During the last half of the 20th century, the field of strabismus did not undergo as many major advances as other areas of ophthalmology. In recent years, an increase in basic science research has fostered important advances in our understanding and treatment of disorders of binocular vision. This article identifies 4 important questions that need to be addressed by the pediatric ophthalmology and adult strabismus community: (1) What terms should be used to describe muscle dysfunction? (2) By what mechanism does strabismus surgery work? (3) What is the role of orbital imaging in the management of strabismus? (4) What is the role of refractive surgery in the treatment of patients with amblyopia and strabismus?

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When I was an ophthalmology resident in the early 1970s, I attended the annual May meeting of the Chicago Ophthalmological Society. That year the meeting featured talks about the treatment of retinal disorders, cataracts, and strabismus. The retinal surgeons spoke about the great new advance in their field: pars plana vitrectomy. At last there was treatment available for a host of serious disorders that previously could not be treated. Then the cataract surgeons presented data about the new innovation in their subspecialty: intraocular lens (IOL) implantation. Patients undergoing cataract surgery would no longer have to wear thick aphakic spectacles or contact lenses. Then Martin Urist, MD, the moderator of the strabismus section, began to speak. “You know,” he said, “there have not been any major advances in the treatment of strabismus in over 50 years!” At the time, I had already decided on a career in pediatric ophthalmology, and I found Urist’s words to be both discouraging and challenging. I am now pleased to say that the field of pediatric ophthalmology and strabismus has risen to that challenge. As translational research has bridged the gap between the clinic and the laboratory, the management of strabismus has made major advances in recent years. This article presents 4 major questions that need to be addressed by the field of pediatric ophthalmology and adult strabismus. They are certainly not the only important questions, but they are ones that I believe to be of great value.

WHAT TERMS SHOULD BE USED TO DESCRIBE MUSCLE DYSFUNCTION?

When an eye moves excessively into the field of action of an extraocular muscle on version testing, that muscle is traditionally described as being overacting. Consider the patient in Figure 1. On elevation in right gaze, the left eye elevates higher than the right eye. This phenomenon is typically referred to as overaction of the left inferior oblique muscle. However,Traditionally, these patterns have been referred to as overaction of the left inferior oblique muscle. However, this term can be misleading because it assumes an etiology based solely on an instant clinical observation. In fact, many conditions exist in which such a motility pattern may be caused by factors completely unrelated to the left inferior oblique muscle. These conditions include Duane syndrome of the left eye, dissociated vertical deviation in the left eye, craniofacial syndromes, anti-
elevation syndrome after inferior oblique muscle transposition in the right eye, \(^1\) mechanical restriction of the right inferior rectus muscle, right superior rectus muscle paresis, pseudo-inferior oblique muscle over-action with a Y or V pattern, \(^5\) or pulley heterotopia. \(^4,5\) In addition, when an abnormal motility pattern like that seen in Figure 1 is caused by the left inferior oblique muscle, multiple different pathophysiologic situations can make the muscle seem to overact. The abnormal elevation of the left eye on adduction can be caused by an increase in the elastic force (decreased elasticity) or an increase in the contractile force (increased strength) of the left inferior oblique muscle. \(^1\) This latter condition can be a result of increased innervation to or sensitivity of the muscle, an increase in muscle bulk (cross-sectional area), or changes in the types of muscle fibers within the muscle. \(^1\) Consequently, the term \textit{overaction} can lead to misunderstanding as to what is causing a perceived motility disturbance, which can then lead to inappropriate treatment. For example, a routine weakening procedure on the left inferior oblique muscle may not benefit the patient in Figure 1 if the elevation of the left eye on adduction was caused by any of the aforementioned mechanisms that did not involve an abnormality of that muscle.

We should consistently use the term \textit{abnormal elevation (or over-elevation)} in adduction to describe a pattern such as that depicted in Figure 1, unless it is clear that the problem is caused by the left inferior oblique muscle. Similarly, the term \textit{abnormal depression (or over-depression)} in adduction should be used to describe what is commonly called superior oblique muscle over-action. The converse holds for so-called underaction of these 2 muscles. Similar suggestions have been made by Demer. \(^6\)

\section*{BY WHAT MECHANISM DOES STRABISMUS SURGERY WORK?}

Traditional teaching suggests that strabismus surgery works by either creating slack or increasing tension in the operated-on muscle (Starling law). \(^1,7\)\(^-\)\(^9\) Recessing an extraocular muscle places the muscle's length at a point on the length-tension curve at which both forces are both less than they were before recession; resecting an extraocular muscle shifts the muscle length to a point on the curve at which both forces are increased (Figure 2). This effect has been referred to as an induced advancement. \(^6\) For a hypothetical eye with an axial length of 24 mm, a 35 \(\Delta\) strabismus surgery will result in an induced advancement of approximately 3.5 mm. Thus, if the surgery to correct the 35 \(\Delta\) deviation consisted of a 5-mm recession of the ipsilateral medial rectus muscle, the muscle would have shortened by only 1.5 mm (the 5-mm recession minus the 3.5-mm induced advancement). Even more perplexing is the fact that the antagonist ipsilateral lateral rectus muscle will shorten as a result of a similar induced recession by 3.5 mm (Figure 4). A 5-mm recession of a medial rectus muscle to correct a 35 \(\Delta\) esotropia actually results in more shortening of the lateral rectus muscle than the medial rectus muscle if the eye straightens. The situation is complicated further by similar induced effects that occur in the fellow eye or the antagonist lateral rectus muscle if it is resected. These induced effects have previously been elaborated in detail. \(^6\) Clearly, the classic concept of strabismus surgery working by altering the length-tension relationship within the extraocular muscles cannot explain the entire picture.
The advent of computed tomography and magnetic resonance imaging has given physicians previously unavailable opportunities to visualize the extraocular muscles' anatomy and function. Certain circumstances exist in which orbital imaging has a clear role in the management of complex strabismus. For example, dynamic imaging can show if there is still contractile function in a damaged or severed extraocular muscle. This, in turn, can affect treatment decisions (Figure 6). Slippage of an extraocular muscle as the eye moves into eccentric gaze (pulley instability) can be diagnosed with dynamic imaging. Orbital imaging has shown the heavy eye syndrome to be caused by a herniation of a large myopic eye between the superior and lateral rectus muscles. This observation has led to treatments that correct the strabismus by addressing the underlying anatomic abnormality. Dynamic imaging may be useful in differentiating extraocular muscles that either have slipped in the capsule or have an elongated scar from muscles that are lost (eg, not attached to the globe). The former 2 conditions show a characteristic fusiform enlargement that is posterior to the globe when the muscle in question contracts (Figure 7).

An evolving body of literature suggests that many cases of incomitant strabismus, A or V patterns, presumed superior oblique muscle palsy, or elevation or depression in adduction are caused by a relative esotropia of the extraocular muscle pulleys. If these observations are

### Figure 3
Rotation of the site of the medial rectus muscle insertion (M) and lateral rectus muscle insertion (L). A, An eye is deviated inward 35 prism diopters (Δ). B, If the eye straightens the entire 35Δ, point M will rotate forward in the orbit and point L will rotate posteriorly in the orbit. For an eye with a hypothetical axial length of 24 mm, this 35Δ rotation will approximate 3.5 mm.8

### Figure 4
Rotation of the site of the medial rectus muscle insertion (M) and lateral rectus muscle insertion (L). A, A pair of eyes in which the right eye (left) is 35 prism diopters (Δ) esotropic. B, The right medial rectus muscle is recessed 5 mm (from its original insertion point at M1 to M2). The right lateral rectus muscle is resected 5 mm and left inserting at the original insertion point L. C, If the surgery completely corrects the 35Δ esotropia and if the right eye has a hypothetical axial length of 24 mm, the induced advancement of the recessed right medial rectus muscle is approximately 3.5 mm as M2 rotates completely forward in the orbit, resulting in only 1.5 mm of actual shortening of the muscle. The antagonist lateral rectus muscle will undergo an induced recession of approximately 3.5 mm, thus shortening this resected muscle more than the recessed medial rectus muscle.

### Figure 5
Anatomy of the horizontal rectus muscles, including depiction of the orbital pulleys. A, The medial rectus muscle originates at the apex of the orbit, is reflected at the site of its pulley (P), and inserts on the globe at point M. B, If the medial rectus muscle is recessed to point M2 and the muscle is still constrained at its pulley, the muscle will now have less tangency with the globe, thereby decreasing its effective lever arm and weakening its torque. This is the mechanism by which recessions decrease torque according to the torque vector theory.

### Figure 6
Slippage of an extraocular muscle as the eye moves into eccentric gaze (pulley instability) can be diagnosed with dynamic imaging. Orbital imaging has shown the heavy eye syndrome to be caused by a herniation of a large myopic eye between the superior and lateral rectus muscles. This observation has led to treatments that correct the strabismus by addressing the underlying anatomic abnormality. Dynamic imaging may be useful in differentiating extraocular muscles that either have slipped in the capsule or have an elongated scar from muscles that are lost (eg, not attached to the globe). The former 2 conditions show a characteristic fusiform enlargement that is posterior to the globe when the muscle in question contracts.

### Figure 7
Anatomical curves to surgery with fixed suture loops,9,10,11 have similar dose-response curves to surgery with fixed sutures.10-12 In theory, surgery performed with a suspension technique (hangback) have similar dose-response curves to surgery with fixed sutures. In theory, surgery performed with a suspension technique should have a lesser response than fixed-suture surgery in the initial postoperative period because the functional insertion would still be at the original site before the cut end of the muscle has bonded with the globe.

**WHAT IS THE ROLE OF ORBITAL IMAGING IN THE MANAGEMENT OF STRABISMUS?**

The advent of computed tomography and magnetic resonance imaging has given physicians previously unavailable opportunities to visualize the extraocular muscles' anatomy and function. Certain circumstances exist in which orbital imaging has a clear role in the management of complex strabismus. For example, dynamic imaging can show if there is still contractile function in a damaged or severed extraocular muscle. This, in turn, can affect treatment decisions. Slippage of an extraocular muscle as the eye moves into eccentric gaze (pulley instability) can be diagnosed with dynamic imaging. Orbital imaging has shown the heavy eye syndrome to be caused by a herniation of a large myopic eye between the superior and lateral rectus muscles. This observation has led to treatments that correct the strabismus by addressing the underlying anatomic abnormality. Dynamic imaging may be useful in differentiating extraocular muscles that either have slipped in the capsule or have an elongated scar from muscles that are lost (eg, not attached to the globe). The former 2 conditions show a characteristic fusiform enlargement that is posterior to the globe when the muscle in question contracts.
valid, they may represent a major advance in our understanding of ocular motility disorders. Many of the reported cases of pulley ectopia as a cause of incomitant strabismus are in fact subtle. The location of the muscle pulley in question deviates from the location described as normal by only 1 or 2 standard deviations. Images to diagnose pulley ectopia must be generated according to a strict protocol. Moreover, the location that has been considered the normal position for the extraocular muscle pulleys has changed over time. Although I consult regularly with qualified neuroradiologists, some of whom have a great deal of expertise in interpreting orbital images, they are usually unable to diagnose these subtle instances of pulley ectopia. A readily usable protocol is needed for strabismologists and neuroradiologists to diagnose these conditions. Such a protocol needs to provide established norms, ranges outside those norms that are considered significant, and a method for obtaining and interpreting the images. Finally, these observations of incomitant strabismus that result from subtle pulley ectopia need to be replicated by other investigators.

WHAT IS THE ROLE OF REFRACTIVE SURGERY IN THE TREATMENT OF PATIENTS WITH AMBLYOPIA AND STRABISMUS?

Intraocular lens implantation became the standard of care for adult cataract surgery during the 1970s. For many years thereafter, there was justifiably great caution about implanting IOLs in children. With the exception of a series of pediatric IOLs led by Hiles and Watson,24 the early reports of IOL use in children from North America were by anterior segment surgeons. Many of these focused primarily on the anatomical result obtained, without much attention paid to amblyopia or binocularity. Subsequent pioneering work by pediatric ophthalmologists in the late 1980s moved the art and science of pediatric IOL implantation to its current sophisticated level.25-28

The issue of refractive surgery in patients with amblyopia and strabismus is currently reminiscent of the status of pediatric IOLs in the early 1980s. That is not to assume that there will be a role for refractive surgery in this population; possibly there may not be a major one. However, it is crucial that studies investigating this question pay careful attention to the nuances of amblyopia and strabismus. Any reports of improvement in the best-corrected acuity of eyes with amblyopia must be conducted with a masked examiner. Testing conditions should be carefully controlled with respect to lighting, optotypes used, crowding, the Hawthorne effect (individuals perform better if they know they are being studied), learning curve, and apparent improved acuity with increased effort.29 One need only recall the history of the Cambridge Amblyopia Vision Stimulator.30,31 This treatment, which involved having the patient look at a rotating spatial frequency grating, was initially heralded as an easier alternative to occlusion therapy for overcoming amblyopia. However, a prospective randomized masked clinical trial proved the treatment to be ineffective.32

The important relationship between accommodation and convergence needs to be considered when
Figure 7. This boy had undergone bilateral medial rectus muscle recessions 3 years earlier. His eyes were initially well aligned after surgery. A, Shortly thereafter he began manifesting a progressively increasing right exotropia. B, There was limited adduction of the right eye. C, Dynamic orbital imaging shows the right medial rectus muscle to be attached to the globe. D, On attempted adduction, the left medial rectus muscle shows a thin band of noncontractile tissue attaching to the globe (arrow). Well posterior to that is a fusiform dilation of the muscle, representing the contractile tissue. This is characteristic of a muscle that has slipped in the capsule. E, After advancement of the right medial rectus muscle and excision of 14 mm of empty muscle capsule, the eye is well aligned in the primary position. F, The right eye has good adduction after surgery.

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