptosis. In both surgical techniques, the anterior periorbita is incised circumferentially, and the posterior periorbita is incised radially to increase herniation of the soft tissues. The osteotomies are usually made as large as circumstances allow, depending on criteria

Table 1. Decompression Averaged Monocular Maximum Ductions Δ before and after Translid Surgery and Coronal Decompression Surgery

	Before Surgery	**After Surgery**	
	(Pooled, $n = 30$)	**Translid ($n = 10$)**	**Coronal ($n = 20$)**
Δ Abduction	39.3 ± 10.5	39.9 ± 9.8	***33.6 ± 9.0***
Δ Adduction	44.8 ± 6.2	46.8 ± 3.3	44.2 ± 3.9
Δ Elevation	26.2 ± 7.8	24.8 ± 10.7	23.3 ± 8.1
Δ Depression	55.5 ± 6.6	57.5 ± 4.6	56.4 ± 5.1

Maximum ductions in degrees ± SD from primary position. Average maximum ductions that undergo significant ($P < 0.05$) displacements from before to after surgery compared with all preoperative (both precoronal and pretranslid) positions are indicated in bold italic type.

assessed by the surgeon, such as the amount of preoperative proptosis, and on peroperative accessibility of bony areas and flexibility of intraorbital tissue.

Masking

The researcher localizing rectus muscle paths (MDA) was masked to orthoptic findings, and the researcher performing orthoptic examination (MELdG) was masked to rectus muscle path findings.

Statistical Analyses

Averages are presented as mean ± standard deviation (SD). Rectus muscle path positions were compared with a two-tailed Student's *t*-test. Centrifugal displacements are defined as either vertical or horizontal displacements of the muscle path away from the orbital center. The t value for multiple comparisons was corrected with the Bonferroni adjustment method.[19] To correlate rectus muscle path displacements to duction and diplopia changes, displacements were computed for each patient from the translid and coronal groups by subtracting the preoperative muscle path x- and y-positions from the postoperative x- and y-positions (in mm). Duction changes (Δ) for each patient were computed as the difference between the absolute value of the duction after surgery minus the absolute value of the duction before surgery (in degrees). Correlation coefficients (r) were computed using Pearson's product moment correlation function and compared using the statistic $t = \sqrt{\frac{n-2}{1-r^2}}$.[19] Linear regressions were computed using square error minimization. Data analysis was performed on computer (Excel 7.0; Microsoft Corp, Seattle, WA).

RESULTS

Baseline Characteristics

The mean age at inclusion was 48.4 ± 11.2 years (translid group, 49.2 ± 12.8; coronal group, 48.0 ± 10.7). The mean duration of Graves orbitopathy before surgery was 3.4 ± 3.3 years (translid group, 2.6 ± 2.2; coronal group, 3.8 ± 3.8). Five percent of patients were males (translid group, 14%; coronal group, 0%). The maximum ductions before and after surgery are given in Table 1. There were no significant changes from before to after surgery, except for a significant ($P = 0.04$) 5.7° average decrease in maximum abduction after coronal decompression. The distribution of diplopia changes was: in the translid-group, horizontal diplopia: not worse 6 (60%), worse 1 (10%), much worse 3 (30%); vertical diplopia: not worse 4 (40%), worse 2 (20%), much worse 4 (40%). In the coronal group, horizontal diplopia: not worse 5 (25%), worse 7 (35%), much worse 8 (40%); vertical diplopia: not worse 16 (80%), worse 2 (10%), much worse 2 (10%).

Path Positions and Displacements

Path positions were measured in primary position. Averaged x- and y-positions of the rectus muscle paths of the patient before and after decompression are summarized in Table 2. The averaged positions before decompression of all translid and coronal group patients were not significantly different ($P > 0.15$) from the average positions in normal subjects found in the study by Clark et al.[16] Nevertheless, the SDs of the averages of the translid and coronal groups were larger than the SDs in normal subjects. The average positions before decompression of the translid group were not significantly different from the average positions before decompression of the coronal group.

There was usually no difference ($P > 0.1$) between the averaged positions of the translid group before and after decompression surgery, except for a significant ($P < 0.00005$) centrifugal displacement of the inferior rectus muscle path (average displacement 2.1 mm). There was also no difference ($P > 0.1$) between the average positions of the coronal group before and after decompression, except for a significant ($P < 0.00005$) centrifugal displacement of the MR muscle path (average displacement 2.5 mm; Table 2, Fig. 4).

Paths and Motility

Correlation coefficients of muscle path displacements with changes in maximum duction and diplopia were determined in the translid group (Table 3) and coronal group (Table 4). Table 3 shows the correlation coefficients of vertical muscle path displacements with motility changes in the translid group.

Table 2. Averaged Rectus Muscle Path Positions before and after Translid Decompression Surgery and Coronal Decompression Surgery

	Before Surgery		**After Surgery**			
	(Pooled, $n = 30$)		**Translid ($n = 10$)**		**Coronal ($n = 20$)**	
	x	y	x	y	x	y
MR	12.8 ± 1.2	−0.1 ± 1.0	13.0 ± 1.0	−1.0 ± 1.2	***15.1 ± 1.4***	−1.5 ± 1.0
IR	2.8 ± 1.5	−11.8 ± 1.0	2.7 ± 0.9	***−13.9 ± 1.7***	3.1 ± 1.4	−12.5 ± 1.2
LR	−12.1 ± 1.1	−1.8 ± 1.0	−12.9 ± 1.4	−1.2 ± 1.4	−13.0 ± 1.3	−2.2 ± 1.4
SR	−0.4 ± 1.4	11.8 ± 1.2	−1.0 ± 1.2	13.0 ± 1.1	−1.0 ± 1.3	11.2 ± 1.0

Positions in mm ± SD relative to orbital center. Average positions that undergo significant ($P < 0.001$) displacements after surgery compared with all preoperative (both precoronal and pretranslid) positions are indicated in bold italic type. MR, medial rectus muscle path; IR, inferior rectus muscle path; LR, lateral rectus muscle path; SR, superior rectus muscle path.

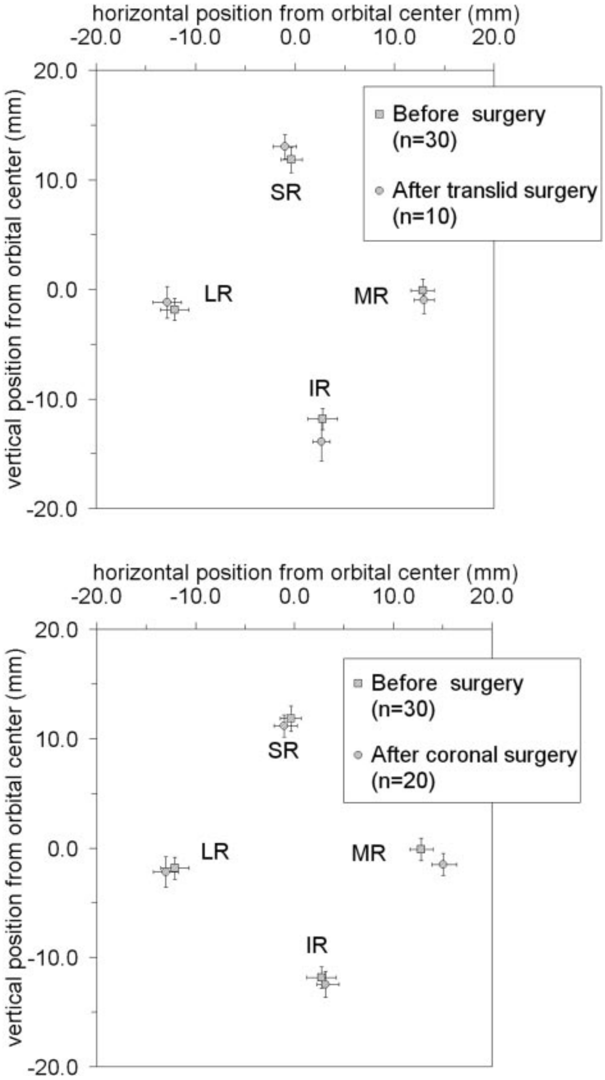

FIGURE 4. Averaged rectus muscle paths positions in plane 1 (*top*) before surgery and after translid decompression surgery and (*bottom*) before surgery and after coronal decompression surgery. The averaged positions before surgery are the same in both instances and have been averaged over all patients in the translid and coronal groups. The positions of the paths 2 to 4 mm anterior to the globe–optic nerve junction (plane 1) are shown in millimeters relative to the orbital center and as if facing the subject, for a right-side orbit. Paths for the left orbit have been mirrored. Error bands, ±1 SD. SR, superior rectus muscle path; IR, inferior rectus muscle path; LR, lateral rectus muscle path; MR, medial rectus muscle path.

There was a significant ($P < 0.007$) positive correlation ($r = 0.9$; 95% confidence interval [CI], 0.74–0.98) between the increase of maximum depression and the amount of centrifugal displacement of the inferior rectus muscle path. This relationship is illustrated in the scatterplot in Figure 5, with a linear regression of $R^2 = 0.72$ also shown. There was also a significant ($P < 0.004$) positive correlation ($r = 0.9$; 95% CI, 0.79–0.98) between an increase in vertical diplopia and the amount of centrifugal displacement of the inferior rectus muscle path. All other correlations of any displacement with any vertical or horizontal motility changes, and especially with superior rectus displacement and maximum elevation, were not significant ($P > 0.2$) in the translid group patients.

Table 4 shows the correlation coefficients of horizontal muscle path displacements with motility changes for the coronal group. There was a significant ($P < 0.003$) negative correlation ($r = -0.7$, 95% CI, −0.92 to −0.43) between increase in maximum abduction and the amount of centrifugal displacement of the medial rectus muscle path. Thus, a larger displacement correlates with a decreased maximum abduction. This relationship is illustrated in Figure 6, with a linear regression of $R^2 = 0.58$ shown. There was also a significant ($P < 0.05$) positive correlation ($r = 0.6$; 95% CI, 0.14–0.82) between an increase in horizontal diplopia and the amount of centrifugal displacement of the medial rectus muscle path. All other correlations of displacements with vertical and horizontal motility changes, and especially maximum adduction, were not significant ($P > 0.2$) in the coronal group.

TABLE 3. Correlation between Centrifugal (from the Orbital Center Outward) Vertical Muscle Path Displacement δ_y to Increase in Maximum Duction Δ and to Change in Diplopia in the Translid Group

	MR δ_y	IR δ_y	LR δ_y	SR δ_y
Δ Abduction	0.0	−0.1	−0.3	0.2
Δ Adduction	0.2	0.7	−0.4	0.4
Δ Elevation	−0.7	0.0	0.4	0.6
Δ Depression	0.1	***0.9***	−0.5	0.6
Horizontal diplopia	0.1	0.1	0.3	−0.2
Vertical diplopia	0.4	***0.9***	−0.6	0.4

A positive correlation means that a centrifugal displacement is correlated to an increase in maximum duction or more diplopia. Significant correlations ($P \leq 0.05$) are shown in bold italic type, others in regular type. SR, superior rectus muscle path; IR, inferior rectus muscle path; LR, lateral rectus muscle path; MR, medial rectus muscle path. $n = 10$.

Table 5 shows that rectus muscle cross-sectional areas in plane +1 did not significantly ($P > 0.4$) change as a result of decompression surgery. The x- and y-coordinates of the center of the globe did not shift significantly ($P > 0.15$) relative to the orbital center from before to after surgery in either group.

Path Stability as Gaze Varies

The average motion computed using DCM of the rectus muscles in plane 1 perpendicular to the orbital axis was 0.25 ± 0.12 mm per gaze change of 8°, for all muscle paths in both the translid and coronal groups, for both horizontal and vertical gaze sequences and both before and after surgery. Visual inspection of the sequences showed the motion to be regular over the entire gaze trajectory, without sudden changes at the extremes of gaze.

TABLE 4. Correlation between Centrifugal Horizontal Muscle Path Displacement δ_x to Increase in Maximum Duction Δ and to Change in Diplopia in the Coronal Group

	MR δ_x	IR δ_x	LR δ_x	SR δ_x
Δ Abduction	***−0.7***	−0.2	−0.4	0.0
Δ Adduction	0.0	−0.2	0.5	−0.4
Δ Elevation	0.3	−0.2	0.5	−0.2
Δ Depression	0.1	−0.5	0.4	−0.2
Horizontal diplopia	***0.5***	0.0	0.3	−0.2
Vertical diplopia	−0.2	−0.3	0.3	−0.4

A positive correlation means that a centrifugal displacement is correlated to an increase in maximum duction or more diplopia. Significant correlations ($P \leq 0.05$) are shown in bold italic type, others in regular type. SR, superior rectus muscle path; IR, inferior rectus muscle path; LR, lateral rectus muscle path; MR, medial rectus muscle path. $n = 20$.

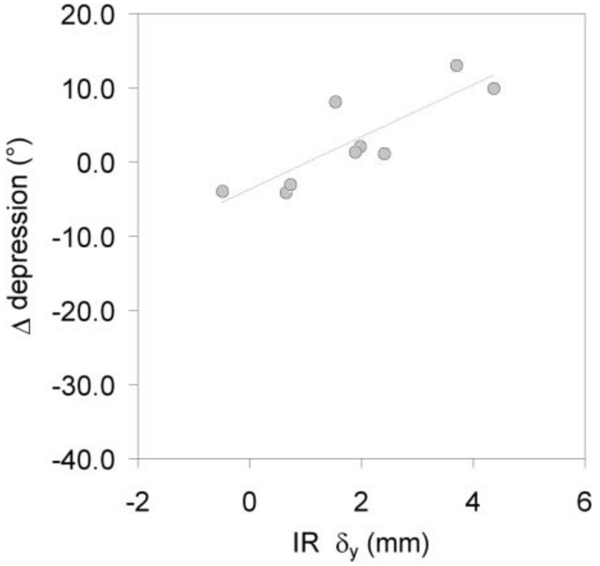

FIGURE 5. Scatterplot of centrifugal (i.e., from the orbital center outward) vertical displacement of the inferior rectus muscle path IR δ_y (in mm), resulting from translid decompression versus increase in maximum depression Δ (in degrees); $n = 10$. The *straight line* is a linear regression with least squares $R^2 = 0.72$.

DISCUSSION

The findings indicate that (1) anterior rectus muscle path positions in patients with Graves orbitopathy, with similar restricted motility as the patients in this study, are the same as in normal subjects[16]; (2) rectus muscle path stability (as gaze varies) in patients with Graves orbitopathy, with similar restricted motility as the patients in this study, is the same as in normal subjects[16]; (3) rectus muscle path positions are generally unchanged from before to after decompression surgery, with two exceptions: Translid surgery results in an average of 2.1 mm centrifugal displacement of the inferior rectus muscle path, and coronal surgery results in an average 2.5 mm centrifugal displacement of the medial rectus path; (4) rectus muscle path stability (as gaze varies) is unchanged from before to after decompression surgery; and (5) the amount of centrifugal displacement as measured in the semiorbitocentric coordinate system (which may lead to less accurate results than measurements in an oculocentric coordinate system, as discussed later) is related to the amount of change of two reasonably objective parameters of ocular motility disturbance: the amount of change of maximum duction and the amount of change of diplopia as a result of decompression surgery.

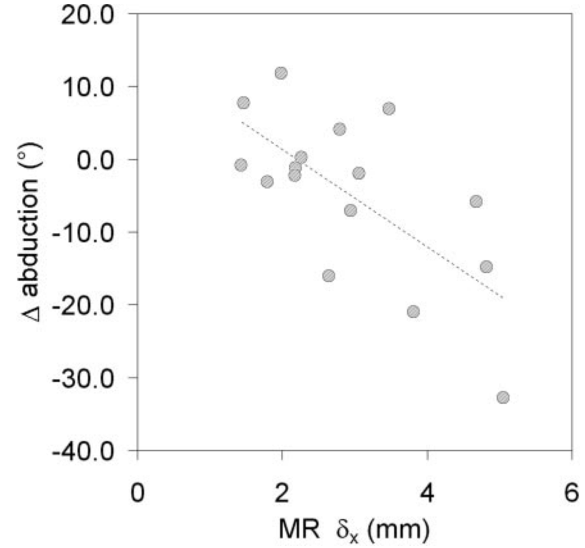

FIGURE 6. Scatterplot of centrifugal horizontal displacement of the medial rectus muscle path MR δ_x (in mm), as a result of coronal decompression versus increase in maximum abduction Δ (in degrees); $n = 20$. The *straight line* is a linear regression with least squares $R^2 = 0.50$.

TABLE 5. Averaged Rectus Muscle Cross-Sectional Areas before and after Surgery (Translid and Coronal Groups)

	Before Surgery	After Surgery
MRM	32.5 ± 9.1	32.7 ± 09.1
IRM	20.3 ± 6.4	21.5 ± 07.9
LRM	18.5 ± 3.5	19.7 ± 04.2
SRM	16.8 ± 4.3	17.1 ± 04.7

Differences are not significant ($P > 0.5$). SRM, superior rectus muscle; IRM, inferior rectus muscle, LRM, lateral rectus muscle; MRM, medial rectus muscle. Data are expressed in mean mm^2 ± SD.

It can be argued that the displacements are not the effect of surgery, but of measurement errors or the fact that the muscle paths are unchanged in primary position only and are unstable as gaze varies because of weakened coupling to the orbital walls. Indeed, our method of inferring rectus muscle paths differs from that in the literature, in that the voxel size in the volumes obtained by this method is larger than that used by Clark et al.,[16] and the normalization interpolation may have introduced subtle shifts. However, we have taken great care to validate our method, as mentioned in the Methods section, and there were no significant differences between positions in normal subjects, determined by our methods and those described by Clark et al. The larger standard deviations compared with those in Clark et al. are probably an effect of the larger and more variable cross-sectional muscle areas due to the orbitopathy. (The advantage of our method is that patients must fixate a single target for only 15 seconds, resulting in less motion artifacts and MR noise.)

Another argument in favor of an effect of surgery is that specifically the muscles closest to the largest osteotomy (i.e., the orbital floor in translid surgery and the medial wall in coronal surgery), were found to have the largest displacements. That the displacements are due to surgery and not an effect of gaze position, caused for example by weakened coupling, is indicated by the results from the MRI-DCM motion study. These indicate that muscle paths both before and after surgery move only relatively slightly as gaze varies. If the motion is assumed to be regular over the whole trajectory, a motion of 0.25 ± 0.12 mm per gaze position corresponds to average displacements of 0.75 ± 0.36 mm on abduction of 24°, 1.0 ± 0.48 mm on adduction of 40°, 0.75 ± 0.36 mm on elevation of 24°, and 0.75 ± 0.36 mm on depression of 24°, which are similar to the displacements found in normal subjects.[16]

Our findings indicate that the positions of most rectus muscle paths remain unchanged by decompression surgery. Nevertheless, specific extraocular muscle paths are displaced in a specific, centrifugal manner—namely, the inferior rectus muscle path after translid surgery and the medial rectus path after coronal surgery. This is not surprising, in view of the close relationship of the involved muscles and their bony support (the orbital floor respectively the medial wall), which is removed. It is important to understand that the displacements are relative to the functional center of the orbit. For example, the path of the superior rectus muscle can obviously not be displaced upward as a result of translid surgery, because the orbital roof is not removed. However, because the orbital contents are shifted downward, the functional center also shifts downward, and relative to this center, the path may be displaced upward in some patients.

How do these specific displacements cause ocular motility disturbances? The findings indicate that the amount of centrifugal displacement of a rectus muscle path is related to the amount of specific changes in maximum duction and diplopia after both translid and coronal surgery. The amount of centrifugal displacement of the inferior rectus muscle path was found to be related to an increase in maximum depression and vertical diplopia after translid surgery in each patient. Similarly, the amount of centrifugal displacement of the medial rectus muscle path was found to be related to a decrease in maximum abduction and horizontal diplopia after coronal surgery. Because the center of the globe did not shift significantly from before to after surgery, the centrifugal displacement of the anterior path of a muscle results in an increase in the length of its path to the globe to an even larger amount (because the muscle has to 'fold' through the pulley). The result is an increase in the elastic component of the muscle force, causing either an increased duction in the direction of action of that muscle or a decreased duction in the direction of the antagonist of that muscle. In this regard, the pulley is part of the problem: If the pulley were not there or were more elastic, the path would not have to deviate so much.

Other explanations that have been proposed for the induction of postoperative motility disturbance after decompression surgery include posterior removal of the ethmoid,[22] amount of proptosis reduction,[23] preoperative abnormal motility,[23,24] activity and severity of Graves orbitopathy, and previous radiotherapy.[25] However, little evidence has been brought forward to support these explanations, and most of the studies have been retrospective and based on comparisons of outcome of different surgical techniques. Size and extent of osteotomy, muscle paths, and postsurgical muscle displacements were never determined. In a study of 138 patients from the same institution and operated by the same surgeon as the patients in this study, Kalmann[25] was unable to establish any relationship of age, gender, duration of orbitopathy, severity of orbitopathy, previous treatment with steroids, previous treatment with radiotherapy, amount of proptosis reduction, or amount of preoperative motility disturbances, of ductions or of diplopia, to newly induced or aggravated diplopia by either coronal or translid decompression surgery. Of note, Seiff et al.[26] observed that not incising the anterior periorbita leads to a lower incidence of postoperative diplopia. This fits with the mechanism introduced in this study, because the rectus muscle pulleys that determine the muscle paths insert into the anterior periorbita. In another retrospective study, Goldberg et al.[27] showed that balanced decompression surgery (of the lateral and medial wall) results in less postoperative diplopia than unbalanced decompression surgery (lateral wall only). The coronal decompression can be thought of as "balanced" and the translid decompression as "unbalanced," if the decompression of the floor is discounted. Our findings do not give evidence that the centrifugal displacement of the medial rectus muscle is less with the balanced approach than with the unbalanced approach. However, the osteotomy in the medial wall is much smaller in the translid than in the coronal approach, and in the coronal approach the osteotomy in the lateral wall is much smaller than that in the medial wall. One may, on the basis of our findings, be justified in expecting the centrifugal displacements of the medial and lateral rectus muscle paths to be of comparable size as a result of balanced decompression surgery and, possibly, a lower frequency of manifest diplopia and ocular muscle imbalances, provided that lateral and medial wall decompression results in lateral and medial osteotomies of comparable size. Other theoretical explanations for duction changes, such as muscle atrophy or hypertrophy are unlikely, because the findings indicate that muscle cross-sectional areas do not change as a result of surgery.

In the present study, muscle path positions were measured in semiorbitocentric coordinates.[16] The effect of muscle actions is determined by their topographical relation to the (center of the) globe, and an oculocentric coordinate system is expected to be more precise in modeling the effect of muscle path position on ocular motility.[17] For the present study, a semiorbitocentric coordinate system was chosen to allow comparisons of our results to earlier muscle path studies in normal subjects[16] and because the pulleys stabilize the muscle paths relative to the orbit, so that displacements of these paths should also be measured relative to the orbit. The two coordinate systems do not exclude each other and are, mathematically speaking, dependent.

Theoretically, a postoperative centrifugal displacement of one of the muscle paths could have been accompanied by a shift of the globe center in the same direction—something that could not be detected if just the muscle paths are measured relative to the orbital center—and in that case, the proposed mechanism could not apply. However, the center of the globe was found not to shift significantly as a result of surgery.

In contrast to what might be expected on the basis of the studies by Clark et al.,[12,28] and Krzizok et al.,[29] it is not the postoperative position, per se, of any muscle path, but the surgically induced displacement of the path that is related to motility parameters.

It is important to emphasize the implication of the finding that the rectus muscle paths generally remain unchanged from before to after decompression surgery, even though the insertions of the pulleys on the periorbita and orbital wall have been damaged or removed altogether. The implication is that either the anterior connective tissue in the orbit is stable enough to permanently hold the muscle paths in their proper positions without the direct coupling to the orbital wall or periorbita ever being restored, or the connective tissue is capable of holding the paths in their normal relative positions long enough for their normal direct attachments to the orbital wall and periorbita to become reinserted, so that direct coupling is reestablished.

The findings in the current study do not allow the assertion of either the first or the second hypothesis, because we were unable to reliably determine the rectus muscle paths immediately after surgery. This was found to be very difficult, because MRI scans obtained at this time are of low quality because of the edematous orbital tissues, which interferes with the T_1 signal from the fat. However, anecdotal evidence suggests that the coupling to the orbital wall may not be very important. The ocular motility of these patients was evaluated quite frequently after decompression surgery with cover and duction and prism tests, and no important differences were found between the motility at 2 weeks and at 6 months after surgery (MELdG, personal communication, 2001). In either case, the stability indicates that the anterior orbital connective tissue forms a functional skeleton of connective tissue that is able to maintain spatial relationships between orbital structures, even without direct coupling to the bony orbit. These findings seem to confirm the observations of Koornneef[30] and Demer et al.,[31] that the connective tissue posterior to Tenon's capsule has sufficient stiffness to maintain spatial relationships among orbital structures,[30,31] which may also explain why motility disturbances after decompression surgery do not occur more often.

In conclusion, in the patients in this study, rectus muscle paths were found to be the same in patients with Graves orbitopathy as in normal subjects. Decompression surgery was found not to influence the stability of the paths as gaze varied and was also found not to cause displacements of the paths, except for translid surgery, which was found to displace the path of the inferior rectus, and coronal surgery, which was found to displace the path of the medial rectus muscle to a greater or lesser degree. A biomechanical mechanism for the motility disturbances caused by decompression surgery may be that the osteotomies cause a centrifugal displacement of the closest rectus muscle path and may so increase the elastic component of the muscle force. Further study in larger groups is required to confirm these findings, to see whether it is possible to predict which patients are the most susceptible to centrifugal muscle displacements and whether decompression surgical techniques can be adapted to prevent displacements in the future. Meanwhile, to prevent ocular motility disturbances as much as possible, it may be advisable to avoid osteotomies near the locations of the pulleys, or extending them to the orbital rim, and avoid incision of the anterior periorbita (and the posterior periorbita over the muscles).

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