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

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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...
study of abnormal extraocular muscles. Demer and Miller 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 collaborators used MRI to demonstrate atrophy of involved muscles in abducens and oculomotor paralysis. Horton and associates 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.

Orbits were imaged using one of the following scanners: MR-Max (0.5 tesla magnet) or Signa (1.5 tesla) (General Electric, Milwaukee, WI) or Vista (1.5 tesla) (Picker, Columbus, OH). General aspects of the scanning protocol have been described elsewhere. 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. 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

<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>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>29</td>
<td>Left</td>
<td>Traumatic</td>
<td>11</td>
<td>20</td>
<td>5</td>
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<td>2</td>
<td>Male</td>
<td>18</td>
<td>Left</td>
<td>Congenital</td>
<td>18</td>
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<td>7</td>
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<tr>
<td>3</td>
<td>Male</td>
<td>32</td>
<td>Right</td>
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<td>1</td>
<td>4</td>
<td>5</td>
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<tr>
<td>4</td>
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<td>Right</td>
<td>Congenital</td>
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<td>30</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Male</td>
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<td>Traumatic</td>
<td>1</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>Female</td>
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<td>Right</td>
<td>Congenital</td>
<td>22</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Male</td>
<td>21</td>
<td>Left</td>
<td>Congenital</td>
<td>21</td>
<td>40</td>
<td>10</td>
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FIGURE 1. (left) An axial localizer magnetic resonance image of the right orbit of a normal subject, illustrating the vertical orientation of the head in the scanner and levels of 12 contiguous coronal image planes used for analysis. Numerals indicate the designation of coronal image planes, with plane zero defined as that having the greatest SO cross-sectional area in primary gaze. (right) Coronal magnetic resonance images of the right orbit of a normal subject at an intermediate antero-posterior distance, repeated in three directions of gaze. In down gaze, note the upward displacement of the optic nerve (ON), large cross-section of the inferior rectus (IR) and superior oblique (SO) muscles, and small cross-section of the superior rectus (SR) muscle. The cross-section of the SO has been digitally outlined in the image obtained in primary gaze, in which all muscle cross-sections are intermediate. In up gaze, note the downward displacement of the ON, the large cross-section of the SR, and the small cross-sections of the SO and IR muscles.

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 the superior rectus (SR) muscle. The cross-section of the SO has been digitally outlined in the image obtained in primary gaze, in which all muscle cross-sections are intermediate. In up gaze, note the downward displacement of the ON, the large cross-section of the SR, and the small cross-sections of the SO and IR muscles.

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 $24.1^\circ \pm 4.5^\circ$ (mean $\pm$ SD). Using measurements from reconstructed sagittal images, the mean angle in the sagittal plane was found to be $19.5^\circ \pm 6.5^\circ$. 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-
Superior Oblique Imaging

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>
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<td>Axial</td>
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<td>256 × 128</td>
<td>16</td>
<td>400</td>
<td>16</td>
<td>1</td>
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<tr>
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<td>Coronal</td>
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<td>10</td>
<td>550</td>
<td>15</td>
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<tr>
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<td>Axial</td>
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<td>1</td>
<td>192 × 192</td>
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<td>1</td>
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<tr>
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<td>Coronal</td>
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<td>128 × 128</td>
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<td>750</td>
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<td>2</td>
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<tr>
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<td>Axial</td>
<td>2.5</td>
<td>0</td>
<td>192 × 128</td>
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<td>300</td>
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<td>1</td>
</tr>
<tr>
<td>Picker Vista</td>
<td>1.5</td>
<td>Coronal</td>
<td>3</td>
<td>0</td>
<td>256 × 256</td>
<td>10</td>
<td>817</td>
<td>20</td>
<td>1</td>
</tr>
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</table>

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.](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933185/ on 04/06/2017)
normal SO muscles was 0.190 cm$^2 \pm 0.040$ cm$^2$, with a range of 0.126 to 0.269 cm$^2$. 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 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-ante-ro-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 cm² to 0.111 cm², exhibiting no overlap with the distribution for 16 normal muscle cross-sections. The mean mid-orbital, cross-sectional area of 0.044 cm² ± 0.046 cm² for palsied SO muscles was significantly smaller than the comparable value of 0.190 cm² ± 0.040 cm² 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 cm² ± 0.030 cm², 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. 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 finding was not surprising because the anterior portion of the muscle, deep in the orbit. This last finding was not surprising because the anterior portion of the SO is tendinous.

The findings in SO palsy were consistent: The palsied muscle was either absent altogether or was significantly 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 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 denervated 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 involved head-deprived muscle was uniformly small or absent. Presumably, the variation in degree of binocular misalignments observed in these subjects resulted from factors in addition to simple SO weakness, most likely innervational 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 innervational 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 diagnosis and management of acute, traumatic SO palsies. Although contractility can be expected to be lost immediately 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 significant 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 significant medial rectus hypertrophy at 6 months, although resolution of this hypertrophy at later times seems a possibility. It is unknown if the human SO muscle responds to denervation in the same manner as the primate

FIGURE 6. Mean cross-sectional area of SO muscles in three directions of gaze in the palsied and normal orbits of seven subjects with unilateral SO palsy. The cross-sectional area of the normal SO muscle decreased in up gaze, and the plane of maximum cross-sectional area moved anteriorly. In down gaze, the plane of maximum cross-sectional area moved posteriorly. For palsied muscles, the cross-sectional area was significantly smaller (P < 0.005).
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, neuro-ophthalmology, strabismus, superior oblique muscle

**Acknowledgments**
The authors thank Laura Hovis and Mary Johnstone for assistance with magnetic resonance imaging. The public does not have to anticipate MRI for 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.

**References**