Ocular motility revised

Sidney Júlio de Faria e Sousa *

The study of ocular motility is a sort of challenge to the beginner. There are a large number of informations that must be assimilated before a good understanding of the subject is made. The difficulty is aggravated by the fact that most of the available textbooks fail to present these informations in a sequential order. The Sherrington's law is given with Hering's law, ductions with versions and so on.

This paper is an attempt to present the basic concepts of the ocular motility under a logical sequence.

The Extraocular Muscle

The oculorotary muscle has some anatomical characteristics that differentiate it from the other skeletal muscles. It has five types of muscle fibers, a high ratio of motoneurons to muscle fibers and two distinct neuromuscular systems, the singly and the multi-innervated.

The muscle fibers are distributed in two layers which may overlap to some extent. The orbital layer is situated along the muscle surface that faces the orbital bone. It contains two fiber types of small diameter, one with single and one with multiple innervation. The bulbar layer composes the rest of the muscle. It contains four types of muscle fibers, one type of intermediate size with multiple motor innervation and three other types (large, intermediate and small fibers) with single innervation. The small singly-innervated fibers of the both layers, being morphologically identical, belong to a same type. As a consequence, the total number of fiber layers turns to be five and not six[1].

The singly-innervated fibers seem to have the same attributes of the fast neuromuscular system of the other skeletal muscles. They respond to stimulation with a fast contraction followed by relaxation. The multi-innervated fibers conform better to the amphybian and avian neuromuscular system which respond only to repetitive stimuli with graded and sustained contraction[2].

A full appreciation of the eventual advantages of these anatomical attributes is not yet possible. However, there are some promissing observations. The small fibers of the orbital layer for example, play the predominant role during fixation and slow persuit rotations of the eye. Part of them are active even at extreme gaze outside the field of action keeping the muscles on stretch at all eye positions. The bulbar fibers provide the major activity during the fast conjugate eye rotations[6].

The Muscle's Force

The main function of the extraocular muscle (EOM) is to provide force to move the eye to the various positions of the gaze and to hold it there. The active tension is derived from the contractile properties of the muscle under the innervational control of the CNS. The muscle's tension is increased by increasing the number of simultaneously acive motoneurons and by increasing the discharge frequency in the recruited neurons. Each motoneuron has a discharge rate and a threshold associated to the eye position. During the slow smooth rotations, the low threshold fibers of the superficial muscle layers, recruit earlier but increase slowly their activity in the direction of the active contraction. High threshold fibers of the deeper layers recruit later but increase their activity more rapidly. During the fast eye rotations, both large and small fibers are turned on maximally in the first portion of the movement and decay logarithmically to a new equilibrium value with a time constant of about one-half the total duration of the rotation.

The contracting muscle that moves the eye in a certain direction is called agonist. The muscle that moves the eye in the opposite direction is the antagonist. Opposing to the rotational force of the agonist, one find the passive visco-elastic forces of the orbital tissues and the active force of the antagonist. The active forces of each pair of agonist-antagonist muscles are in perfect coordenation. This coordination is controlled by the so-called Law of Sherrington or law of reciprocal innervation which states that: the contraction of an agonist muscle is always accompained by a proportional relaxation of its antagonist. The law not only explains the smoothness of the ocular ro

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* University of São Paulo — Ribeirão Preto.

tations but also suggests that the real functional unit of these rotations is not the isolated muscle but each pair of agonist-antagonist.

The ranges of tension an isolated muscle is under physiological conditions is summarized in the figure 1.

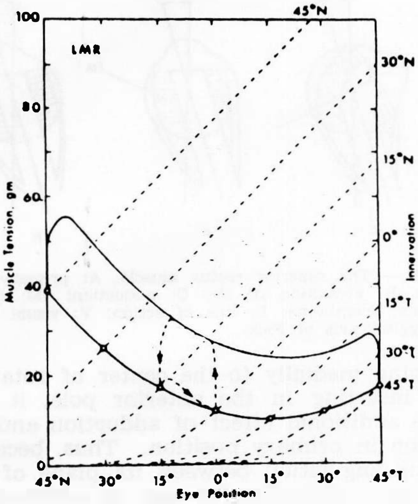

Fig. 1 — The operational envelope of the left medial rectus. (After Collins et al [7]).

The dashed lines in the background of the figure represent a family of length-tension curves of the left medial rectus muscle (LMR) for innervations shown on the right hand ordinate. They were obtained by isometric measurements with a strain gauge attached to the muscle [7]. Some of their points, identified with open circles, define a parabolic curve termed the static locus of fixation forces which depicts the tension required to hold the eye in each position noted on the abcissa. From a point about 15° in the temporal side, corresponding to the resting length position of the LMR. the curve rises toward the nasal side due to the active contraction of the muscle. It also rises toward the temporal side due to the stretching of the muscle during the active contraction of its antagonist. Thus, the oculorotary muscle is constantly kept under some degree of tension even outside of its field of activity. Muscle slack is avoided at all times.

The upper havy line represents the maximum tension recorded at the tendon of the LMR as the eye moves, as fast as possible, from the extreme temporal to the extreme nasal gaze. A typical length-tension loop for a smaller rotation, of the same nature, is shown in the figure as a counter — clockwise dashed curve with arrows extending between two open circles on the static locus.

The two solid curves enclose a tensional area termed the operational envelope. Under normal circunstances, all the passive and active muscle forces lie inside of it Only under abnormal conditions such as adhesions and contractures do the muscle forces leave it. Surgeries for correction of muscle imbalances change the shape and location of the operational envelope on the background of the altered family of length — tension curves of the operated muscle. The large area over the envelope, on the length-tension diagram, reflects the functional reserve of the muscle.

The effectiveness of the muscle tension in promoting eye rotation around its hypothetical center of rotation is given by M = T x d, wherein M is the moment of rotation (torque) of the force T and d is the lever arm or the perpendicular distance from de line of action of the force to the center of rotation. Thus, a medial rectus muscle pulling on the globe with a force T will adduct the eye with a moment of T x d.

The line of action is the middle line that joins the origin of the muscle to the portion where it first touches the sclera surface. The latter site is termed physiological insertion since it is the real site where the muscle applies its force on the globe. The region between the anatomical and physiological insertion is called arc of contact. As the globe rotates the arc of contact changes, but as long as it is present, the physiological insertion is kept unchanged preserving the rotational effectiveness. Once the arc is lost, the physiological insertion superposes the anatomical insertion and starts moving with the globe. It comes progressively closer to the center of rotation carrying with it the line of action of the muscle. The effectiveness of the rotational force decreases accompaining the reduction of the lever arm (figure 2).

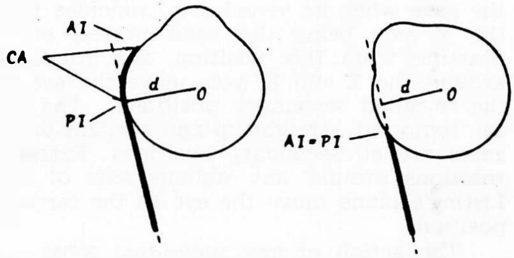

Fig. 2 — The concept of arc of contact. AI: anatomical insertion; PI: physiological insertion; AC: arc of contact; d: lever arm.

Certain surgical procedures can effect the rotational force throught reduction of arc of contact. This is the case of the recession surgery, where the muscle is disinserted from the globe and reattached more posteriorly. The rotational force is affected progressively more as the eyeball moves in the direction of the recessed muscle. However, this is not the only mechanism this surgery affects the muscle's pull. A recession places a muscle on lower length-tension curves, decreasing thereby the tension generated during active contraction. As a matter of fact, the latter mechanism seems to be more important than the former in crippling the ocular rotation[3].

The Actions of the EOM

Before studying the actions of the extraocular muscles it is worth being acquainted with the nomenclature of the basic ocular rotations. The rotations of the eyeball are traditionally described in relation to a orthogonal system, of three axes fixed in the orbita. termed system of Fick. It includes: the vertical or Z axis, the horizontal or X axis and the saggital or Y axis. The vertical and horizontal axes define the Listing's plane, a frontal plane approximately coincident with the equatorial plane of the eye when it is directed straight forward.

The rotations of the fixing eye around these axes are called ductions. The horizontal rotations are done around the Z axis When the visual line approaches the nose one have an adduction; when it departs from the nose one have an abduction. The vertical rotations are done around the X axis. The elevation of the eye is a supraduction and the depression an infraduction. Rotations around the saggital axis are called cycloductions. An incycloduction occurs when the upper pole of the vertical meridian of the cornea approaches the nose; when it departs from the nose one have an excycloduction.

The eye is in the primary position of the gaze when its visual axis coincides with the Y axis being the head perfect erect. Starting from this position, the rotations around the Z and X axes move the eye to the so-called secondary positions. The nasal, temporal, straight up and straight down gazes are all secondary positions. Extreme rotations around any oblique axis of the Listing's plane move the eye to the tertiary positions.

The action of any individual EOM depends on the relative angulation between the visual axis and its plane of action. Plane of action is the one defined by the line of action and the center of rotation. The superior rectus muscle (SRM), for example, being inserted in the top of the globe is obviously an elevator of the eye (figure 3).

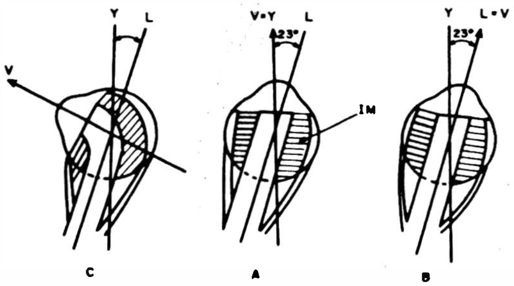

Fig. 3 — The superior rectus muscle. A: primary position; B: abduction of 23°; C: adduction; IM: intermuscular membrane; L: line of action; V: visual line; Y: saggital axis of Fick.

Running medially to the center of rotation and inserting in the anterior pole, it has some additional effect of adduction and intorsion in primary position. Thus, because of the angulation between its plane of action and visual axis it has in addition of the primary action of elevation, the secondary actions of adduction and incycloduction. With the rotations of the eye, this picture changes. At 23° of abduction, the visual axis superposes the plane of action of the SRM. Being no angulation between them, the secondary actions disappear; all the muscle's tension is available for elevation. The primary action gains force at the expenses of the secondary actions. When the eye is rotated to the opposite direction, the angulation between the visual axis and the plane of action increases. The secondary actions gain force at the expenses of primary action. Nevertheless, the SRM continues to be the most important elevator irrespective to the mechanical disadvantage in adduction. This is thought to be not only to its wide insertional area but also to the restrictive role of the intermuscular membrane that prevent the muscle to slide sideways on the globe. Similarly, the inferior rectus is the main depressor of the globe in all positions of the gaze. Recent studies[5,8] have reinforced the following concepts:

1. The primary action of the horizontal recti in all positions of the gaze is horizontal. Their secondary actions are insignificant.
2. The primary action of the vertical recti in all positions of the gaze is

vertical. They also exhibit significant horizontal and torsional actions.

3. The primary action of the oblique muscles in all positions of the gaze is torsional. They also exhibit significant horizontal and vertical secondary actions.

With these concepts in mind, one can define the so called field of action of an extraocular muscle as the field of the monocular gaze where the muscle exerts its primary action most efficiently. Thus, the fields of action of the medial and lateral rectus muscles are in the nasal and temporal side respectively. The fields of action of the superior and inferior rectus muscle are in the upper and lower temporal quadrants respectively. The field of action of the oblique muscles is at about 40° of abduction; the upper and lower nasal quadrants are fields of test of the vertical actions of the oblique muscles and not their fields of action.

If a single muscle often participates in more them one eye movement (primary and secondary actions) it seems obvious that the inverse is also true. The same eye movement may result from the association of two or more muscles. The muscles of the same eye that rotate the globe in a certain direction are called synergists for this movement. The superior rectus and the inferior oblique, for example, are synergists in the elevation of the eye in adduction.

Binocular Eye Rotations

After the foregoing brief considerations of the actions of the oculorotary muscles one may gain an appreciation of the two eyes working together. When someone looks to the right, both right and left eyes must turn to the right by an equal amount and at the same time to maintain binocular vision. This means that the lateral rectus muscle of the right eye and the medial rectus muscle of the left eye must contract simultaneously and proportionaly. The two muscles act as if they were yoked together like a pair of oxen and are hence termed yoke muscles. Despite the fact that this rotation is favored by other muscles, the term is applied only to those muscles that most successfully fulfill the desired movement. There are other yoked groupings of oculorotary muscles but one of them deserves special attention. Classicaly, the superior rectus muscle is considered the yoke muscle of the contralateral inferior oblique muscle in the upper lateral gaze. This misconception derives from another one that considers that the main elevator in adduction is the inferior oblique. The superior rectus of the abducted eye is in reality yoked to the contralateral superior rectus and inferior oblique muscles.

The coordenation of the yoke muscles are regulated by a hypothetical innervational law called Hering's law. It may be stated as follows: yoke muscles receive proportional innervation. The original term was "equal innervaion". The inappropriation of latter term is easily understood in the previous example. Being the medial rectus stronger than the lateral rectus, if the innervation were equal the rotations of the two eyes would be necessarily different. The Hering's law is not only valid for versions but also for vergences.

Versions are the synchronous rotations of the eyes to the same direction. They are often studied asking the patient to follow a moving target in the various positions of the gaze. They include: dextroversion, levoversion, supraversion, infraversion, supra-dextroversion, supra-levoversion, infra-dextroversion and infra-levoversion. Normal versions depend on a perfect balance of forces in the yoke muscles. This balance is regulated by Hering's law that distributes proportional innervation dictated by the fixing eye. If the fixing eye turns to be paretic it will ask for an excess of innervation that will also flow to the fellow eye. The latter being normal, will have its rotation exagerated as if it were overacting to the stimulus of fixation. When the normal eye takes the fixation, the paretic eye receives a normal innervation that is insufficient for its condition of weakness. The resulting rotation is limited in the field of the underacting muscle. Therefore, overactions and underactions are different manifestations of the same phenomenon — an imbalance between yoked muscles. It is interesting to note that even the more modest muscle paresis, insufficient to determine any monocular limitation of rotation, can cause enough yoke muscle imbalance to be detected on versions. That is the reason versions are so important in the study of strabismus of paretic origin.

Voluntary versions can be fast or slow. When someone changes the fixation between two points of the space he does it with a fast version termed saccade. Saccade is the most rapid movement of the eye. Its purpose is to direct the eyes from one target to another in the shortest possible time. The velocity and the tension in the agonist muscle during a saccade, is markedly decreased by muscle paresis but not influenced by mechanical restrictions. As a consequence, the study of the velocity during an unrestrained saccade and the tension of the agonist muscle during a restrained saccade is a useful procedure for differentiating paresis from restrictions.

Slow versions are observed when someone follows a target that moves slowly in the field of vision. These rotations are termed smooth persuit movements and the objective of them is to ensue clear vision of the moving object by maintaining its image in the central fovea. If the velocity of the target exceeds a certain limit the smooth rotation is interrupted by following saccades.

Cycloversions are examples of involuntary versions They are part of the so-called postural rotations coordenated by the vestibular apparatus. They are stimulated by the tilting of the head to one shoulder. The cycloversional rotation results from the synchronous contraction of the ipsilateral superior rectus and superior oblique and the contralateral inferior rectus and inferior oblique muscles. Though of little physiologic significance the phenomenon has some clinical value in the study of the balance of the cyclovertical muscles with emphasis to the superior oblique muscle. It is the base of the Bielschowsky, Parks and Bicas[4] tests. Another example of involuntary version is the optokynetic nistagmus; the fast fase is a saccade and the slow fase a smooth persuit rotation.

Vergences are slow synchronous rotations of the eyes in the opposite direction. They include: convergence, divergence, vertical vergences and cyclovergences.

Horizontal vergences are done around the Z axis of Fick. They are separated in three basic types: accomodative, fusional and tonic.

The accomodative vergence is intimately associated to the accomodative effort. It is put into action whenever the eye accommodates. The usual stimulus is the image blur in the retina when the focus is behind it. Accommodative vergence is frequently estimated by the AC/A ratio which is the amount of vergence elicited by a unit of accomodation. The fusional vergence is the motor response of the vergence system to the binocular retinal disparity. It is usually estimated by its amplitude, measured with the accomodation under control. Accommodative and fusional vergences are both reflex innervational activities of retinal origin designated to control the visual axes alignment.

Tonic vergence is the disjunctive rotation that moves the eyes from the anatomical position to the physiological position of rest. The anatomical position of rest is reached when all the EOM are free from innervation, a condition closely obtained under general anesthesia with curarization. The physiological position of rest is obtained in the awake state, preventing the eyes of fusing and accommodating. Tonic vergence is probably a consequence of the difference in the effective force between the medial and lateral rectus muscles to the overall increment of innervation of extra-retinal origin that follows the recovery of the consciousness[9].

SUMMARY

An attempt to present the basic concepts of the ocular motility under a logical sequence is made. Some new concepts that haven't yet come into widespread clinical use are also discussed.

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