Muscle path length in horizontal strabismus

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BACKGROUND Sarcomere adaptation has been proposed as a mechanism for the adjustment of rectus muscle length in regulating binocular alignment. The purpose of this study was to investigate whether horizontal rectus muscle paths have abnormal lengths in subjects with intermittent or alternating strabismus.

METHODS High-resolution, surface coil magnetic resonance imaging was obtained in 2 mm thick axial planes in strabismic patients who had not undergone prior surgery and normal control subjects. The lengths of horizontal rectus muscle paths were measured digitally in central gaze for the fixating eye only and compared.

RESULTS A total of 12 strabismic subjects and 13 controls were included: 8 subjects had esotropia averaging 30$^{\Delta}$, and 4 had exotropia averaging 47$^{\Delta}$. The sample had 80% power to detect muscle path length changes of at least the typical surgical doses appropriate to strabismus surgery for correction of the mean deviations in each group, had such changes existed. Mean (± standard deviation) medial rectus path length was 35.0 ± 4.1 mm in controls, not significantly different from 36.3 ± 1.7 mm in exotropia ($P = 0.56$) or 35.8 ± 2.9 mm in esotropia ($P = 0.62$). Mean lateral rectus path length in controls was 35.7 ± 4.0 mm, not significantly different from the values of 39.6 ± 3.8 mm in exotropia ($P = 0.09$) and 37.8 ± 3.3 ($P = 0.19$) mm in esotropia.

CONCLUSIONS Horizontal rectus muscle path lengths are not significantly abnormal in commonly encountered intermittent or alternating esotropia and exotropia. (J AAPOS 2014;18: 4-9)

Why does an esotropic eye turn inward? In incomitant strabismus, that is, paralytic or mechanical strabismus, end organ extraocular muscle function is clearly affected. However, in the more common types of comitant strabismus, the possible role of abnormal muscle structure and function remains enigmatic.[1] Are there abnormalities of the horizontal rectus muscles, or is strabismus related to maldevelopment of normal cerebral visuomotor circuits?

Animal studies have shown that if a skeletal muscle is passively stretched or shortened, sarcomere length initially increases or decreases, respectively, resulting in suboptimal actin–myosin overlap and decreased contractile efficiency.[2-4] However, if skeletal muscle length is maintained for several weeks, sarcomere adaption occurs. If the skeletal muscle is stretched, new sarcomeres are laid down in series (end to end), thus allowing each sarcomere to return to its initial optimum length. Conversely, if the muscle is shortened, sarcomeres drop out serially so that sarcomere length returns to normal. The same process also occurs in response to muscle length changes induce by chronic nerve stimulation.[2] Biological mechanisms mediating these sarcomere adaptations are unclear,[5] but the physiologic benefit is evidently to maintain optimum actin and myosin filament overlap to maximize efficiency of muscle contraction.

In 1994 Scott[6] demonstrated that extraocular muscles in monkeys, like skeletal muscles, could adapt their sarcomere lengths. He sutured one eye of a monkey to the lateral orbital wall in a position of 30° to 45° of exotropia. After maintaining exotropia for 2 months, sarcomere length in the treated eye was similar to those of the control eye; since the muscle lengths themselves were presumably altered, this implied that the numbers of sarcomeres in each muscle had changed. This modification of extraocular muscle length by sarcomere adaptation has been hypothesized to explain persistence of strabismus in Duane syndrome, and following transient injury, botulinum paralysis, or surgical recession.[6-8]

Guyton and colleagues[9] elaborated the sarcomere adaptation concept to include a three-level feedback system as the basis for several types of "sensory" strabismus,

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suggesting that changes in vergence tonus in strabismus drive extraocular muscle length adaptation bilaterally, in turn decreasing the need for chronic changes in vergence tonus. Guyton[9-10] has hypothesized that this mechanism may explain increasing "basic" deviation in accommodative esotropia, torsional deviation associated with A and V patterns,[11] recurrent esotropia with presbyopia,[12] divergence insufficiency in presbyopic patients,[9] and cyclovertical deviations mimicking superior oblique paresis.[10]

Alternatively, work in primate models[13-16] and clinical observations argues against primary extraocular muscle abnormality as the cause of comitant strabismus. Tychsen and colleagues[15] found no differences in horizontal rectus cross-sectional areas, extraocular muscle paths, innervation densities, or cytoarchitecture in monkeys with spontaneous early-onset esotropia ranging from 7^{Δ} to 24^{Δ} compared with normal animals on high-resolution MRI and whole-orbit histopathology.[15]

The present study sought to determine whether abnormalities in path lengths of the horizontal rectus muscles are associated with commonly encountered intermittent or alternating esotropia and exotropia, testing the common presumption that muscles shorten in the direction of the habitual deviation. An experimentally accessible parameter might at first be thought to be overall muscle rest length, the length of a completely relaxed muscle not subjected to external mechanical loading. Presumably rest length would change because of sarcomere adaptation. The observed lengths of extraocular muscles change from their rest lengths as a function of elastic tensile loading, among other factors. Rest length, however, is not an observable parameter in vivo, since its measurement under zero loading would require extraocular muscle extirpation. Furthermore, since living muscles contract and relax to change their lengths during duction, any interpretable study must be performed with the eye in the same, reference, position. Central gaze seems a reasonable choice of reference position. However, if rectus muscles always followed the shortest paths from origin to insertion, then their lengths could only vary with globe and orbit size but would never otherwise vary as long as the eye remained in the reference position. Until recognition of the role of the orbital connective tissues in regulation of extraocular muscle paths, the foregoing consideration made it seem likely that rectus muscles would always have the same lengths in the reference eye position, regardless of the presence of strabismus. Were this true, there could be no empirical way of interpreting muscle lengths in the pathophysiology of strabismus; however, it is empirically possible to measure extraocular muscle path length.

Anatomical[17,18] and functional imaging studies[19-21] have established that the orbital pulley system inflects rectus muscle paths in both orthogonal directions transverse to their long axes, especially for the lateral rectus.[22] Inflected or curved paths are necessarily longer than straight paths. Indeed, markedly bowed, elongated muscle paths have been demonstrated in older adult patients with acquired strabismus due to sagging eye syndrome.[23] The authors postulated a similar phenomenon in other forms of strabismus. In esotropia, for example, a shortened medial rectus might hypothetically have increased tensile force in central gaze and resist path inflection by the pulley system, resulting in a straighter path and shorter length than normal. A lengthened lateral rectus, on the other hand, might hypothetically have less tensile force and thus a larger inflection in central gaze, resulting in a longer path than normal.[24] Because rectus muscle path length has not heretofore been studied in other forms of strabismus, the present study examined path lengths of the medial rectus and lateral rectus muscles in concomitant esotropia and exotropia, including intermittent or alternating forms. While the approach of measuring path length in standard gaze position still cannot determine resting (ie, externally unloaded) length, it represents the only possible systematic method of evaluating the role of muscle length in strabismus.

Subjects and Methods

Written informed consent was obtained according to a protocol approved by the Institutional Review Board of the University of California Los Angeles and in conformity with the Health Insurance Portability and Accountability Act of 1996. Paid control subjects underwent complete examinations to verify normal corrected vision, normal ocular versions, orthotropia in all gazes positions, and normal Titmus stereopsis of 40 arcsec. Subjects with esotropia or exotropia were recruited from an academic strabismus practice into a long-term, prospective study on strabismus and underwent sensorimotor evaluation and MRI. The ongoing study includes an overabundance of potentially eligible subjects. We selected from the study database the first alphabetically consecutive 13 controls and 12 strabismic cases with adequate imaging quality for analysis. Exclusion criteria included cases of paralytic or restrictive strabismus. No patient had a history of strabismus surgery. Heterotropia was measured at distance and near by prism and cover testing.

A 1.5-T MRI scanner (Signa; General Electric, Milwaukee, WI) was used for imaging using T1-[25-26] or T2-weighted fast spin-echo sequences.[27] These scanning protocols provide equivalent measurements. Crucial technical aspects, detailed elsewhere,[20,28-29] include use of a dual-phase surface coil array (Medical Advances, Milwaukee, WI) and fixation targets. High-resolution (312 μm) axial images of 2 mm thickness and matrix of 256 $\times$ 256 perpendicular to the long axis of the orbit were obtained in target-controlled central gaze.

To avoid confounding measurements by contractile changes in muscle path lengths induced by varying eye position, measurements were obtained in central gaze only, on both eyes in normal patients and on the fixating eye in strabismic patients. This constraint imposed a uniform reference eye position on all measurements. In order to verify gaze position, we measured the angle of the fixating eye. A line was drawn on the MRI image from the corneal apex through the lens center to the retina, and a second