Magnetic Resonance Imaging of the Functional Anatomy of the Superior Oblique Muscle

Joseph L. Demer* and Joel M. Miller%

Purpose. To study the size and contractile changes of the normal superior oblique (SO) muscle using high-resolution magnetic resonance imaging (MRI), and to evaluate the abnormalities in these characteristics produced by SO palsy.

Methods. Multiple coronal MRI image planes were obtained using a surface coil to span the antero-posterior extent of each orbit and were repeated in multiple directions of gaze. Digital image analysis was used to measure muscle cross-sectional area for evaluation of size and contractility.

Results. Data for 16 orbits of 11 subjects without SO palsies established norms for morphology and contractility. On SO contraction in down gaze, maximum cross sectional area was significantly (P < 0.001) greater than on relaxation in up gaze, and the point of maximum cross-section shifted posteriorly with contraction. In seven subjects with clinically unilateral chronic SO palsies, the affected muscle was significantly smaller than normal (P < 0.001) and lacked contractile changes; clinically normal fellow SO muscles exhibited normal cross-sections and contractile changes.

Conclusion. High-resolution MRI, coupled with quantitative morphometric analysis, can demonstrate the size and contractility of the normal SO muscle. The technique, which can be employed using widely available clinical equipment, is also sensitive enough to detect anatomic and functional changes expected in chronic SO palsies. Invest Ophthalmol Vis Sci. 1995; 36:906-913.

The actions of the oblique extraocular muscles are mechanically complex, and, in contrast with the recti muscles, oblique muscle dysfunction is often not clinically obvious from inspection of ocular ductions and versions. One classical ambiguity in the diagnosis of hypertropia is determining the presence of superior oblique (SO) palsy. A large body of clinical practice has evolved on the basis of clinical evidence, but the mechanical state of the SO muscle belly itself has been inaccessible to direct study. Thus, many inferences concerning SO function remain presumptive. Recent advances in imaging now provide another means of evaluating SO function. Simonsz first used computed radiographic tomography for evaluation of extraocular muscle paths during changes in gaze. Miller used high-resolution, surface-coil magnetic resonance imaging (MRI) along with three-dimensional reconstructions and quantitative morphometry to demonstrate the functional anatomy of the recti muscles of normal subjects. These studies revealed the following novel aspects of rectus muscle functional anatomy: The paths of the recti muscle bellies remain highly constrained in the orbit despite the largest attainable ductions; during contraction, a muscle’s cross-sectional area increases and the point of maximum cross-sectional area shifts posteriorly in the orbit; during relaxation, a muscle’s cross-sectional area decreases and the point of maximum cross-sectional area shifts anteriorly in the orbit. This means that MRI can demonstrate the function and contractile state of recti extraocular muscles.

There has been little application of MRI to the...
TABLE 1. Characteristics of Subjects With Unilateral Superior Oblique Palsy

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Side</th>
<th>Cause</th>
<th>Duration (years)</th>
<th>Primary Position Deviation (Hyper Δ)</th>
<th>Excyclodeviation (°)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>29</td>
<td>Left</td>
<td>Traumatic</td>
<td>11</td>
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<td>5</td>
<td>Male</td>
<td>19</td>
<td>Left</td>
<td>Traumatic</td>
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study of abnormal extraocular muscles. Demer and Miller7 presented qualitative MRI data in anecdotal cases of lateral rectus and SO atrophy in abducens and trochlear palsies, as well as congenital ectopy of the horizontal rectus muscles in "A" pattern exotropia. Nishida and collaborators8 used MRI to demonstrate atrophy of involved muscles in abducens and oculomotor paralysis. Horton and associates9 reported qualitative evidence of SO atrophy in a patient with trochlear palsy. However, the functional anatomy of the normal SO muscle as it depends on gaze direction has not been studied using MRI, and no quantitative studies have been performed in SO palsy. The present investigation was conducted to characterize the normal quantitative morphology and contractility of the SO muscle and to determine the effects on these parameters of SO palsy.

METHODS

Orbital MRI studies were prospectively performed in volunteer subjects who, after receiving an explanation of the research, gave written informed consent according to a protocol approved by the institutional review board for the protection of human subjects and conforming to the tenets of the Declaration of Helsinki. Ten orbits were studied in seven subjects who had no abnormalities of ocular motility. Six orbits were studied in four subjects who had various forms of strabismus but no suspicion of SO abnormalities. The mean age of these control subjects was 38 ± 16 years. Fourteen orbits were studied in four subjects who had various forms of lateral rectus and SO atrophy in abducens and trochlear palsies, as well as congenital ectopy of the horizontal rectus muscles in "A" pattern exotropia. Data on the reed muscles are reported elsewhere.14-15

While using widely available clinical MRI hardware and software, we used procedures optimized for extraocular muscles. The fundamental principle is to use scanner settings permitting the highest resolution images of the orbit to be obtained in a time period sufficiently brief that subjects can maintain continuous fixation on a defined target. Control of fixation and avoidance of movement artifacts then permit quantitative analysis of images for determination of muscle contractility. There is necessarily a trade-off between image acquisition time on the one hand and image quality on the other. Smaller detector coils improve resolution but reduce the tissue volume that can be imaged. Use of 75-mm to 125-mm diameter surface coils, rather than the larger and more commonly used cranial coil, provides higher resolution images limited to the extent of the orbit.

Subjects' heads were oriented in the scanner so that the axis of the scanned orbit was vertical, as illustrated in Figure 1A. This permits acquisition of coronal plane images that are as close to perpendicular to the axes of all of the extraocular muscles as possible. Data on the recti muscles are reported elsewhere.14 One eye was always occluded, and the fellow eye viewed the fixation target. Fixation targets consisted of small black crosses in the center of 1.5-cm diameter, brightly colored adhesive disks affixed to the inside of the scanner magnet. Primary position was always used. In most subjects, scans were repeated in 20° elevation and in 20° depression. The eccentric position chosen was the greatest that could be comfortably sustained.

TABLE 1. Characteristics of Subjects With Unilateral Superior Oblique Palsy

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<td>Congenital</td>
<td>21</td>
<td>40</td>
<td>10</td>
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for the typically 3-minute, 38-second duration of each scan. The actual position of the eye during scanning was verified by measurement from the images of the position of the globe-optic nerve junction, which moves in the opposite direction from the cornea.

For each orbit, an axial localizer image (Fig. 1A) was taken at low resolution using settings in Table 2 to select the optimal antero-posterior location of subsequent high-resolution coronal image acquisition planes. Scanning parameters were chosen to obtain a series of 12 adjacent 2.5-mm to 3-mm thick images spanning the antero-posterior extent of each orbit. No gap was left between image planes. For most orbits, a set of 12 planes permits imaging from the annulus of Zinn in the orbital apex to a level just anterior to the trochlea.

Settings for each of the MRI instruments used are specified in Table 2. Subjects were instructed to maintain steady fixation during scanning and to blink as little as possible. The ventilator fan inside the scanner magnet was switched off during fixations because air flow produced by the fan causes rapid corneal desiccation and induces frequent blinking, especially in up gaze. For images most commonly acquired in a 256 (horizontal) × 192 (vertical) pixel matrix over a 10 × 10 cm field of view, pixel resolution was 0.39 × 0.52 mm in the image plane. Resolution between planes was equal to the thickness of the image slice, 2.5 or 3 mm.

Magnetic resonance images in the early phase of this study were printed on conventional radiographic film at approximately ×2 magnification with centering on the orbit, and they were digitized using a Scanjet II flatbed optical scanner (Hewlett-Packard, Palo Alto, CA) at 150 dots per inch and 256 levels of gray scale. Later images were directly converted from scanner magnetic tape data files using locally written software that also optimized contrast and brightness. In either case, images were converted to standard 8-bit tagged image file format (TIFF) for quantitative analysis on Macintosh II or Quadra (Apple Computer, Cupertino, CA) computers using the public domain NIH Image program obtained from the National Institutes of Health (W. Rasband). Spatial calibration was performed through the NIH Image program. The SO muscle was identified near the antero-posterior center of the orbit and traced anteriorly and posteriorly in sequential images. The border of the SO was manually traced using a cursor (Fig. 1B), and the cross-sectional area of the muscle was automatically computed. This procedure was replicated for each orbit and each direction of gaze.

As a consequence of head positioning, the path of the SO muscle was angled from the normal to the coronal plane. Using measurements from the axial localizer images, the mean angle in the axial plane was found to be 24.1° ± 4.5° (mean ± SD). Using measurements from reconstructed sagittal images, the mean angle in the sagittal plane was found to be 19.5° ± 6.5°. Measured cross-sectional areas were trigonometrically corrected for these angles so that reported areas represent true perpendicular cross-sections.

Superior oblique cross-sectional areas were plotted against image plane number, as registered to the number zero assigned by convention to the image plane having the greatest cross-sectional area in pri-
TABLE 2. Magnetic Resonance Scanner Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>Field (tesla)</th>
<th>Plane</th>
<th>Thickness (mm)</th>
<th>Gap (mm)</th>
<th>Matrix</th>
<th>Field of View (cm)</th>
<th>Repeat Time (msec)</th>
<th>Echo Time (msec)</th>
<th>Excitations</th>
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<td>GE Signa</td>
<td>1.5</td>
<td>Axial</td>
<td>4</td>
<td>2</td>
<td>256 × 128</td>
<td>16</td>
<td>400</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>GE Signa</td>
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<td>Coronal</td>
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<td>0</td>
<td>256 × 192</td>
<td>10</td>
<td>550</td>
<td>15</td>
<td>2</td>
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<tr>
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<td>400</td>
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<tr>
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<td>15</td>
<td>750</td>
<td>30</td>
<td>1</td>
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<tr>
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<td>2.5</td>
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<td>192 × 128</td>
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<tr>
<td>Picker Vista</td>
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<td>Coronal</td>
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<td>256 × 256</td>
<td>10</td>
<td>817</td>
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mary position. This registration was necessary because of variations in individual orbital depth and in the number of image planes obtained for each orbit. Registration against primary position was maintained for studies of eccentric gaze in the same orbit. Statistical comparisons were made using Student’s t-test.

RESULTS

Normal Superior Oblique Muscles

The findings in normal subjects were the same as those in patients with strabismus with normal SO function, so these groups were merged for analysis. In magnetic resonance images, the SO muscle could be readily identified as it coursed from its origin posteriorly to the trochlea anteriorly (Fig. 2). In the primary position, the greatest cross-sectional area of the SO muscle occurred about midway in the antero-posterior extent of the orbit. In down gaze, the cross-sectional area of the muscle increased (Fig. 1B), and the plane in which the maximum cross-sectional area occurred was more posterior. In up gaze, the cross-sectional area of the muscle decreased (Fig. 1B), and the image plane in which the maximum cross-sectional area occurred was more anterior.

The mean maximum cross-sectional area for 16

![FIGURE 2: Coronal magnetic resonance images of a normal right orbit repeated in up (upper row), primary (middle row), and down (lower row) gaze. For clarity, alternate image planes are omitted so that images are displayed every 6 mm throughout the orbit. The position of the globe-optic nerve (ON) junction confirms gaze position. In the second column from the left, note the smaller superior oblique (SO) cross-section in up gaze and the large cross-section in down gaze. IO = inferior oblique muscle; IR = inferior rectus muscle; LPS = levator palpebrae superioris muscle; LR = lateral rectus muscle; MR = medial rectus muscle; SOM = SO oblique muscle; SOR = reflected portion of SO tendon; SOT = SO tendon in vicinity of the trochlea; SR = superior rectus muscle.](https://iovs.arvojournals.org/doi/abs/10.1167/iovs.933185)
TABLE 3. Maximum Superior Oblique Cross-Sectional Area in Normal Subjects

<table>
<thead>
<tr>
<th>Gaze</th>
<th>Mean (cm²)</th>
<th>Standard Deviation (cm²)</th>
<th>Orbits</th>
<th>Area Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From Primary Gaze (within subjects)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up</td>
<td>0.170*</td>
<td>0.054</td>
<td>11</td>
<td>-0.055†</td>
</tr>
<tr>
<td>Primary</td>
<td>0.190</td>
<td>0.040</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Down</td>
<td>0.217*</td>
<td>0.043</td>
<td>11</td>
<td>0.076†</td>
</tr>
</tbody>
</table>

* Up area significantly different from down, P < 0.025.  
† Change significantly different from zero, P < 0.0005.

normal SO muscles was 0.190 cm² ± 0.040 cm², with a range of 0.126 to 0.269 cm². Pooled mean cross-sectional areas for all normal SO muscles, averaged for each direction of gaze, are plotted in Figure 3. Between up and primary gaze, the maximum pooled mean cross-sectional area increased and shifted about 3 mm posteriorly. Between primary and down gaze, there was a broadening of the peak in cross-sectional area, with an increase in cross-sectional area for the most posterior image planes. From primary to down gaze, the maximum pooled mean maximum cross-sectional area did not increase. Table 3 indicates mean values for maximum individual cross-sectional areas observed in each subject for the SO muscle in down gaze, primary position, and up gaze. It should be noted that these values were obtained by averaging the maximum values for each subject and thus are greater than the maximum values of the mean aligned areas. Mean SO cross-sectional area in down gaze was significantly greater than in up gaze (P < 0.025). Pooled areas for up gaze and down gaze did not differ significantly from those for primary position (P > 0.05). However, when interindividual differences were controlled by computing for each individual the change in SO cross-sectional area from primary position to eccentric gaze, the differences were significant (Table 3, P < 0.0005). The mean change in SO cross-sectional area during gaze changes is plotted as a function of antero-posterior location in the orbit in Figure 4. This plot shows that contraction and relaxation of the SO muscle during gaze changes occurs primarily in the posterior half of the muscle, deep in the orbit.

With these basic data available on the normal functional anatomy of the SO, similar investigations were made in seven subjects with unilateral SO palsies (Table 1). Three patterns of abnormality were found in the palsied muscles, as illustrated, for representative subjects in Figure 5. In subject 1, only the posterior half of the affected left SO muscle belly was smaller than normal (Fig. 5A); the maximum cross-section of this muscle did not occur in its normal mid-antero-posterior orbital position. Instead of being maximal in image plane 0, the maximum cross-section for the left SO of subject 1 occurred in image plane 3, where...
FIGURE 5. Coronal magnetic resonance images of right (left column) and left (right column) orbits of subjects with unilateral superior oblique (SO) palsy. Images were obtained in primary gaze. From top to bottom, image pairs are arranged from posterior to anterior. (A) Subject 1. Segmental atrophy of the posterior half of the left SO muscle (open arrow) compared with the normal right SO (solid arrow). (B) Diffuse atrophy of the entire left SO muscle in subject 5. (C) Absence of the left SO muscle in subject 7.

its value was double the 95th percentile for normal SO cross-sectional area in this image plane. This pattern is interpreted as posterior atrophy with anterior hypertrophy of the affected SO. In subjects 2 to 5, the entire muscle belly was smaller than normal (Fig. 5B). The clinically palsied SO muscle appeared to be entirely absent in subjects 6 and 7 (Fig. 5C), corresponding to zero cross-sectional area. To account for the segmental SO atrophy observed in subject 1, statistical comparisons were made at the mid-antero-posterior orbital position, where SO cross-section is normally greatest. The range of mid-orbital maximum cross-sectional areas for palsied SO muscles was 0.000 cm$^2$ to 0.111 cm$^2$, exhibiting no overlap with the distribution for 16 normal muscle cross-sections. The mean mid-orbital cross-sectional area of 0.044 cm$^2$ ± 0.046 cm$^2$ for palsied SO muscles was significantly smaller than the comparable value of 0.190 cm$^2$ ± 0.040 cm$^2$ for normal muscles ($P < 0.0005$).

Cross-sectional area data for palsied SO muscles was pooled and plotted as a function of image plane in Figure 6, which also illustrates data for clinically normal fellow muscles in the same subjects. These data indicate that SO palsy has two functional anatomic characteristics—atrophy manifested by reduced cross-sectional area of the involved muscle, and absent contractility manifested by the lack of increase in cross-sectional area and lack of posterior displacement of the muscle belly during down gaze compared with up gaze. The average maximum SO cross-section for the fellow SO muscles was 0.173 cm$^2$ ± 0.030 cm$^2$, not significantly different from the normal muscles ($P > 0.1$). The normal fellow SO muscles exhibited normal size and contractility (Fig. 6).

DISCUSSION

Miller first demonstrated that surface-coil MRI can indicate the contractile state of extraocular recti muscles.$^6$ The present study extends this finding to the SO muscle and establishes statistical norms for the size of this muscle. As in recti muscles, SO contraction is evidenced by an increase in cross-sectional area and a posterior displacement of the point of maximal cross-
with findings by Horton and collaborators of an
range when assessed at the antero-posterior position
clinically palsied SO muscles were below the normal
every case, the cross-sectional areas in primary gaze of
finding was not surprising because the anterior por-
terior extent of the muscle, deep in the orbit. This last
sectional area. In addition, as in recti muscles, the contractile changes in the SO occurred in the poste-
rior extent of the muscle, deep in the orbit. This last finding was not surprising because the anterior por-
tion of the SO is tendinous.

The findings in SO palsy were consistent: The pal-
sied muscle was either absent altogether or was sig-
nificantly smaller than normal and did not exhibit normal contractile changes in up and down gaze. In
every case, the cross-sectional areas in primary gaze of clinically palsied SO muscles were below the normal range when assessed at the antero-posterior position in the orbit where the normal maximum occurs. The small size of palsied SO muscles is perhaps due to chronic denervation atrophy and absence of contractility in SO palsy. It is proposed that such objective findings provide direct proof of the diagnosis of SO palsy. We report elsewhere that sometimes hypertropia simulates many of the classical clinical findings of SO palsy, but MRI confirms normal SO size and contractility. This observation should not be surprising because it is likely that after transient traumatic or ischemic denervation of the SO muscle, hypertropia may be perpetuated by mechanical or innervation factors despite recovery of SO contractility. Indeed, biomechanical modeling indicates that changes of <10% in resting lengths of certain recti and oblique muscles, each contracting normally, can produce patterns of binocular misalignment clinically typical of SO palsy.

There are some intriguing implications for the diag-
nosis and management of acute, traumatic SO palsies. Although contractility can be expected to be lost immedi-
ately after traumatic denervation, it is unclear how quickly muscle atrophy develops in the human SO muscle. Data in the medial rectus muscles of monkeys subjected to oculomotor section suggest that the initial phase of denervation hypertrophy observed at 1 month gives way to sig-
nificant atrophy by 2 months, although atrophy was much more profound by 4 months. Further, recovery of SO size and contractility is expected with the common spontaneous reinnervation of the SO muscle. In the monkey denervation study, reinnervation was associated with sig-
nificant medial rectus hypertrophy at 6 months, although resolution of this hypertrophy at later times seems possible. It is unknown if the human SO muscle responds to denervation in the same manner as the primate is consistent with dynamic damage or denervation of the SO muscle. Porter and colleagues observed that there was hypertrophy to 156% of control cross-sectional area following spontaneous reinnervation after experimental oculomotor nerve section. This suggests that trauma in subject 1 may have permanently dener-
vated only the most posterior part of the muscle and that the anterior part may have become reinnervated and hypertrophic. Extraocular muscle hypertrophy also occurs in the acute phase of denervation as a consequence of vacuolization and organelle dispersion, but in experimental denervation in the primate, this resolved within 2 months of denervation. In the other patients with SO palsy, the initial phase of denervated muscle was uniformly small or absent. Presumably, the variation in degree of binocular misalign-
ments observed in these subjects resulted from factors in addition to simple SO weakness, most likely innerva-
tional factors, and secondary mechanical changes in SO connective tissues and the other extraocular muscles.

Surface-coil MRI, as described here, is sufficiently
sensitive to demonstrate the normal pattern of SO contractility. It is thus easy to demonstrate atrophy and absence of contractility in SO palsy. It is proposed that such objective findings provide direct proof of the diagnosis of SO palsy. We report elsewhere that sometimes hypertropia simulates many of the classical clinical findings of SO palsy, but MRI confirms normal SO size and contractility. This observation should not be surprising because it is likely that after transient traumatic or ischemic denervation of the SO muscle, hypertropia may be perpetuated by mechanical or innervation factors despite recovery of SO contractility. Indeed, biomechanical modeling indicates that changes of <10% in resting lengths of certain recti and oblique muscles, each contracting normally, can produce patterns of binocular misalignment clinically typical of SO palsy.
The authors thank Laura Hovis and Mary Johnstone for Acknowledgments

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medial rectus. Adequate evaluation of the time course of recovery of SO size and contractility would require serial imaging studies that have not yet been performed, although normal SO contractility and size have been observed in one patient 3 months after spontaneous recovery from a traumatic SO palsy (Demer, unpublished data, 1993). Further study is required to determine if MRI can be useful in ascertaining the likelihood and completion of spontaneous recovery from SO palsy.

Key Words
extraocular muscle, magnetic resonance imaging, neuroophthalmology, strabismus, superior oblique muscle

Acknowledgments
The authors thank Laura Hovis and Mary Johnstone for assistance with magnetic resonance imaging. The public domain NIH Image program was written by Wayne Rasband at the U.S. National Institutes of Health and is available from the Internet by anonymous ftp from zippy.nimh.nih.gov or on floppy disk from NTIS, 5285 Port Royal Road, Springfield, VA 22161, part number PB89-50486.

References