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Mechanical properties and functional importance of pulley bands or '*faisseaux tendineux*'

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Abstract

Introduction: Connective tissue bands connect the horizontal rectus muscles at the level of the posterior pole to the orbital wall. These bands, referred to as pulley bands or *faisseaux tendineux*, purportedly act like springs to keep the rectus muscle bellies in place during eye movement out of the plane of the muscle. We examined the mechanical properties of these bands in human specimens obtained during surgery. In addition, we examined eye motility and stability of rectus muscles in a patient who had no functional pulley bands.

Methods: Exenterations were carried out on two patients with sebaceous gland carcinoma. Pulley bands were identified and force-elongation behavior was examined with a forceps and a force gauge. Stability of rectus muscles was examined in a patient with severe Crouzon's syndrome by orbital CT scans and during surgery under local, eye drop, anesthesia.

Results: The pulley bands showed leash-like mechanical behavior: they were slack over approximately 10 mm and became taut when stretched further. In the patient with Crouzon's syndrome, both CT and observation of the muscle during surgery showed little sideways displacement of the muscle bellies in eye movement out of the plane of the muscle, despite the lack of functional pulley bands.

Discussion: The leash-like mechanical behavior of the pulley bands seems unsuited for stabilization of the muscle bellies. The patient with Crouzon's syndrome had relatively good eye motility and stable rectus muscle paths despite the lack of functional pulley bands.

Keywords: Anatomy; Eye motility; Orbital biomechanics; Pulley

1. Introduction

Connective tissue bands connect the horizontal rectus muscles at the level of the posterior pole to the orbital wall, coursing anteriorly towards the medial and lateral canthi. These connections are referred to as '*faisseaux tendineux*' by Tenon (1816) and as pulley bands by Demer (2002). In a magnificent anatomical description presented by Tenon as a lecture to the Anatomy and Zoology section of the National Institute in 1805, published posthumously in 1816, Tenon describes their function for the lateral rectus muscle as follows: 'The abductor, being the thickest and longest of the rectus muscles, also has the thickest and strongest tendinous fascia; this fascia arises on the outside of the muscle, behind the tendon, after which it proceeds anteriorly and laterally, at an ever greater distance from the muscle, to the lateral corner of the orbit, where it attaches to the bone very near the lower edge of the lacrimal gland. Due to this position, the fascia forces the tendon of the

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abductor to bend; by changing its direction in this way, it plays the role of pulley in relation to the tendon and the entire muscle. In effect, when the abductor contracts, its tendinous fascia gradually elongates, but without completely eliminating the angle that it forces the abductor to make; thereafter, as soon as the muscle ceases contracting, the elasticity that the tendinous fascia possesses brings everything back to the original state. 'Tenon used fresh specimens for anatomical dissection and advised: '...lift the muscles up by the posterior ends and dissect them carefully, working from the rear to the front: soon you will encounter the fasciae in question and their ends'. The functional importance of the pulley bands has been emphasized by Demer (2002) in recent studies. In his Active Pulley Hypothesis the pulley bands act like springs to stabilize the rectus muscle paths in eye movements out of the plane of the muscle.

In the first computerized model of eye motility (Robinson, 1975) the problem of the stabilization of the rectus muscle paths first became clear: when a horizontal rectus muscle would always follow the shortest path from origin to insertion, it would shift vertically when the eye looks up or down. Similarly, a vertical rectus muscle would shift horizontally when the eye looks left or right. It has been found, however, that the rectus muscle bellies stay in place in movement out of the plane of the muscle (Miller, 1989; Simonsz, Härting, de Waal, & Verbeeten, 1985). The question then is, whether the pulley bands could accomplish this stabilization. To stabilize a muscle belly this band has to exert sufficient force on the muscle to keep it in place but, at the same time, it should be able to elongate sufficiently: the insertion of the pulley band on the horizontal rectus muscle moves 9 mm forward and 9 mm backward when a person looks 45° left or 45° right. A pulley band between muscle and orbital wall has to allow for such large eye rotations. Conversely, in the absence of pulley bands, eye motility should be deficient and rectus muscle paths should be unstable. Whether it is the pulley bands that keep the muscle bellies in place or other structures, the consequence is that the effective direction of pull of a muscle partly rotates with the eye in eye movements out of the plane of the muscle. If the structures that keep the muscle bellies in place are connected to the orbital wall, the effective direction of pull will rotate considerably in eye rotations out of the plane of the muscle. If, however, the structures are connected with the eye and with other eye muscles the rotational effect will be less. This mechanism has first been formally defined by Miller (1989) as the 'pulley'.

In this study, we examined the mechanical properties of pulley bands in fresh human specimens obtained during exenteration for sebaceous gland carcinoma and examined eye motility and stability of rectus muscles in a patient with Crouzon's syndrome who had no bony orbital wall and, hence, no point of attachment for the pulley bands.

2. Methods

Two fresh exenteration specimens were studied. The exenterations were carried out in a 75-year-old-male and a 50-year-old-female, both with sebaceous gland carcinoma of the eyelids of the left eye. Both patients gave full oral informed consent, specifically for mechanical measurements on the exenterated specimen. Immediately after removal from the orbit, measurements were performed over a period of approximately 3 min. Measurements took place during the period that bleeding in the orbit was controlled by packing the orbit with gauze and exerting pressure for 5 min. The region of the sebacious gland carcinoma, i.e., the eyelid margins, was not in any way involved in the measurements. After the measurements the specimens were immediately transported to the Department of Pathology where, after fixation and sectioning, the diagnosis, obtained by preoperative biopsy, was confirmed.

For exenteration of the orbital contents the skin was incised with a wide margin around the eyelids up to the orbital rim. The periorbit was circularly incised at the orbital margin and lifted off the orbital wall. Carefully the points of attachment of the periorbit to the medial and lateral canthus were marked, as these were the origins of the pulley bands. Finally the rectus muscles, the superior oblique muscle, the levator muscles, the optic nerve and the orbital fat were cut at approximately 10 mm behind the posterior pole of the eye (Fig. 1).

The following structures were identified in the specimens: eyelids, eyeball, rectus muscle stumps, orbital fat, Tenon's capsule and the white connective tissue surrounding each of the rectus muscles at the level of the posterior pole. The latter represented the location of the insertion of the pulley bands (Fig. 2, triangle) and is called 'pulley ring' in the Active Pulley Hypothesis.

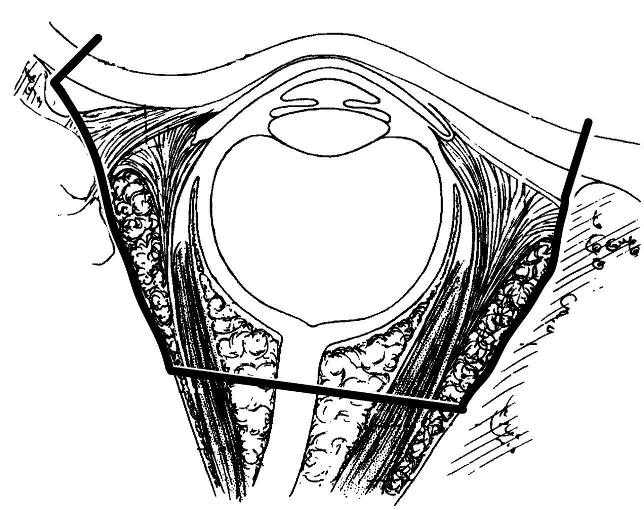

Fig. 1. Schematic drawing of the exenteration procedure, redrawn after Fink (1962). After skin incision to the orbital rim, the periorbit is lifted off the bony orbital wall and the orbital contents are cut-off, through the optic nerve and the four rectus muscles.

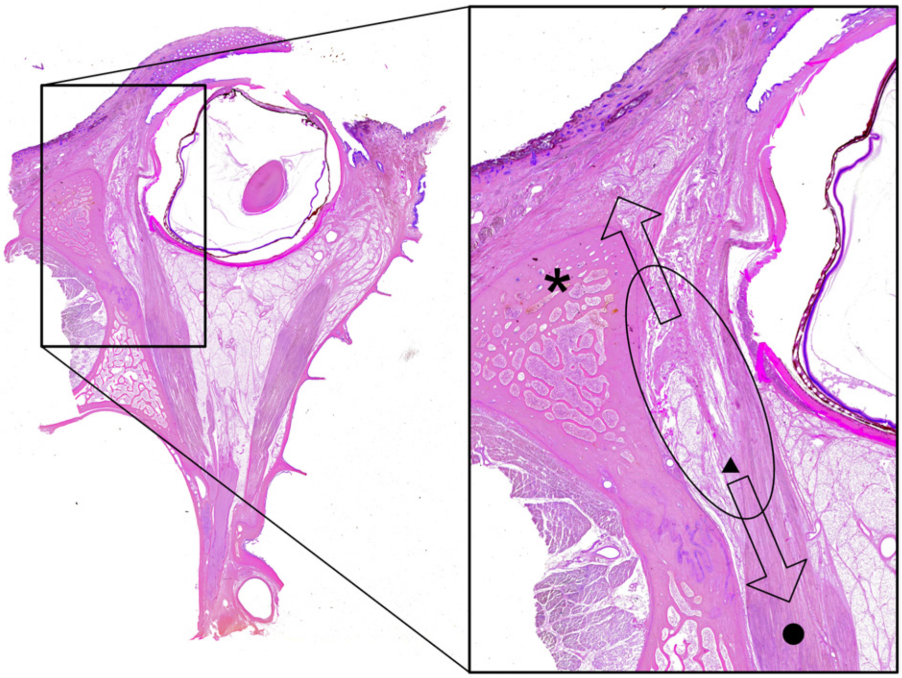

Fig. 2. In some of the horizontal sections of a human orbit (26-year-old person, 80 μm section, hematoxylin–eosin stain) by Koornneef (1977), the *faisseaux tendineux* or pulley bands could be identified histologically as coursing from the anterior edge of the periorbit near the lateral canthus to the white connective tissue encircling the rectus muscles at the lateral side (triangle). The asterisk marks the left zygomal bone. The filled circle marks the left lateral rectus muscle.The arrows mark the direction of pull during the force-elongation measurement. During our measurements, the anterior edge of the cut-off periorbit was grasped with a forceps, while the white connective tissue encircling the rectus muscle was hooked onto the spring gauge.

In some of the horizontal sections of a human orbit by Koornneef (1977), the pulley band could be identified histologically (Fig. 2). The periorbit was incised during the course of the exenteration at the bony orbital rim. The pulley bands originate from the periorbit slightly posterior to this point, behind the medial and lateral canthi, as can be seen on the horizontal section by Koornneef. Therefore, the edge of the cut-off periorbit could be taken as origin of the pulley band.

This edge was grasped with a forceps. With a second forceps the white connective tissue encircling the rectus muscle at the level of the posterior pole (the pulley ring) was grasped. In this way the pulley band was held at both ends. To get an impression of the stiffness, these two points were moved relative to each other along the length of the band in both directions, similar to the relative movement of the two points during large horizontal eye rotations (Fig. 2, arrows). Reaction force was estimated manually.

During the second exenteration, a spring gauge was substituted for the second forceps, allowing for more accurate force measurement. The degree of deformation was measured using a millimeter scale posed behind the pulley band. The measurements were recorded on video for analysis of the applied displacement and measured forces.

Eye motility and stability of rectus muscle paths were examined in a 69-year-old patient with a severe Crouzon's syndrome. The patient presented with severe exophthalmos and limitation of depression of the left eye. He had been treated at age 9 by bilateral partial tarsorraphy because the eyelids kept slipping behind the eye. The range of eye motility was documented on video.

The orbits were so shallow that the aperture of the bony orbit was situated at the level of the posterior pole of the eye. Therefore, he did not have a bony orbital wall for attachment of the pulley bands. Coronal CT scans were made of both orbits at the level of the posterior pole, while the patient looked with the right eye in five directions of gaze: ahead, approximately 25° up, down, left, and right. Sideways displacement of the rectus muscles during eye movements out of the plane of action of these muscles was documented in these scans.

The limitation of down-gaze of the left eye was treated by surgical resection of the inferior rectus muscle of the left eye under local eye-drop anesthesia. During surgery the inferior oblique muscle was found to be long and thin. It was easily separated from the inferior rectus muscle, there was only a minimal Lockwood's ligament. As the orbit was extremely shallow, during surgery a video could be made from below visualizing the inferior rectus muscle still attached to the eye. The patient looked far left and right with both eyes to elicit sideways displacement of the inferior rectus muscle belly at the level of the equator and a few millimeters more posterior.

The motility of the eye was unaffected by the eye-drop anesthesia.

3. Results

The white circular connective tissue surrounding the rectus muscles was firmly attached to the perimysium of the rectus muscle, on both the global and the orbital side of the muscle. When force was applied to the pulley band with two forcepses (patient 1) or with a forceps and a spring gauge (patient 2), it showed a highly non-linear elastic behavior. In the first patient, reaction force was estimated manually: the bands were slack but felt like a leash when elongated. In the second patient, a spring gauge was used and the bands stretched consistently over approximately 10 mm (Video 1) with very little force applied (5–10 g), indicating a very elastic initial behavior. As the load increased the pulley bands got taut and rigid. With higher forces applied (up to 60 g) additional lengthening was hardly noticeable (Video 2). Hence, the pulley bands could be characterized as having leash-like mechanical properties: initially a very elastic behavior followed by high rigidity on further lengthening. The bands were the only structures that had a high rigidity on elongation: other parts of the specimen in that region, except the eye muscles themselves, were pulled apart with the two forcepses with relative ease.

The patient with severe Crouzon's syndrome had a divergent strabismus with left hypertropia, V-pattern motility and upshoot in adduction of the left eye. The range of monocular motility was relatively good in both eyes: the right eye had 22° elevation, 30° depression, 40° abduction, and 40° adduction. The left eye had 18° elevation, 15° depression, 35° adduction, and 38° abduction, as assessed with a synoptometer. The limitation of depression of the left eye was disturbing because the left lower eyelid was retracted, causing corneal irritation. A 6-mm resection of the left inferior rectus muscle was performed in local, cocaine eye drop anesthesia. Eye movements did not strictly follow Listing's law; some deviant torsion occurred (Video 3) when the left eye moved in tertiary positions.

Orbital CT scans showed that the medial and inferior parts of the orbital rim were situated at the level of the posterior pole of the eye. Scans in primary and four secondary positions of gaze showed little displacement of the vertical rectus muscle bellies in eye movements out of the plane of the muscle, i.e., in left and right gaze (Fig. 3). Similar stability of the muscle bellies was observed for the lateral and medial rectus muscles in up and down gaze.

A thick intermuscular membrane interconnected the superior rectus and levator muscles to the lateral rectus muscle and the latter to the inferior rectus muscle. Interestingly, the intermuscular membrane was particularly pronounced in regions where no orbital wall was present.

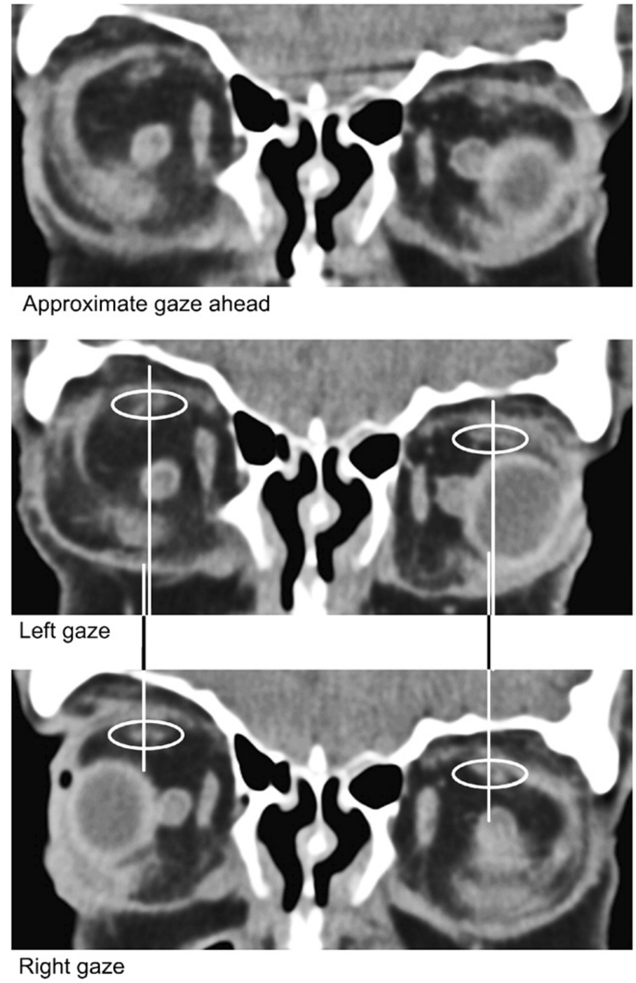

Fig. 3. CT scans in three positions of gaze of the patient with Crouzon's syndrome. Little displacement of the bellies of the superior and inferior rectus muscles occurred in left as compared to right gaze, despite the absence of the bony orbital wall. Note the conspicuous intermuscular membrane.

During surgery it was found that no sideways displacement of the inferior rectus muscle occurred on left and right gaze (Video 4), although the (thin) inferior oblique muscle had been severed from the inferior rectus muscle and the orbital floor was lacking.

4. Discussion

As quoted in Section 1, Tenon (1816) stated in 1805 that the *faisseaux tendineux* or pulley bands could be easily identified when preparing through the orbit from posterior to anterior. We could confirm that, it is easy to identify these bands in the orbit when preparing from back to forth. There were several indications that we identified the pulley bands correctly. As evident from the horizontal section by Koornneef, the pulley band courses from the periorbit, slightly posterior to the bony orbital rim behind to the medial and lateral canthi, to the white circular connective tissue surrounding the rectus muscle at the level of the posterior pole of the eye. The edge of the cut-off periorbit was taken as origin of the pulley band. The bands we identified were the only structures in the region that had a high rigidity on elongation.

Histology was done for the entire specimen in search of dissemination of the sebaceous gland carcinoma and the pathologist could not perform a quantitative content analysis of the pulley bands (e.g., collagen, elastin, and smooth muscle). On the other hand, such results are under way: McNeer, Tucker, Goldberg and McClung reported on the "Anatomy & Histology of the Check Ligament and Muscle Fiber Orientation in a Human Lateral Rectus Muscle Specimen" at ARVO 2005. They performed extensive histology on an exenteration specimen, but did no mechanical measurements on the bands. It seems very difficult to do the two studies on the same specimen: tissue that has been subjected to stress will be damaged and pathologists usually are very reluctant to identify tissue in damaged specimens.

Lengthening of the pulley bands was possible with little force over approximately 10 mm but, once taut, hardly any additional lengthening was possible. Thus, the mechanical behavior of the pulley bands was not that of springs. The only limitation here is a possible influence of smooth muscle cells, because all innervation was cut at the time of the exenteration.

The patient with Crouzon's syndrome had relatively good eye motility and stable rectus muscle paths despite the lack of functional pulley bands. During horizontal eye movement hardly any displacement of the superior and inferior rectus muscle bellies was observed. During surgery, the inferior rectus muscle stayed in place during left and right gaze. Interestingly, Dimitrova, Shall, and Goldberg (2003) found good conservation of ocular motility after removal of the lateral orbital wall in primates and cats.

Considering these findings, it seems difficult to conceive that the pulley bands or *faisseaux tendineux* play an important role in stabilizing the rectus muscle bellies. A role in limiting of ocular excursion would be possible: similar bands are found in joints elsewhere in the body.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2005.04.016.

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