Reprinted from OPHTHALMOLOGY, Vol. 100, No. 4, April 1993
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Effect of Transposition Surgery on Rectus Muscle Paths by Magnetic Resonance Imaging

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Purpose: To evaluate effects of transposition on extraocular rectus muscle paths in middle and deep orbit.

Methods: The effect of various transposition procedures was assessed in five patients, using surface coil magnetic resonance imaging (MRI), performed with controlled gaze before and after surgery. Path changes were compared with those expected under conventional concepts of functional orbital anatomy, quantified by biomechanical modeling.

Results: Vertical rectus transpositions of 6 to 10 mm produced changes in muscle paths of 3 mm or less, assessed posterior to the equator of the globe. Lateral rectus transpositions as large as 10 mm resulted in almost no movement of muscle bellies. Conventional modeling predicted much larger changes.

Conclusion: The authors observed less movement of rectus muscle bellies relative to orbital walls than would be expected under the traditional assumption that transposed muscles follow the shortest path from origin to insertion. This implies that middle and deep orbital tissues (connective tissues and compartmentalized orbital fat) constrain the paths of rectus muscle bellies, preventing them from sliding freely to follow their transposed insertions. The authors propose that these tissues function as "pulleys" elastically coupled to the orbital wall, and that they are important determinants of extraocular muscle function. *Ophthalmology 1993;100:475–487*

Extraocular rectus muscles are commonly transposed to correct strabismus due to complete extraocular muscle paralysis and "A" and "V" pattern misalignments.[1] In contrast to procedures like recession and resection, which mainly alter muscle force, transposition mainly alters direction of muscle action. The effects of muscle transposition are not completely predictable, and only a few of the many transpositions with therapeutic potential are attempted by clinicians. To better understand the effects of transposition and other strabismus surgery, quantitative biomechanical models of orbital static mechanics have been developed.[2–11] These models are systems of equations, implemented as computer programs, which attempt to account for all elastic and contractile forces acting on the globe in any gaze position. Models able to simulate clinical alignment tests reflect the innervational linkage of the two eyes, and therefore have been called models of binocular alignment. A correct and complete model would be able to predict the effects of any manipulation of innervation or orbital mechanics.

Biomechanical models are no better than the physiologic knowledge they embody, and current models all assume that rectus muscle bellies are relatively free to move about the orbit during eye rotation. We believe that this

Originally received: February 10, 1992.
Revision accepted: October 22, 1992.

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Presented in part at the Association for Research in Vision and Ophthalmology Annual Meeting, Sarasota, May 1992.

Supported by grant 1RO1 EY08313 from NIH/NEI, Bethesda, Maryland (Drs. Demer and Miller), core facilities grant EY06883 from NIH, Bethesda, Maryland, to Smith-Kettlewell Eye Research Institute, core facilities grant EY00331 from NIH, Bethesda, Maryland, to University of California, Los Angeles, a Research to Prevent Blindness/Research Manpower Award, New York, New York (Dr. Demer), and a Karl Kirchgessner Foundation Award, Los Angeles, California (Dr. Demer).

Dr. Demer was a Research to Prevent Blindness William and Mary Greve International Research Scholar.

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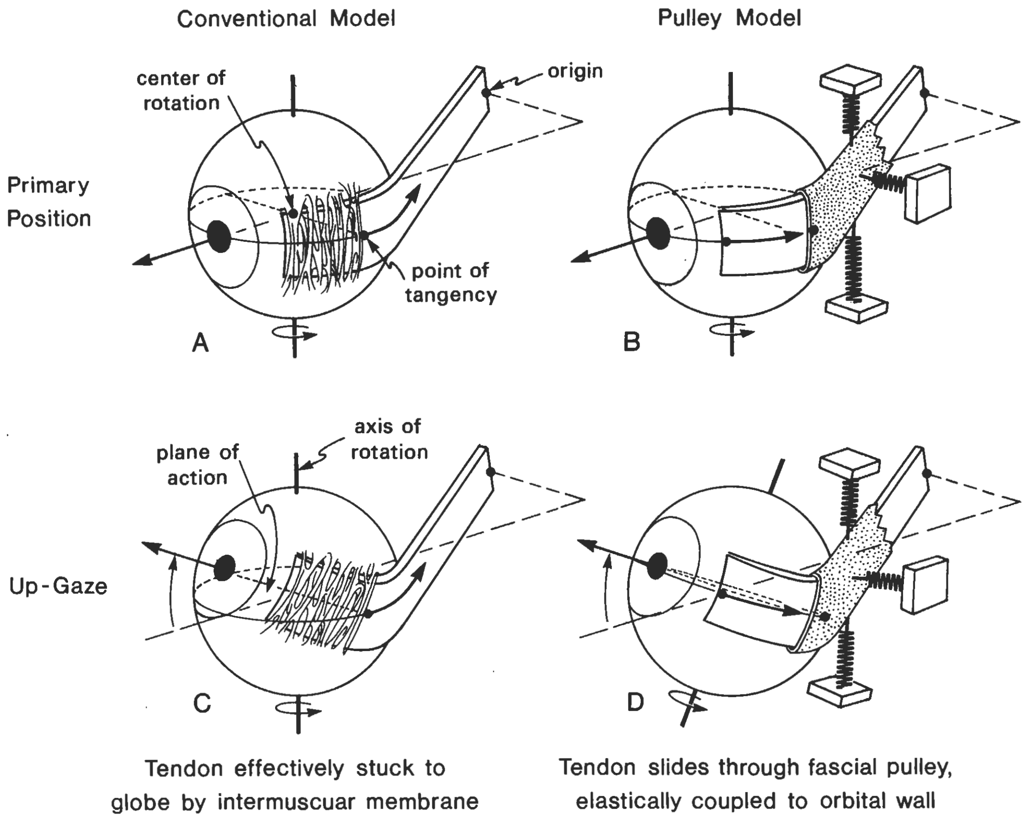

Figure 1. Diagrammatic representation of the relationship between a lateral rectus muscle and the globe, showing two possible explanations for the observed immobility of rectus muscle bellies relative to the orbit. A and C, the conventional model supposes that rectus tendons are bound to the globe by intermuscular membranes and muscle "foot plates" and are otherwise unconstrained as they course from their points of tangency with the globe to their origins in the orbital wall. B and D, the pulley model supposes that rectus tendons pass through connective tissue pulleys that are elastically coupled to the orbital walls.

assumption is the reason why these models predict greater effects from muscle transposition surgery than are actually observed (unpublished observations). That is, the models fail in simulating transposition surgery because they do not reflect the fact that the paths of muscle bellies are significantly constrained by orbital connective tissues. This failure limits the clinical usefulness of these models, and highlights a fundamental deficiency in our understanding of oculomotor physiology.

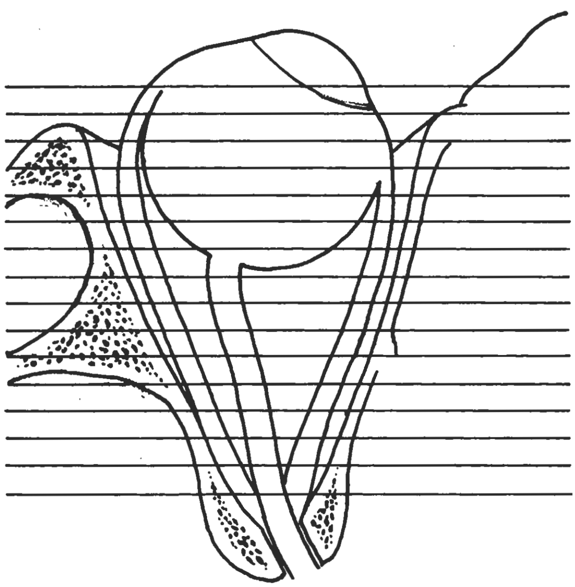

Figure 2. Diagram of magnetic resonance imaging "scout scan" shows location of slice planes perpendicular to the orbital axis.

Recent imaging studies suggest the importance of orbital connective tissues. Miller and Robins[12] sutured metallic markers to the extraocular muscles of monkeys and used plane film x-rays to visualize their paths as a function of gaze. They found that, although anterior muscle tendons (of course) move with the rotating eye, the paths of muscle bellies remain essentially fixed relative to the orbital walls. Miller[13] used surface coil magnetic resonance imaging (MRI) and quantitative three-dimensional reconstruction to demonstrate rectus muscle functional anatomy in cardinal positions of gaze. Confirming in normal human subjects the previous findings in monkey, Miller[13] found that rectus muscle bellies are immobile in the orbit over the full range of normal gaze. This finding is in agreement with a computed tomographic study by Simonsz et al.[14]

The stability of rectus muscles can be explained in two ways, illustrated in Figure 1. The first explanation (Figs 1A and 1C) is based on what we take to be the *conventional model* of orbital connective tissues[2] according to which anterior orbital connective tissue stabilizes each rectus muscle with respect to the globe, from insertion to point

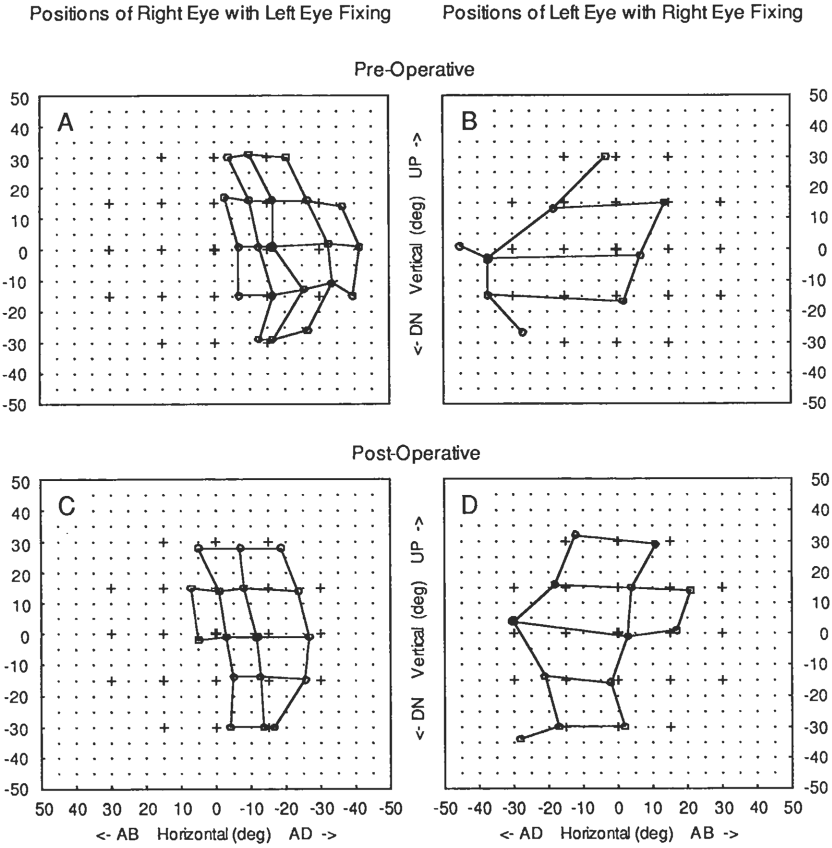

Figure 3. Case 1. Hess charts show positions assumed by each eye moving passively as the fellow eye fixates targets at standard gaze angles. Abscissa is horizontal eye position in degrees of arc (abduction [AB] positive); ordinate is vertical eye position in deg (elevation [UP] positive). Crosses (+) are attempted fixations; corresponding circles (O) are actual positions of the passively moving eye. The heavy cross and circle in each panel correspond to primary gaze position. Positions of the right eye are shown on the left, and positions of the left eye on the right (reversing the usual Hess chart convention for consistency with the convention for clinical photographs). A, preoperative positions of the right eye. B, preoperative positions of the left eye. Measurements are missing for the many fixation directions that could not be attained. C, postoperative positions of the right eye. D, postoperative positions of the left eye.

of tangency. Intermuscular membranes, forming a sort of cap around the anterior globe, might serve this function. Under the conventional model, the *axis of rotation* (the axis about which contraction of the muscle tends to rotate the globe) is perpendicular to the *muscle plane* or *plane of action,* which plane is determined by the *center of rotation, origin,* and *point of tangency.* The muscle acts as though it were inserted at the point of tangency, and posterior to this point the muscle path is assumed unconstrained until it reaches the origin. Depending on the exact configuration and stiffness of intermuscular membranes, the point of tangency, and so the axis of rotation, may be stable during rotation out of the muscle plane (compare Fig 1A with 1C). Such anterior connective tissues would be severed by transposition surgery, which would therefore be expected to produce large changes in the deep orbital positions of otherwise unconstrained rectus muscle bellies.

The second explanation (Figs 1B and 1D) supposes that the connective tissue sheaths through which the muscles pass act like pulleys elastically coupled to the orbital wall. The orbital dissection studies of Koornneef[15] delineate an extensive retinaculum of orbital connective tissues, surrounding the rectus muscles, and coupling them to the orbit and to each other. These fasciae were found consistently across subjects and, with the orbital fat they enclose, could support a pulley mechanism. Whether they do remains an empirical question because Koornneef's anatomic and histologic studies provide no measure of the mechanical effects of these tissues. Note that orbital me-

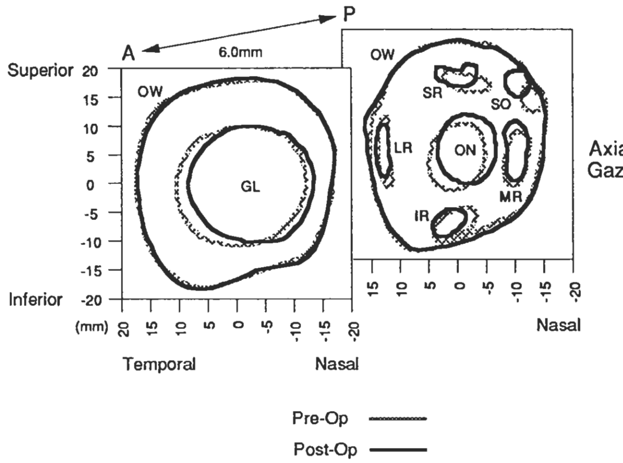

Figure 4. Case 1, magnetic resonance imaging slice data. Outlines of orbital structures traced from magnetic resonance imaging slices perpendicular to the orbital axis, before (light lines) and after (dark lines) transposition surgery. Pre- and postoperative data were aligned with reference to the orbital walls. An image is shown at the level of the junction of the globe and optic nerve (P = "posterior"), and a slice several millimeters anterior to this (A = "anterior"). Orbital structures shown are: OW = orbital wall; GL = globe; ON = optic nerve; LR = lateral rectus muscle; MR = medial rectus muscle; SR = superior rectus muscle; IR = inferior rectus muscle; and SO = superior oblique muscle. Data shown are for case 1's right eye, in which superior rectus and inferior rectus were transposed to the insertion of the lateral rectus (details of surgery are given in the Case Report section). Both the superior and inferior rectus muscle bellies are seen to resist transpositions of their insertions.

chanics is fundamentally different under a pulley model. Here, the axis of rotation is determined by the center of rotation, the effective location of the pulley, and the anatomic insertion. Unlike the conventional model, the pulley model predicts that gaze movements out of the muscle plane will cause the axis of rotation to tilt with the globe; the muscle does not act as though inserted at the point of tangency (compare Fig 1B with 1D). If mid-orbital fasciae functioned as muscle pulleys with firm elastic connections to the orbital wall, then insertional transposition would have little effect on posterior muscle paths, because the muscle bellies would lie within and posterior to the mid-orbital, stabilizing pulleys. It would require surgery that (somehow) frees muscles from their pulleys to produce the much larger effects predicted by binocular alignment models that ignore pulleys.

We must mention a popular intuitive model of orbital geometry, which suggests that even unconstrained muscle bellies should not move much in response to insertional transposition. This model imagines rectus muscle insertions to lie at the base angles, and muscle origins to lie at the apex, of an orbital triangle or cone, leading one to expect for geometric reasons alone that a given movement of an insertion would result in smaller and smaller movements of the muscle's path as one looked toward the apex. It should be obvious, however (see Fig 2) that, with the possible exception of the medial rectus in extreme adduction, this is a poor model. Even if we suppose that the muscle simply wraps around the globe, the distance between a rectus muscle's path and the orbital axis would have to first *increase* as we moved posteriorly from its insertion. Additionally, as is apparent in Figure 2, and as demonstrated in imaging studies by Simonsz et al[14] and Miller,[13] rectus muscles are bowed outward more than

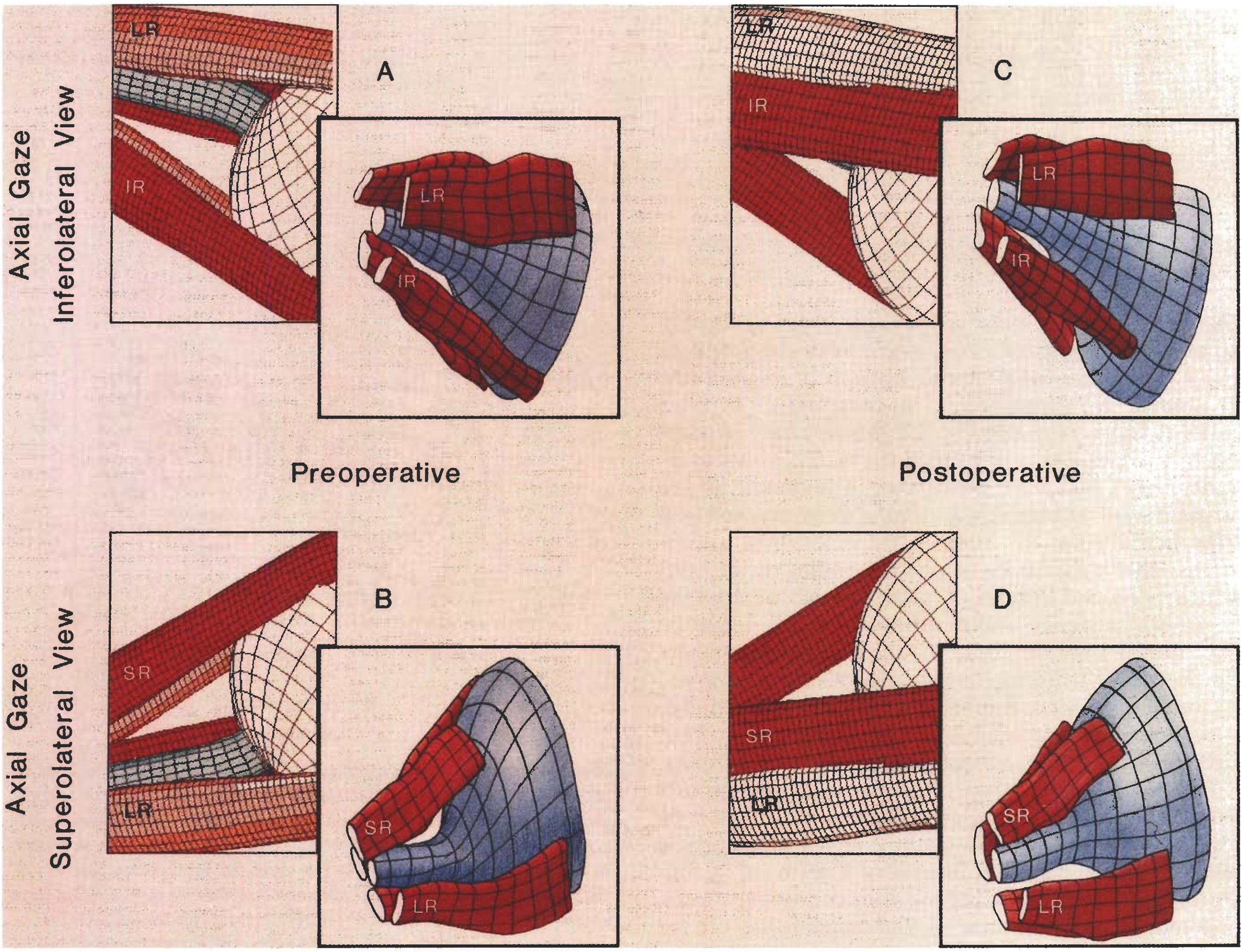

Figure 5. Case 1. Three-dimensional magnetic resonance imaging orbital reconstructions and SQUINT simulations. Pre- and postoperative data show inferior rectus in relation to lateral rectus and superior rectus in relation to lateral rectus. Orbital structures are labeled as in Figure 4. In each lettered panel (A–D), a plane drawn to appear in front shows the magnetic resonance imaging data, and a plane, partly occluded so as to appear in back, shows the corresponding simulation. (The color saturation of the simulated muscles indicates tension, not discussed in the current analysis.) **A**, inferolateral view of the preoperative right eye. **B**, superolateral view of the preoperative right eye. **C**, inferolateral view of the postoperative right eye. **D**, superolateral view of the postoperative right eye.

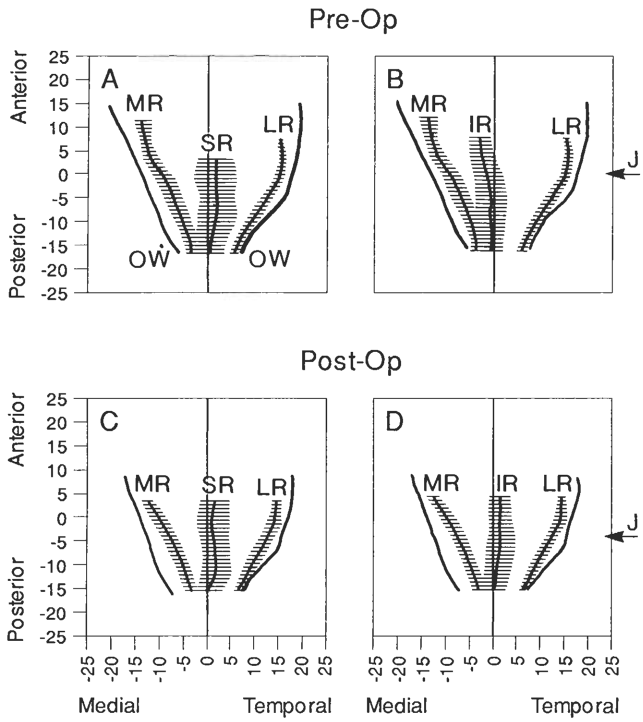

Figure 6. Case 1. Projections of three-dimensional magnetic resonance imaging reconstructions. Orbital structures are projected onto a plane that bisects the horizontal recti. A solid line connects the centroids of the slices for each muscle shown. Projections of the orbital wall (OW) and arrow "J", which locates the junction of the globe and optic nerve, are shown for reference. **A**, superior view of the preoperative right eye shows the superior rectus muscle along with other structures, labeled as in Figure 4. **B**, superior view of the preoperative right eye shows the inferior rectus muscle. **C**, superior view of the postoperative right eye shows the superior rectus muscle. **D**, superior view of the postoperative right eye shows the inferior rectus muscle.

necessary to circumvent the globe (probably on account of elastic connective tissue or hydrostatic pressure in the intraconal fat), and the point of maximum distance from the orbital axis is even further posterior than globe geometry requires.

Therefore, it is wrong to assume that the paths of even freely moving muscle bellies would always move less than their transposed insertions. This depends on the muscle, on gaze position, and on the depth in the orbit at which movement is evaluated. Accordingly, we have eschewed intuitive models, generating predictions of the conventional muscle path model by means of a computational model.[6]

The question of whether effective muscle pulleys exist is of theoretical and practical importance. Although muscle paths could be the same under conventional and pulley models (compare Fig 1A with 1B, and Fig 1C with 1D), axes of rotation respond differently to gaze (compare Fig 1C with 1D), making muscle actions fundamentally different. In consequence, brain stem control of muscle coordination must be different under the two models, for both visually and vestibularly determined eye movements. Understanding of existing modes of eye muscle surgery should improve with a more realistic model of orbital mechanics, and development of new surgeries should be facilitated. It might be possible to develop surgeries altering pulley functioning.

Because muscle paths are the same under both models, MRI studies of normal subjects cannot distinguish the two explanations of muscle path stability or clarify the role of mid-orbital fasciae. However, muscle transposition surgery, which severs anterior orbital connective tissue, provides a way to see if the remaining mid-orbital connective tissue continues to stabilize muscle paths. With these issues in mind, we conducted the current study, using high-resolution MRI to visualize rectus muscles deep in the orbit, and biomechanical modeling to assess the functional significance of the images.

Subjects and Methods

Magnetic resonance imaging studies were performed on volunteer patients who were undergoing rectus muscle transposition surgeries for longstanding paralytic strabismus or "pattern" misalignments. All patients gave written informed consent to a protocol approved by the Institutional Review Board at each involved institution.

High-resolution MRIs were collected with scanners having 0.5-Tesla (MR Max, GE Company, Fairfield, CT) or 1.5-Tesla (Signa) superconducting magnets, and 3.5-inch surface coil detectors. Details of the technique are presented elsewhere.[13] Image sections were 3.0 mm in thickness, and were either contiguous or separated by a

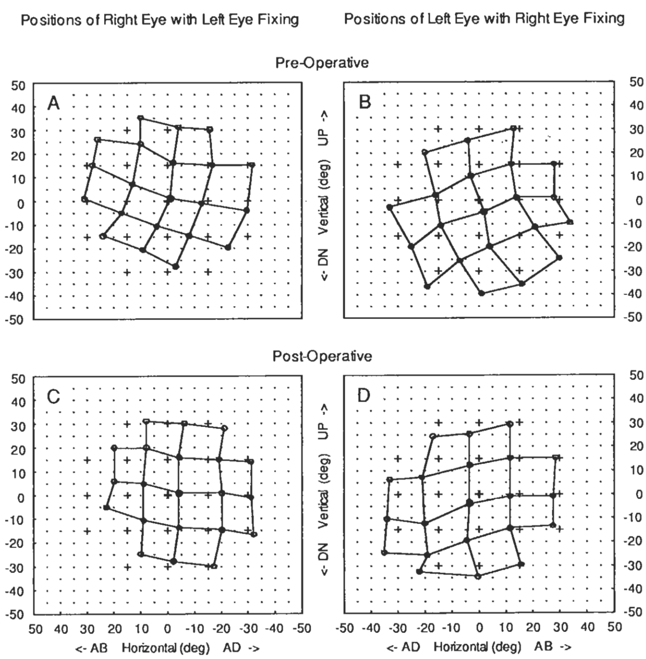

Figure 7. Case 2, Hess charts. Format as in Figure 3. **A** and **B**, before lateral rectus transposition surgery. **C** and **D**, 1 day after bilateral downward lateral rectus transposition surgery.

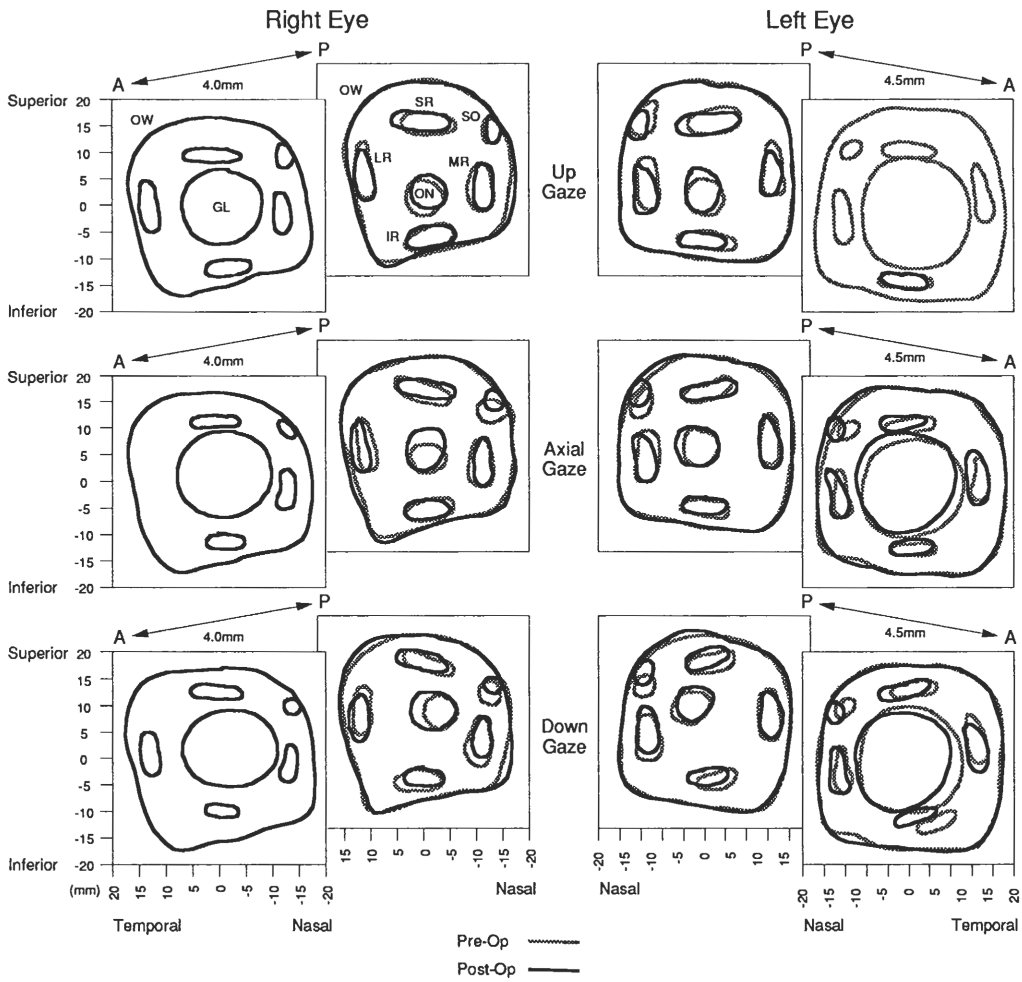

Figure 8. Case 2. Magnetic resonance imaging slice data. Format as in Figure 4, except data are shown for both eyes (right eye on left and left eye on right), and three gaze positions (upgaze, axial gaze, and downgaze). Left and right orbits are oriented as in the head. Structures that could not be clearly distinguished in the anterior slice are omitted from the figure.

1.0-mm gap. Although thicker sections gave better signal-to-noise ratios, spatial resolution was reduced. Thus, we always chose the thinnest and most closely spaced sections available. The field of view was 15 to 16 cm, and resolution in the scan planes varied from 128 × 128 to 256 × 192 pixels.

To obtain image planes as close to perpendicular to the long axes of the rectus muscles as possible, the head of the supine patient was turned so that the orbital axis of the scanned eye was vertical. The surface coil was centered and affixed over the scanned eye. A scout scan was obtained, perpendicular to the long axis of the body, and a set of quasi-coronal planes defined (Fig 2). To control eye position during scans, patients were instructed to continuously fixate with the scanned eye one of several targets affixed to the inside of the scanner magnet. An *axial* target, along the orbital axis (and so approximately 23° temporal) was always presented, along with one or more other targets to elicit gazes elevated, depressed, abducted, or adducted with respect to the axial target. Scan parameters were selected to complete each scan in 2 to 3 minutes. Preoperative scans were performed in several gaze positions to attain a gaze position comparable with that achievable postoperatively.

Magnetic resonance imaging scans were filmed using the same centration and high magnification for all of a patient's images, such that the orbit at its greatest diameter completely filled the image frames. Clearly delineated contours of orbital wall, globe, optic nerve, and rectus muscles were outlined manually on a digitizing tablet, read by a computer. Hydrogen-rich intraorbital fat produced high contrast for these structures in the mid-orbital region. However, within approximately 5 mm of the orbital apex, resolution became difficult due to crowding of structures of interest and the paucity of interstitial fat. More troublesome for our purposes was the loss of resolution anterior to the point of tangency of rectus muscles with the globe. Here, intermuscular fascia became dense (the superior border of the lateral rectus and the lateral border of the superior rectus were usually lost first due to the lateral levator aponeurosis; the inferior rectus was sometimes obscured by Lockwood's ligament) and muscles became tendinous and flat against the globe. Only structures that could be clearly delineated were digitized.

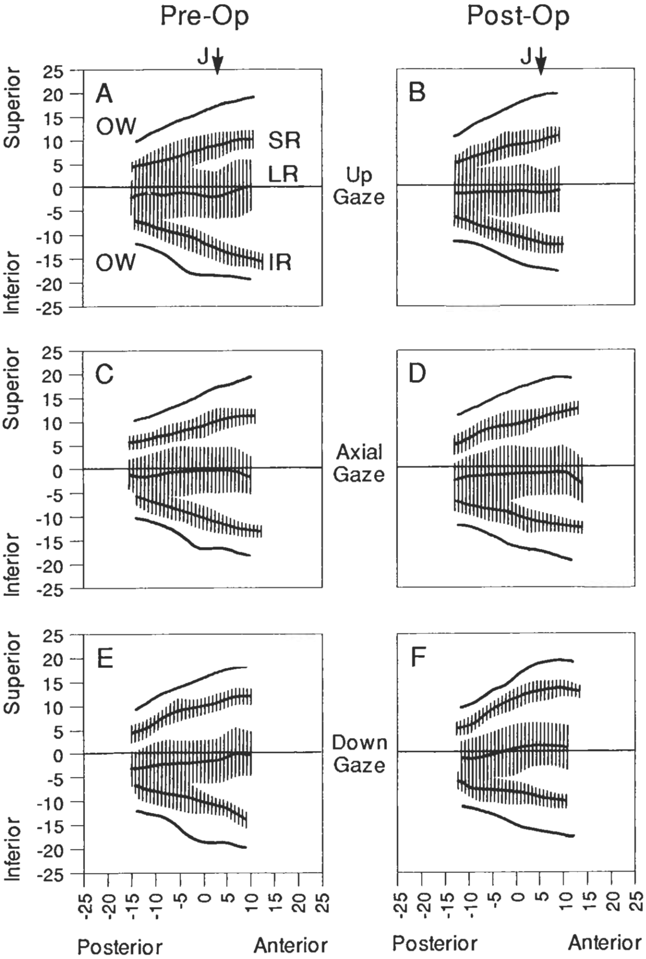

Figure 9. Case 2. Projections of three-dimensional magnetic resonance imaging reconstructions. Labeling as in Figure 6. The lateral rectus is shown against the superior rectus, inferior rectus, and orbital wall for the three gaze positions before downward lateral rectus transposition (**A**, **C**, and **E**) and after transposition (**B**, **D**, and **F**).

Thus, the most anterior slices we present will sometimes not include all muscles.

We used several types of graphic presentation to compare pre- and postoperative slice data, all based on a three-dimensional reconstruction derived from the raw scan data.[13] For some cases, we sliced the reconstructed orbit perpendicular to its axis, and superimposed corresponding pre- and postoperative slices, aligning them with respect to the orbital walls. Corresponding slices were always taken from scans in which the eyes were in gaze positions as similar as possible. These figures are comparable with those of computed tomographic scan studies,[14] and the sort of slice-oriented MRI studies that might be performed clinically. For some cases, *area centroids* of the slice data were computed as summary measures of muscle position. (The area centroid is analogous to the center of gravity of a planar object.) A line connecting the centroids of a muscle in successive image sections was used to define the muscle path. Rendered versions of the three-dimensional reconstructions were produced to summarize the effects of surgery, and for comparison with similar renderings produced by our computational biomechanical model.

The SQUINT model of binocular alignment[2,6] is a computational model that relates orbital geometry, elastic and contractile muscle forces, connective tissue forces, motoneuron innervations, and gaze positions. Given its assumptions, SQUINT is able to answer questions about various of these quantities in terms of the others. In the current study, we use a version of SQUINT that reflects the conventional (i.e., no-pulley) model of orbital mechanics to generate muscle paths for surgeries and gaze angles comparable with those visualized in our MRI scans. That is, we use SQUINT to test the conventional model by drawing explicit predictions about orbital geometry in particular clinical cases. This computational approach replaces the usual "hand waving" arguments about whether some model or concept accounts for a clinical finding. We will see that a clear result emerges concerning the validity of the conventional model.

Case Reports

Case 1. One year previous to our examination, traumatic right abducens paralysis had developed in a 44-year-old woman after closed head trauma sustained in a skiing accident 9 months earlier (Fig 3A). The right eye exhibited primary deviation esotropia of 17° (31$^{\Delta}$) in primary position, increasing in right gaze and decreasing in left gaze; there was a much larger secondary deviation of the left eye (Fig 3B). The patient was unable to actively abduct her right eye to the midline, although the eye could be readily abducted with forceps. Digitally sampled electro-oculography showed that abducting saccades were slowed to less than 200° per second (normal minimum, 400° per second). The right superior rectus was surgically transposed to bring its insertion line parallel to the superior margin of the lateral rectus, 1 mm superior, and immediately posterior to the lateral rectus insertion. The right inferior rectus was similarly transposed to

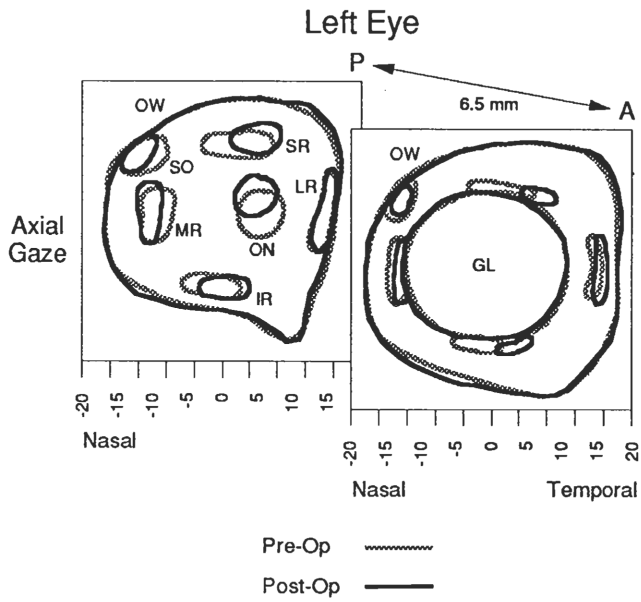

Figure 10. Case 3. Magnetic resonance imaging slice data. Format as in Figure 4.

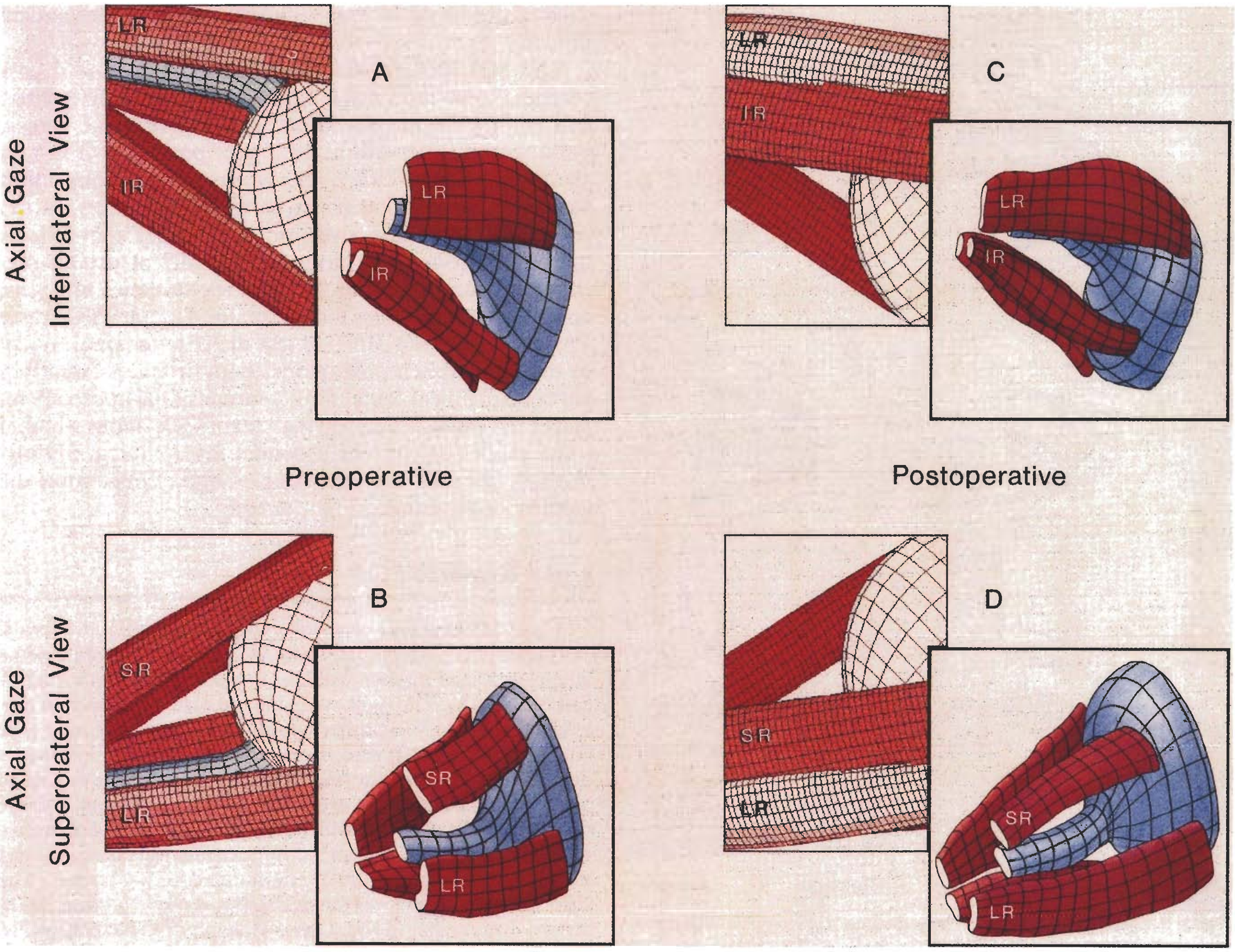

Figure 11. Case 3. Three-dimensional magnetic resonance imaging orbital reconstructions and SQUINT simulations. Format as in Figure 5. **A**, inferolateral view of the preoperative right eye. **B**, superolateral view of the preoperative right eye. **C**, inferolateral view of the postoperative right eye. **D**, superolateral view of the postoperative right eye.

a line 2.5 mm inferior to the inferior margin of lateral rectus. Intermuscular connective tissues around superior rectus and inferior rectus were severed as completely as possible. One day postoperatively, the patient had residual primary deviation esotropia of 11° (19$^{\Delta}$) in primary position, with abduction extending to approximately 5° (9$^{\Delta}$; Fig 3C). Magnetic resonance imaging was performed preoperatively and 2 days postoperatively.

Figure 4 shows the effects of surgery on the globe at the level of the globe equator (A) and of the globe and muscles at the level of the junction of globe and optic nerve (P). In the anterior, equatorial slice, there is medial translation of the globe of approximately 2 mm. At the level of the posterior slice, lateral movements of superior rectus and inferior rectus were approximately 2 mm relative to orbit, and therefore approximately 4 mm relative to globe.

The full sets of pre- and postoperative slice data were used to produce the reconstructions of Figure 5. Comparison of globe and optic nerve in the preoperative (Figs 5A and 5B) and postoperative (Figs 5C and 5D) scans shows that similar gaze positions were achieved in the two scanning sessions, with the eye slightly more depressed in the postoperative scan. Consider first the inferior rectus, visible in the inferolateral views in the top row of Figure 5. In the preoperative eye, the path of the simulated inferior rectus (Fig 5A, back, inferior rectus) is quite similar to that measured in case 1 (Fig 5A, front, inferior rectus). Performing case 1's surgery on the preoperative simulated eye provides a postoperative simulation, which predicts a very large change in the path of the transposed inferior rectus (Fig 5C, back, inferior rectus). Comparison of front and back frames of Figure 5C shows how different the actual surgical outcome was from the prediction of the traditional model. Comparison of preoperative (Fig 5A, front, inferior rectus) and postoperative (Fig 5C, front, inferior rectus) MRI data shows that the inferior rectus belly moved only slightly toward the lateral rectus. Consider next the superior rectus muscle, visible in the superolateral views in the bottom row of Figure 5. Again, the conventional, no-pulley, preoperative simulation (Fig 5B, back) provides a good representation of the preoperative MRI data (Fig 5B, front), but a poor representation of the postoperative MRI data (Fig 5D). Comparison of Figures 5B and 5D shows that the superior rectus belly was little affected by insertional transposition, although the conventional model predicted otherwise.

Parallel projections of the data of Figure 5 are shown in Figure 6, along with lines indicating, for reference, projections of the

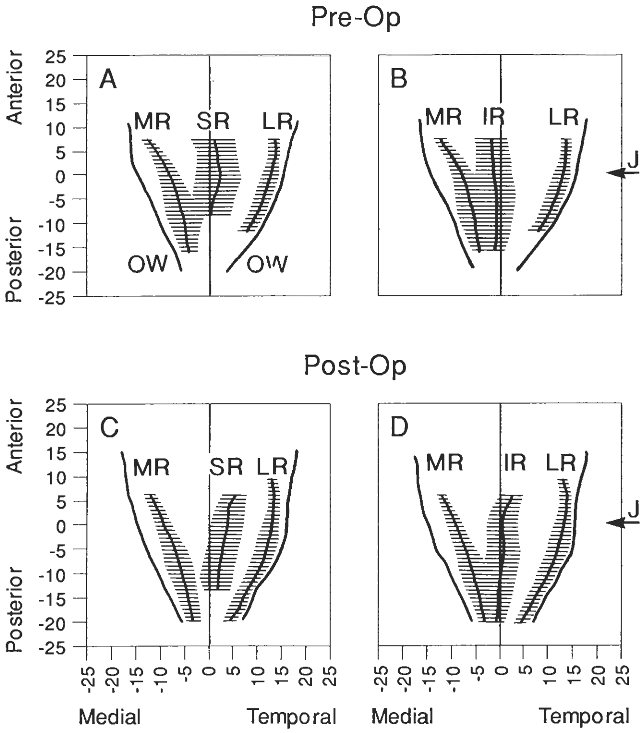

Figure 12. Case 3. Projections of three-dimensional magnetic resonance imaging reconstructions. Format as in Figure 6.

orbital wall. Again, comparison of preoperative (Fig 6A) and postoperative (Fig 6C) MRI data shows no change in the path of the superior rectus, and only a modest 3-mm change in the path of the inferior rectus (Figs 6B and 6D) assessed at the level of the junction of the globe and optic nerve.

Case 2. A 30-year-old man with congenital "A" pattern exotropia complained of intermittent horizontal binocular diplopia. This patient was roughly orthophoric when attempting to fixate primary position. He showed 10° to 15° (18–28$^{\Delta}$) exotropia when attempting to fixate 30° down and 5° (9$^{\Delta}$) esotropia at 30° up. This patient also showed right hypertropia in right gaze, and left hypertropia in left gaze. Hess charts demonstrating preoperative binocular alignment are shown in Figures 7A and 7B.

A bilateral superior oblique tenotomy was performed, slightly relieving the hypertropias, but having little effect on the exotropia. Magnetic resonance imaging scans were performed after the superior oblique tenotomies (these are referred to as preoperative, with respect to the subsequent transposition surgery). Figure 8 (Pre-Op, light lines) shows a "posterior" (P) slice plane, just posterior to the junction of the globe and optic nerve, and an "anterior" slice plane (A) separated by 4.5 mm for the left eye and 4.0 mm for the right. These scans showed anomalous bilateral upward positioning of the bellies of the lateral recti by almost 0.5 tendon width. This lateral rectus ectopy may have been related to the "A" pattern. Accordingly, both lateral recti were transposed downward 10 mm and recessed 3 mm.[a] Intermuscular connective tissues were completely severed, to posterior Tenon's capsule. One day postoperatively, there was a marked reduction in the "A" pattern from 17° to 4° (31 to 7$^{\Delta}$; mean of left and right eyes; Figs 7C and 7D). Magnetic resonance imaging scans were obtained 2 days postoperatively (Fig 8, Post-Op, dark lines). Differences between pre- and postoperative muscle positions are remarkably small. There is little evidence of the downward lateral rectus transposition in either the anterior or posterior slice planes, in any of the three gaze positions, or in either of the two eyes. Some structures, notably the inferior rectus in the left eye (Fig 8, downgaze, anterior slice), were poorly aligned in pre- and postoperative scans, probably because of uncontrollable differences in gaze angle and slice plane. Comparing the data for upgaze, axial (along the orbital axis), and downgaze in Figure 8 (range of approximately 60°), there was little effect of gaze on muscle path in either eye, pre- or postoperatively. There is no evidence that transposition surgery has reduced normal muscle path stability relative to the orbit. The projected left eye data of Figure 9 reinforce the point made by the slice data: there are no systematic differences between the pre- and postoperative lateral rectus paths in any gaze position.

Case 3. A 36-year-old woman developed left lateral rectus paralysis after radiation therapy of an astrocytoma at the base of her brain 5 years previous to our examination. In primary position, she exhibited esotropia of 16° (29$^{\Delta}$). She was able to actively abduct her left eye only to the midline, although it could be fully abducted with forceps with only mild restriction. Abducting saccades in the left eye were markedly slowed, and she had no area of single binocular vision. The left superior rectus was transposed to bring its insertion line parallel to the superior margin of lateral rectus, 1.5 mm superior, and immediately posterior to the lateral rectus insertion. The left inferior rectus was similarly transposed to a line 1.5 mm inferior to the inferior margin of lateral rectus. Intermuscular connective tissues around superior rectus and inferior rectus were severed as completely as possible. Postoperatively, the patient had an exotropia of 3° (5$^{\Delta}$) in primary position with right eye fixing, and improved abduction to 15° past midline.

Figure 10 shows the effects of surgery on orbital contents at the level of the globe equator (A) and at the level of the junction of globe and optic nerve (P). In the equatorial slice, we see that transposition displaced the superior rectus and inferior rectus by approximately 8 mm. The posterior slice shows lateral movement of superior rectus and inferior rectus of approximately 3 mm. From the relative position of the optic nerve in the posterior scan, we can see that gaze was slightly depressed in the postoperative compared with the preoperative scan.

Turning to the three-dimensional representations, comparison of globe and optic nerve in the preoperative (Figs 11A and 11B) and postoperative (Figs 11C and 11D) scans shows that similar gaze positions were achieved in the two scanning sessions. In the preoperative eye, the path of the simulated inferior rectus (Fig 11A, back, inferior rectus) is similar to that measured in case 3 (Fig 11A, front, inferior rectus). Applying data from case 1's surgery to the preoperative simulated eye provides a postoperative simulation (Fig 11C, back). Comparison of front and back frames of Figure 11C shows that the inferior rectus does not approximate the path predicted by the conventional model, which is seen to predict a very large change in the path of the transposed inferior rectus. Comparison of preoperative (Fig 11A, front, inferior rectus) and postoperative (Fig 11C, front, inferior rectus) MRI data shows that the inferior rectus path moved only slightly toward the lateral rectus in its most anterior portions. Similarly, for the superior rectus muscle, the conventional, no-pulley, preoperative simulation (Fig 11B, back) provides a good prediction of the preoperative MRI data (Fig 11B, front), but a poor prediction of the postoperative MRI data (Fig 11D). Comparison of Figures 11B and 11D shows that the superior rectus belly was little affected by insertional transposition, although the conventional model predicted a large effect.

[a] We now know that such surgery does not simply reverse the congenital ectopy, because it alters the position of the insertion much more than it alters the position of the belly.

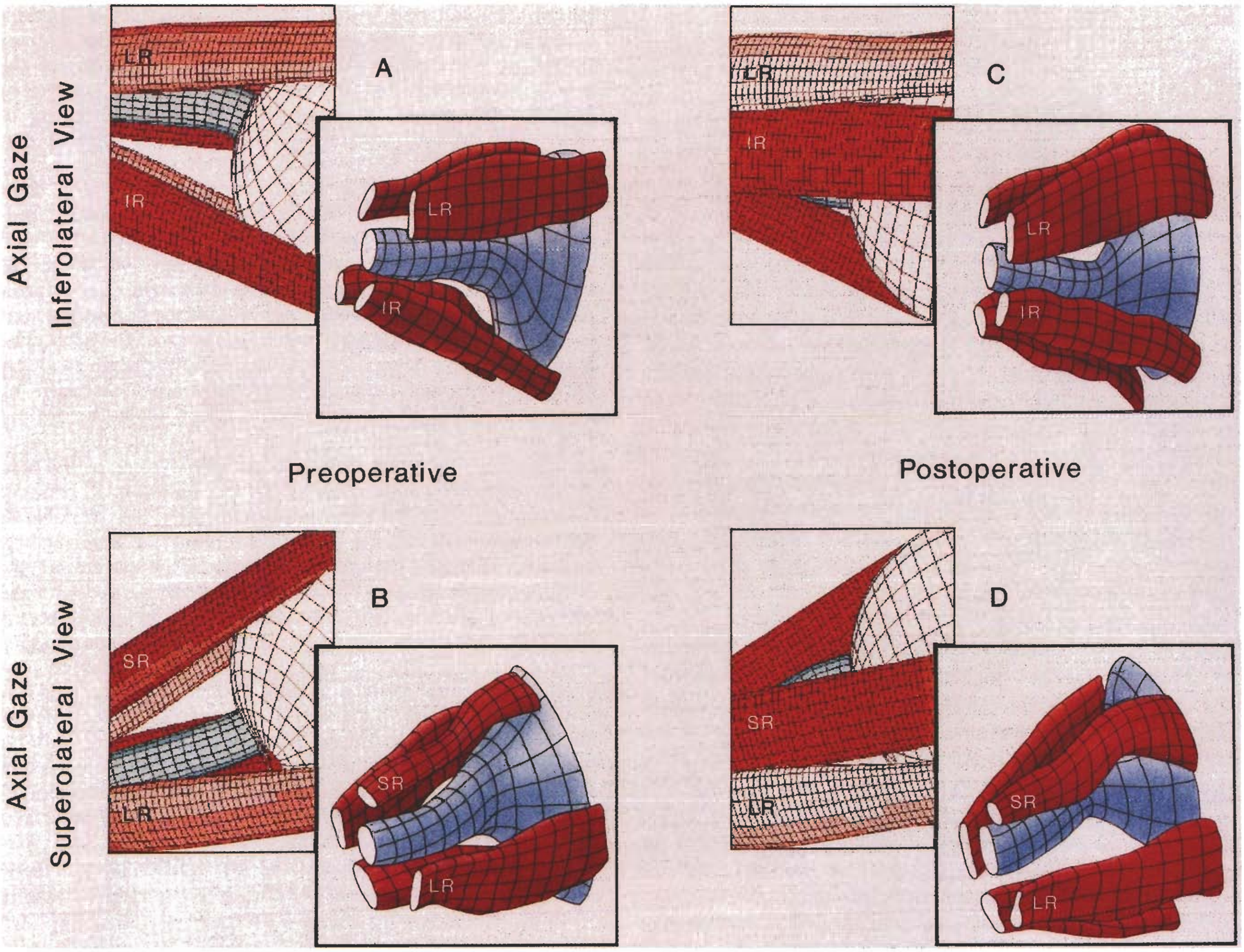

Figure 13. Case 4. Three-dimensional magnetic resonance imaging orbital reconstructions. Format as in Figure 5. **A**, inferolateral view of the preoperative right eye. **B**, superolateral view of the preoperative right eye. **C**, inferolateral view of the postoperative right eye. **D**, superolateral view of the postoperative right eye.

The projective views of Figure 12 make small effects on muscle paths more apparent. Comparisons of panel A with C, and panel B with D, show that only modest lateral displacements in the anterior ends of superior and inferior recti resulted from their lateral transposition.

Case 4. A 19-year-old man presented with right lateral rectus palsy caused by head trauma 8 months earlier. He was unable to abduct his right eye even to the midline, and abducting saccades were profoundly slowed. No active force could be measured in lateral rectus. Oculinum was injected into right medial rectus, bringing the eye roughly to primary position with almost no range of horizontal gaze. The right superior rectus was transposed so that its lateral margin abutted the superior margin of lateral rectus, and its insertion lay on the Spiral of Tillaux[1]; an additional suture, enclosing half of the superior rectus's width, pulled it to the superior margin of lateral rectus at a point 5 mm posterior to the insertion. Similarly, the right inferior rectus was transposed to the inferior margin of lateral rectus, also with a 5-mm posterior suture. Postoperatively, the patient was 15° (27^{Δ}) exotropic in primary position.

Comparison of globe and optic nerve in the preoperative (Figs 13A and 13B) and postoperative (Figs 13C and 13D) scans shows that identical gaze positions were not achieved in the two scanning sessions; the patient's pre- and postoperative ranges of sustainable gaze simply did not overlap. The difference between the two horizontal gaze angles was approximately 5°. If this difference had any effect on muscle paths, the relatively abducted postoperative position would bring the superior and inferior rectus muscle bellies closer to the lateral rectus than in primary position. Instead, comparison of Figures 13A and 13C demonstrates remarkably little displacement of inferior rectus (measured as 2 mm at the level of the junction of globe and optic nerve), and comparison of Figures 13B and 13D, only moderate lateral displacement of superior rectus (5 mm), despite aggressive transposition of their insertions. In the preoperative eye, paths of measured and simulated inferior rectus muscles match well (Fig 13A), as do paths of measured and simulated superior rectus muscles (Fig 13B). However, comparison of front and back frames of Figure 13C shows that case 4's postoperative inferior rectus does not approximate the greatly altered path predicted by the conventional model. Similarly for the superior rectus muscle, the conventional model poorly represents the postoperative MRI data (Fig 13D). Comparison of preoperative (Fig 13A, front) and postoperative (Fig 13C, front) MRI data shows

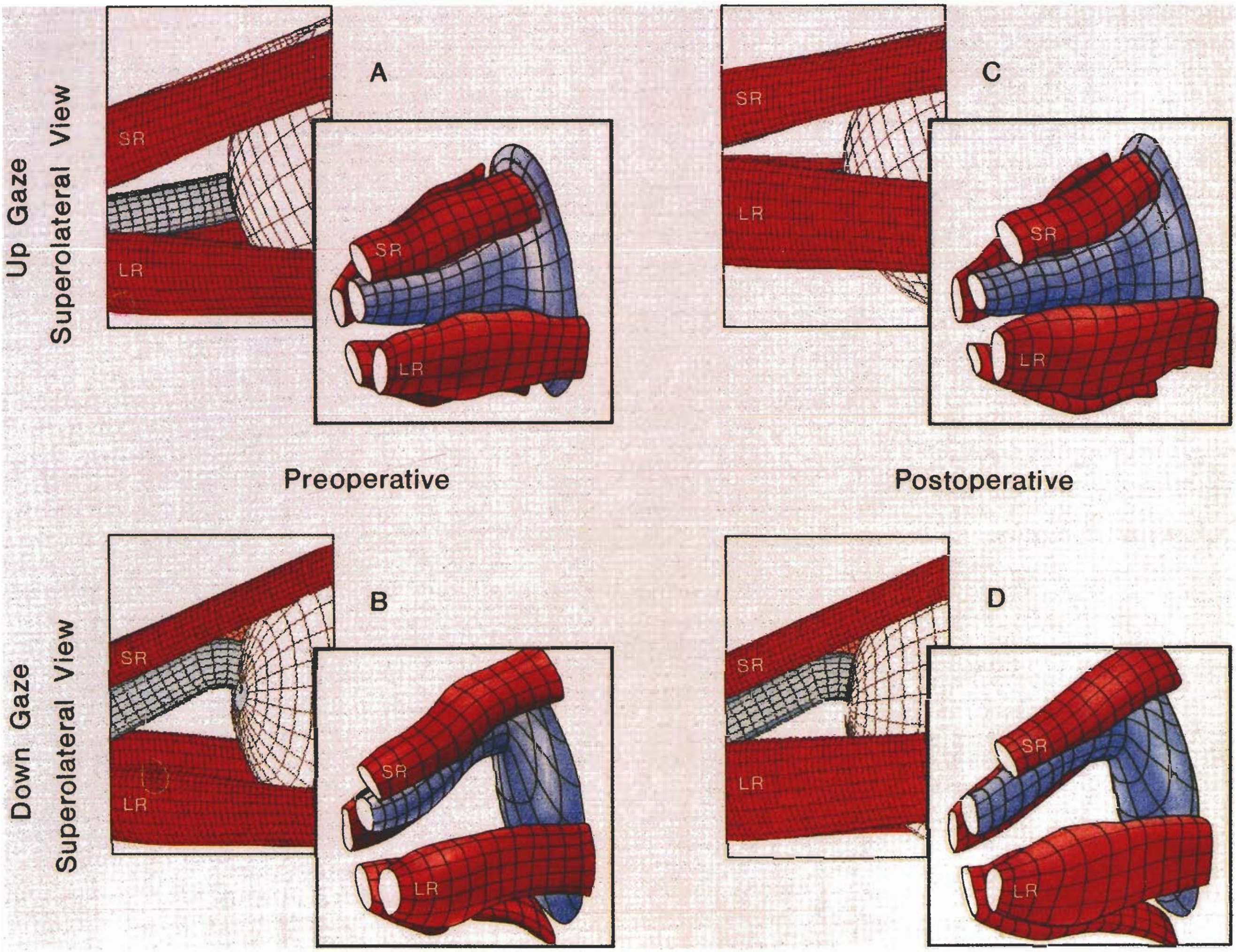

Figure 14. Case 5. Three-dimensional magnetic resonance imaging orbital reconstructions. Format as in Figure 5. **A**, superolateral view of the preoperative right eye in upgaze. **B**, superolateral view of the preoperative right eye in downgaze. **C**, superolateral view of the postoperative right eye in upgaze. **D**, superolateral view of the postoperative right eye in downgaze.

that the inferior rectus path moved only slightly toward the lateral rectus in its most anterior portions; comparison of the front panels of Figures 13B and 13D shows that the superior rectus belly was little affected by insertional transposition.

Case 5. A 14-year-old girl presented with "V" pattern exotropia of 7° (12$^{\Delta}$) secondary to bimedial rectus recession 2 years earlier for congenital "V" pattern esotropia. She then underwent symmetric lateral rectus recessions of 3 mm with upward transposition of 6 mm. Postoperatively, the patient was orthophoric in primary position and the "V" pattern was eliminated. Magnetic resonance imaging was performed pre- and postoperatively.

Figure 14 shows MRI data and simulations for pre- and postoperative states of case 5's right eye in upgaze and downgaze (range of fixation 60°). It can be seen that pre- and postoperative gaze angles are well matched. Clearly, the path of the lateral rectus was little affected, either by gaze (compare Fig 14A front to 14B front, and Fig 14C front to 14D front) or by surgery (compare Fig 14A front to 14C front, and Fig 14B front to 14D front). In contrast, the simulations predict significant changes in lateral rectus path as a result of surgery (compare Fig 14A back to 14C back, and Fig 14B back to 14D back).

Discussion

Two explanations are commonly offered to account for the effects of muscle transposition surgery; both suppose that rectus muscle bellies have no mechanically significant connections to the orbit, globe, or other muscles. The first explanation is that transposition alters the point of tangency of muscle with globe, thereby changing the effective point of mechanical action. The result is a new muscle plane (the plane determined by the origin, point of tangency, and center of rotation), and so, a new axis of rotation (the axis perpendicular to the muscle plane). For example, elevating the lateral rectus would tilt its axis of rotation medially, so that lateral rectus contraction would both elevate and abduct the eye. The second explanation points to a change in muscle path length as a function of gaze.[16,17] For example, a normal medial rectus muscle is supposed to relax in both upgaze and downgaze, having a shorter distance to travel from origin to insertion. An upwardly transposed medial rectus, then, would relax in upgaze but stretch in downgaze, altering horizontal elastic forces so as to correct, for example, "A" pattern strabismus.

Against both of these explanations, which assume that muscle paths are unconstrained posterior to their point of tangency with the globe, we found that deep orbital connective tissues strongly determined the paths of transposed muscles. We visualized the paths of rectus muscles in five strabismus patients before and after various types of clinically effective rectus muscle transposition, measuring 6 to 10 mm. (For cases in which muscle insertion lines were rotated as well as displaced, we calculated the displacement of the center of the insertion along the Spiral of Tillaux.) If muscle bellies were free to follow the transposed insertions, we would have observed large movements of the bellies, according to biomechanical simulations, which we used to quantify the predictions of the conventional model. Instead, bellies moved much less than expected in all cases. The results show that even aggressive transposition surgery has less effect on the paths of rectus muscle bellies than would be expected under the conventional model. It follows that these muscles are significantly constrained by connective tissue or encapsulated fat, posterior to the tissues surgically severed.

Three cases involved lateral transposition of vertical recti, with thorough dissection of anterior connective tissues, to treat lateral rectus palsy. Superior rectus transposition of 10 mm and inferior rectus transposition of 8.5 mm resulted in movements of the muscle bellies of less than 1 and 3 mm, respectively, in case 1; vertical rectus transpositions of 9.5 mm resulted in 3 mm movements of the muscle bellies in case 3. Vertical rectus transpositions of 7 mm with posterior sutures resulted in 2 to 5 mm movements of the muscle bellies in case 4. Two cases involved lateral rectus transposition for "pattern" strabismus. A 6-mm upward lateral rectus transposition resulted in no detectable change at the muscle belly in case 5. Most impressively, bilateral downward lateral rectus transpositions of 10 mm resulted in almost no movement of the muscle bellies in case 2.

The main result of the study is clear: rectus muscles are stabilized relative to the orbit by elastic structures in the middle and posterior orbit; these attachments resist changes in muscle path that would otherwise result from movement of muscle insertions. It also appears that the lateral rectus is more stable in this sense than the superior or inferior rectus. This may be related to differences in musculo-orbital fascia. Comparison of cases 1 and 3 with case 4 suggests that posterior sutures can increase displacement of muscle bellies.

As we noted, our MRI techniques did not resolve rectus muscle tendons anterior to the equator of the globe. This is due to the similar chemical compositions of sclera and extraocular muscle tendon, thinness of the tendon, and the absence of interspersed contrasting tissue (such as orbital fat). Certainly, the portions of the rectus tendons anterior to the equator would have been found to have been moved postoperatively, so that the tendons must take a curved path from the equator to their new insertions. The beginnings of such curved paths are visible in Figure 11C for superior rectus, Figure 11D for inferior rectus, and Figure 13C for superior rectus. A transposed rectus muscle, then, does *not* take the shortest path (a "great circle") across the globe from insertion to point of tangency, and a straight line from there to the origin.

In previous studies of normal orbits, Miller[13] used this MRI technique to demonstrate that the rectus muscle bellies remain stable in the orbit even during the largest ocular ductions. He proposed two possible explanations for this stability of normal rectus muscles in the orbit: (1) elastic intermuscular connective tissues tend to fix the rectus muscles to the globe, balancing the tendency of muscle tension to cause the muscle to take the shortest path from origin to insertion; and (2) elastic musculo-orbital tissues directly stabilize muscles with respect to the orbital wall. If intermuscular elasticities were responsible for stabilizing the paths of rectus muscle bellies, then large changes in paths would be produced by surgical dissection of intermuscular connective tissues. Such dissections were performed in several of the cases presented here. Nevertheless, it was consistently observed that rectus muscle paths resisted the large changes expected under explanation "1." In addition, for cases in which we had MRI data at multiple gaze positions (cases 2 and 5), we found that muscle paths maintained comparable stability during gaze changes as observed preoperatively. This implies that the determinants of rectus muscle paths were not much affected by anterior orbital dissection. With reference to the elegant dissection studies of Koornneef,[15] we think that the sheets of connective tissue surrounding the muscles and attached to the orbit, along with the compartmentalized orbital fat, act as distributed "pulleys," providing the requisite musculo-orbital mechanical coupling, while still allowing the muscles to change length as they rotate the globe.

Clinical experience showing transposition surgery to be an effective procedure is not inconsistent with the finding that transposition has smaller than expected effects on muscle paths. As indicated in the Introduction section, conventional mechanical models (Figs 1A and 1C), which suggest, in effect, that the elastic force of any rectus muscle might through transposition replace that of any other, exaggerate the effects of transposition. A "pulley" hypothesis may provide a more realistic explanation of the more limited effect of transposition that is observed. Thus, it might be useful to conceptualize each rectus muscle as passing through a trochlea, similar to that of the superior oblique, although anatomically more diffuse, and coupled to the orbital wall elastically rather than rigidly. It may be possible to devise useful extraocular muscle surgeries by manipulating the properties of rectus pulleys. Presumably, this would involve manipulation of deep orbital tissues, because the anterior dissections performed in this series did not significantly alter rectus muscle paths.

The current study has provided evidence against conventional models of orbital functional anatomy. However, it should be appreciated that the conventional and pulley models are not strict alternatives: depending on the arrangement and relative stiffness of musculo-global (e.g., intermuscular membranes) and musculo-orbital (pulleys) couplings, a continuum of intermediate models would result. Although we see little alternative to some sort of pulley model, a more specific proposal will only be possible when the requisite biomechanical modeling has been performed.

Acknowledgments. The authors thank Jim Brodale for creating the artwork and Alan B. Scott, MD, for referring case 4.

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