

Extraocular Connective Tissues: A Role in Human Eye Movements?

J. Ross McClung, Brian L. Allman, Diana M. Dimitrova, and Stephen J. Goldberg

PURPOSE. This study presents a detailed anatomic analysis of the undisturbed connective tissues that surround the horizontal extraocular muscles (EOMs) of humans. Emphasis is placed on those EOM orbital side tissues that, in previous MRI studies, were assumed to couple the muscle to the pulley.

METHODS. Serial 5- μ m sections were prepared from paraffin-embedded blocks of the lateral and medial rectus muscles and their surrounding connective tissues. The sections were treated with Masson's trichrome stain for light microscopic examination of muscle fibers (red) and surrounding connective tissues (blue).

RESULTS. Rectus muscle sections demonstrated the orbital connective tissues to be a collagenous bridge between the distal third of the muscle and the orbital periosteum (i.e., check ligament [CL]). The CL attaches to the muscle by investing itself around orbital muscle fibers whereas, at the point of attachment, those fibers remain aligned with the remainder of the muscle. The CL on the orbital side and the reflected bulbar fascia on the global side of the muscle constitute a tubelike sheath. The posterior border of the sheath insinuates into the muscle belly and its anterior aspect blends into the sides of the portal through Tenon's capsule.

CONCLUSIONS. All rectus EOM fibers participate in eye rotation. The CL is the band of tissue present on the MRI images, but was previously described as the orbital layer insertion for the active pulley hypothesis (APH). The APH should now be questioned. Alternate theories incorporating accepted neurophysiological, anatomic, and ophthalmological principles of EOM movement are discussed. (*Invest Ophthalmol Vis Sci.* 2006;47:202-205) DOI:10.1167/iovs.05-0860

Recently, significant attention has been focused on the connective tissues found on the orbital surface (side near the bone) of the extraocular muscles (EOMs) in humans and other mammalian species.¹ These connective tissues have been described in classic anatomic studies and books for over 70 years.² Most anatomic textbooks³ contain descriptions and/or images of check ligaments (CLs) on the orbital side of the lateral and medial recti as well as the fascia behind the globe of the eye (i.e., Tenon's capsule or the fascia bulbi). This fascia reflects back as a sleeve around the muscle and has portals

(openings). The EOMs pass through these portals to insert on the sclera of the eye.

These long known connective tissue elements have apparently been renamed and a pulley function has been ascribed to them. As suggested by Miller,⁴ Demer et al.⁵ formally proposed that the EOMs are held in place and even deflected by pulley-like connective tissue near the portal through Tenon's capsule. The pulley function was further elaborated by noting the presence of smooth muscle with parasympathetic innervation within these tissues. This gave the pulley a dynamic neural control component.⁶

When high-resolution magnetic resonance imaging (MRI) images of the pulley tissues were observed during levoversion and dextroversion of the eye, tissue projections from the orbital side of the EOMs were noted.⁷ These orbital projections were proposed to be the functional insertion of the orbital (peripheral, fine fiber) layer of the rectus muscles. It was further suggested that the orbital projection was a separate tendon of the orbital layer, with distinct neural control of the orbital layer muscle fibers capable of actively positioning the pulley throughout the full range of eye motion (active pulley hypothesis [APH]).^{1,7} This interpretation leaves the global layer muscle fibers alone to move the eye through its insertion on the sclera.

Because recent anatomic studies in monkeys, humans⁸ and rats⁹ have raised concerns regarding the pulleys, we performed a detailed anatomic analysis of the undisturbed connective tissues that surround the horizontal EOMs in humans, with emphasis on the anatomy of the orbital tissues that were shown in MRI images to couple the EOMs to the pulley.⁷ Thus, the purpose of our study was to determine whether the structure attached to the orbital side of the EOMs, observed in the MRI images,⁷ represents a true orbital layer insertion, and to observe whether the connective tissue in the orbit is consistent with pulleylike structures capable of mobility (i.e., adjusting position during EOM contraction) thereby providing a dynamic, anterior, functional origin of the EOMs. Some of this work has been published in abstract form (McNeer KW, et al. *IOVS* 2005;46:ARVO E-Abstract 5721).

METHODS

Tissue was dissected from an orbital specimen taken during craniofacial reconstruction surgery (78-year-old man) and fixed in neutral buffered formalin immediately after removal. This research adhered to the tenets of the Declaration of Helsinki. Because this specimen contained the bones of the surrounding paranasal sinuses and anterior orbit, all the connective tissue elements and muscles around the eye were undisturbed. Serial 5- μ m sections were prepared from paraffin-embedded blocks of the lateral and medial rectus muscles and their surrounding connective tissues. The sections were treated with Masson's trichrome stain for light microscopic examination of muscle fibers (red) and surrounding connective tissues (blue). The horizontal rectus muscles were dissected separately from the intact specimen. The lateral rectus muscle was then cross-sectioned in the coronal plane, and the medial rectus muscle was sectioned longitudinally in the horizontal plane.

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Supported by National Eye Institute Grant EY011249 (SJG), Jeffress Memorial Trust Grant J-745 (JRM), and the Smith-Kettlewell Eye Research Institute.

Submitted for publication July 6, 2005; revised August 9, 2005; accepted November 16, 2005.

Disclosure: **J.R. McClung**, None; **B.L. Allman**, None; **D.M. Dimitrova**, None; **S.J. Goldberg**, None

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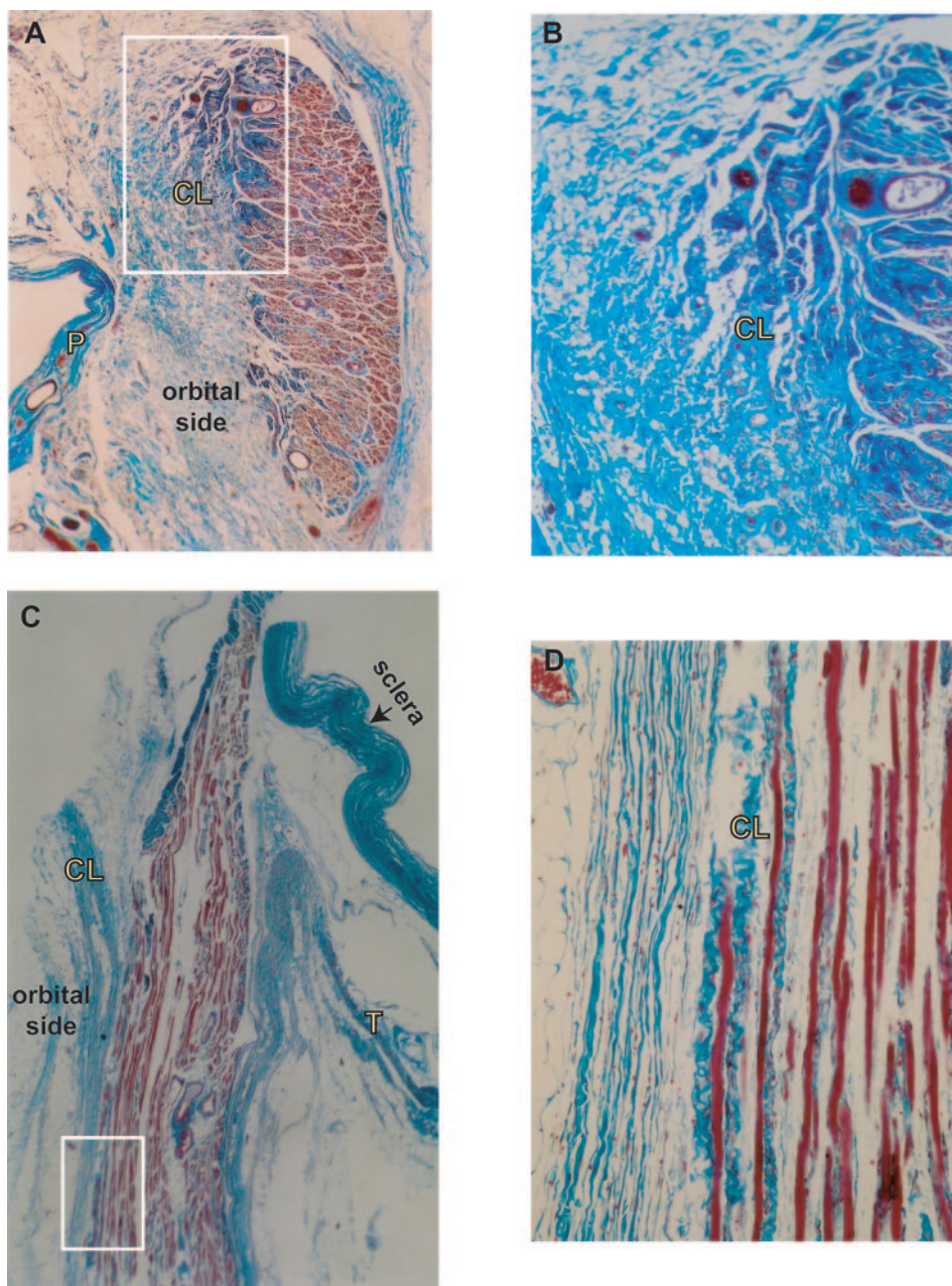


FIGURE 1. (A) A cross-section through the anterior third of the lateral rectus muscle approximately 3 mm posterior to the portal in Tenon's capsule. The periosteum (P) and other connective tissues (blue) are visualized on the orbital side of the muscle (red). Dense bands of collagen are seen bridging the gap between the muscle and the orbit wall. These bands have been defined in the current study and other studies to be the CL. (B) A higher magnification view of the CL from the box in (A), demonstrating a lack of smooth or skeletal muscle (no red-stained fibers) within these bands of collagen. (C) A horizontal section through the superior aspect of the medial rectus muscle approximately 2.5 mm into the muscle belly. The CL can be seen coursing away from the orbital side of the muscle. The sclera of the eye and Tenon's capsule (T) can be observed on the global side of the muscle. Note that no muscle fibers can be observed following the CL along its orbitally directed course. (D) A higher magnification view of the area in the box in (C), demonstrating the CL blending into the orbital side of the muscle by investing collagen filaments around the peripheral (orbital) muscle fibers. This insinuation of the connective tissue layer can also be seen on the global surface of the muscle.

RESULTS

Rectus muscle cross sections with trichrome stain demonstrate the connective tissues on the orbital surface to be a discrete dense collagenous bridge between the distal third of the rectus muscle, proximal to where it passes through Tenon's capsule and the periosteum of the orbital wall (Fig. 1A). This is a classic description of the CL.² No smooth or striated muscle was observed in the collagen bundles of the CL as they insinuate into the muscle belly (Fig. 1B). Both orbital and global muscle fibers remain parallel within their connective tissue sheaths (perimysium) and are lined up with the muscle tendon (Fig. 1C). The CL attaches onto the outer orbital muscle fiber layer by investing itself around individual muscle fibers (Fig. 1D). The orbital muscle fiber layer remains aligned with the rest of the muscle at the point of CL attachment and does not extend outward into the ligament (Figs. 1C, 1D). Both the orbital and global portions of the muscle can be observed to course to-

ward the single tendon of the muscle. There is no bifurcation of the muscle or its tendon. Tenon's capsule was observed behind the sclera of the eye on the global side of the muscle (Fig. 1C). This connective tissue layer, which in serial sections, was seen to wrap around the rectus muscles, also attaches onto the anterior third of the muscles by blending into the connective tissue of the muscle belly. A tubelike sheath is thus defined, with the CL on the orbital side and the reflected bulbar fascia on the global side. The posterior border of the sheath insinuates into the anterior third of the muscle belly and the anterior border of the sheath blends into the sides of the portal in Tenon's capsule.

DISCUSSION

We used histologic analysis to investigate the EOM fiber orientation from a human specimen with undisturbed connective

tissues and to determine whether the orbital layer muscle fibers project to the pulley as suggested by the APH.^{1,7} Also, we examined anatomic structures that may be consistent with a pulley that could shift the functional insertion of the EOMs anteriorly (as is well known for the superior oblique muscle). Contrary to the APH, we present no evidence and found no indications that the orbital layer muscle fibers leave the belly of the muscle to insert on a pulley. Instead, our histologic findings show collagen bundles of connective tissue (usually described as the CL)² that insinuate into the orbital layer of the rectus muscles (Figs. 1B, 1D). Based on an earlier electrical stimulation study,¹⁰ as well as a recent study from our laboratory,¹¹ we believe the CL to be an apt description of these dense collagen bundles. After removal of the lateral orbital wall and connective tissues (i.e., any pulleylike structures), we found an increase in lateral and medial eye movement amplitude and velocity in response to electrical stimulation of the appropriate nerve or nucleus.¹¹ This increased mobility (or release of connective tissue restraint) is consistent with the idea that the orbital collagen bundles are the CLs and have eye restraining (checking) actions.² Thus, we suggest that the orbital projections in the MRI images (that formed the anatomic foundation for the APH⁷) are the collagen bundles of the CL, not a separate insertion for orbital layer muscle fibers. Future modeling of eye movements based on the APH may have to be adjusted accordingly.

Muscle fibers connect to each other by connective tissue sleeves (endomysium and perimysium), which condense into the dense regular connective tissue structure called the muscle tendon. Thus, EOM fibers would ultimately act through their lateral and terminal connective tissues to move the eye. We found that all the muscle fibers (orbital and global) of the EOMs were aligned with the single muscle tendon that inserts on the eye. A recent anatomic study of 21 human cadavers shows both the orbital and global sides of the anterior third of the lateral and medial rectus muscles inserting on the sclera of the eye.¹² Similarly, Felder et al.⁹ clearly showed (in the rat inferior rectus muscle) that the orbital layer continued well anterior to the attachment of the orbital connective tissue band, which we believe is the CL. Therefore, the orbital layer must insert on the muscle tendon that attaches to the sclera. Indeed, physiological studies have shown that major surgical insults to the tendon¹³ or muscle¹⁴ belly do not significantly effect electrically evoked conjugate eye movements¹³ or muscle force.¹⁴ These latter studies confirm that muscle fiber force is transferred laterally within the muscle and ultimately acts on the eye itself.^{15,16}

In contrast with our present study, Ruskell et al.⁸ noted that by following muscle fibers through serial sections, "single muscle fibers, or sometimes two or three, continued for a short distance" (≈ 1.0 mm) and could be observed to enter the orbital connective tissues (the CL). However, a small number of fibers that have a tight relationship with the orbital connective tissues (CL) in no way constitutes a "double insertion"⁸ or a separate orbital layer insertion.¹ Finally, we showed in the present study that collagen fibrils from the global connective tissues also insinuate around the peripheral muscle fibers on the global surface of the muscle. This observation supports that of both Ruskell et al.⁸ and Felder et al.⁹ Therefore, if the orbital layer inserts on a pulley, then the global layer does, as well. This observation, now by three separate laboratories, confounds the idea of an independent pulley action for the orbital layer of the EOMs.

In relation to this exclusive pulley role for the orbital layer of the EOMs, a recent comprehensive review¹ asserted that fundamentally different neural commands would be needed for ocular rotation by the global layer and pulley translation by the orbital layer. We agree with this logical assertion. One would

expect, therefore, distinct motoneuron firing patterns by these two pools of motoneurons (orbital and global) recorded in alert animals during eye movements. However, this does not appear to be the case. All motoneurons have consistently been shown to be involved in every eye movement, and distinct populations of motoneurons with specific firing patterns have not been found.¹⁷ Moreover, the suggestion that the orbital layer serves to control pulley position, but not to rotate the eyeball, conflicts with the finding that feline lateral rectus muscle motor units with muscle fibers located in the orbital layer transmit force to the muscle insertion on the eye, similar to global layer motor units.¹⁸ In addition, a significant portion of feline abducens nucleus single motoneurons innervate muscle fibers in both the orbital and global layers.¹⁸ That is, single lateral rectus motor units are not necessarily confined to a single EOM layer. In humans, horizontal rectus muscles have been shown to produce similar force levels when attached to the globe or disinserted from it (Lennerstrand G, et al. *IOVS* 2003;44:ARVO E-Abstract 2735). These physiological findings do not support the APH but they are consonant with the usual single insertion for EOMs on the eye's sclera.

Of interest, even though we strongly question the separate orbital insertion idea, our findings do not challenge the idea that there are pulleylike restraints on the dynamics of eye movement.^{2,4,5,11} We assume the pulley to be the sling of tissue encircling the portal for the muscle as it passes through the fascia bulbi. This fascia adheres to the bones of the anterior orbit, providing a firm anterior attachment for the EOMs. Therefore, our images showing the rectus muscles having a sleeve of connective tissue firmly anchored into the muscle belly as well as into this portal define a mobile pulley. The movement of the pulley would be accomplished by the shortening of the entire muscle (both orbital and global portions) during muscle contractions that rotate the eye. No differential action of the orbital layer is necessary, and yet the pulley is moved along with the muscle to maintain the distance between the pulley and the scleral insertion of the tendon. As has been stated in the APH, "this coordination of pulley position is proposed to underlie Listing's law of ocular torsion" (Vijayaraghavan A, et al. *IOVS* 2005;46:ARVO E-Abstract 4675).

However, we still must answer a very important question. Are these fascia bulbi tissues strong enough to bend the rectus muscle tendons while force is being applied? The strength of the tissues has yet to be proven (Jampel RS, et al. *IOVS* 2005; 46:ARVO E-Abstract 4677).⁸ These sleeves of connective tissue around the EOMs may act as a pulley or they may not. But certainly, the bands of collagen that attach to the orbital wall and help to restrain EOM movement^{2,11} should still be referred to as CLs. We hope this study will give the scientific and clinical ophthalmology communities a thorough anatomic description of the connective tissues around the pulleys and help with this important modeling of eye movements.

Acknowledgments

The authors thank Robert E. Revels, Jr., for expert assistance with the histology; Keith W. McNeer, MD, and Mary G. Tucker, MD, for supplying the surgical specimen and encouraging us to use histopathology as a means of directly assessing the site of insertion of the orbital myofibers in human EOMs; their ideas and involvement are demonstrated in an earlier version of this work, published in abstract form (McNeer KW, et al. *IOVS* 2005;46:ARVO E-Abstract 5721).

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