

THE EFFECTS OF EXTRAOCULAR MUSCLES ON EYE BIOMECHANICS

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(ABSTRACT)

Over 2.4 million eye injuries occur each year in the United States as a result of trauma. Eye injuries have been investigated for years; however, the role of the extraocular muscles in relation to eye injuries has yet to be quantified. In this research, Computed Tomography quasi-static tests were conducted to investigate the effect of the presence of the extraocular muscles on the biomechanical response of the human eye *in situ*. Three matched pairs of human eyes were displaced in 5 mm increments using a large flat cylindrical indenter to a maximum displacement of 30 mm. The loading was similar to what is experienced during a blunt impact, which is believed to cause the most serious eye injuries. In the matched pair, one eye had the extraocular muscles intact and the other had the extraocular muscles transected. Force, pressure, and displacement measurements were collected for each test. A trend was seen where a greater amount of force was created in the eye with the extraocular muscles intact than in the eye with the muscles transected, and a correlation between them was made. The greatest force measured in an eye with the extraocular muscles intact was 92 N, while the greatest force measured in an eye with the extraocular muscles transected was 80 N. An increase in intraocular pressure was also noticed for an eye with the extraocular muscles attached, rising steadily from 2 kPa to a maximum pressure of just over 50 kPa. It was also noted that during a quasi-static impact the eye can move out of the way of the imposing force. Since the test data set was small, analytical calculations were also conducted.

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CHAPTER 1

Introduction

and

Preliminary Studies

1.1 Introduction

Over 2.4 million eye injuries occur each year in the United States as a result of trauma (Parver 1986). As a result of these injuries over 30,000 of these patients are left blind in at least one eye and 40,000 are left with some type of significant visual impairment (Leuder 2000). Trauma is second only to cataracts as the most common form of visual impairment. Eye injuries are expensive to treat and have a high societal cost. Eye injuries affect a large proportion of the population and can frequently result in long-term disability. Severe eye injuries are often the result of blunt impacts, from sports equipment or contact with an airbag or a steering wheel in automobile crashes. The most severe injuries involve open globe injuries in which the sclera is torn and the eye loses pressure and collapses. In a study containing 50 globe ruptures, 41 were at the equator or anterior to it and 37 were parallel to the equator. Of the 41 anterior ruptures, 33 were located in the superior half of the eye (Cherry 1978). Common characteristics among these types of injuries are high rate loading and large deformations of the globe.

Expansion along the equator of the eye is believed to produce the most serious eye injuries as a result of blunt impact (Parver 1986). The equator of the eye is defined as the circle separating the anterior portion of the eye from the posterior portion. During equatorial expansion failure of the eye, the globe is compressed along the line of impact and is then forced to expand perpendicular to the line of impact, about the equator. As the sclera expands, scleral stresses increase which can cause rupture of the eye. To evaluate this theory, experimental studies have been performed on human, monkey, and porcine eyes. These studies involved blunt objects such as BB's, metal cylinders, foam

particles, paintballs, golf balls, squash balls, and baseballs (Delori 1969, Green 1990, Preston 1980, Umlas 1995, Vinger 1997, 1999). However, these studies are solely based on *in vitro* experiments in which the eyes are removed from the head and placed in supporting gelatin. These types of experiments therefore exclude the effects of the extraocular muscles.

In the study by Kennedy in 2004 the structural integrity of human and porcine eyes under both static and dynamic loading was investigated. Human and porcine eyes were inflated to the maximum internal pressure, ultimately resulting in globe rupture. The rupture pressure of porcine eyes was shown to be higher than that of human eyes under both static and dynamic conditions. Risk functions were created to predict the risk of globe rupture as a function of intraocular pressure (Figure 1). A 50% risk of injury was found at 1.02 MPa, 1.66 MPa, 0.35 MPa, and 0.90 MPa internal pressure for porcine static, porcine dynamic, human static, and human dynamic loading conditions, respectively. These risk functions are used in the laboratory for both experimental and computational work. They can also be used by clinicians to determine the risk of severe eye injury due to increased pressurization of the eye. These risk functions do not include any effects that could be created by the extraocular muscles. Without considering the forces and stresses induced in the sclera from presence of these muscles, the current eye injury criteria may significantly underestimate the risk of serious eye injuries.

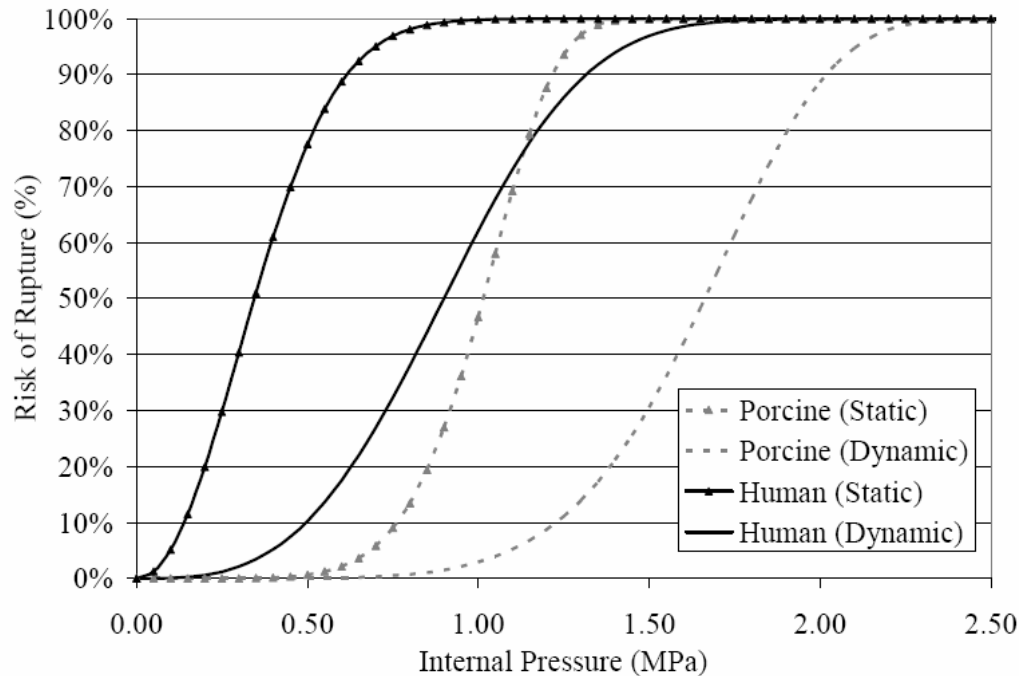


Figure 1. Risk functions for porcine and human eyes predicting the risk of globe rupture as a function of intraocular pressure [Kennedy 2004].

Even though eye injuries have been investigated for years, the role of the extraocular muscles in relation to eye injuries has yet to be quantified. In this research, the effect of the extraocular muscles on eye injury biomechanics will be determined in relation to the force and displacement experienced by the eye under loading similar to what is experienced during a blunt impact. The hypothesis of this research is that when an eye is subjected to blunt trauma, the forces that are created by the presence of the extraocular muscles contribute to the risk of the globe rupturing. Therefore, all previous testing that did not include the muscles may have underestimated the eye rupture strength.

1.2 General Ocular Anatomy

The human eye is an intricate anatomical structure composed of many parts (Figure 2).

The globe of the eye is approximately 2.5 cm in diameter. The eye can be divided into

two main chambers: the anterior chamber and the posterior chamber. The anterior chamber is filled with aqueous humor, which circulates to keep the cornea and lens hydrated. The posterior segment is filled with a jelly-like fluid called vitreous humor that enables the eye to keep its shape. The lens, its connective tissue, and the ciliary body form a boundary between the anterior and posterior chambers. The ciliary body is a set of small muscles that help the lens to focus. The lens can also change shape using its elastic properties to refract light onto the retina at the back of the eye to form images that are transmitted by the optic nerve to the brain for interpretation. The cornea is the clear part of the eye covering the iris and pupil that allows light to enter into the eye. The tough, white, outermost layer of the eye is called the sclera, which also helps maintain the overall shape of the eye. The limbus is the location of the corneal and scleral junction, which is marked on the outer surface of the eye by a slight groove.

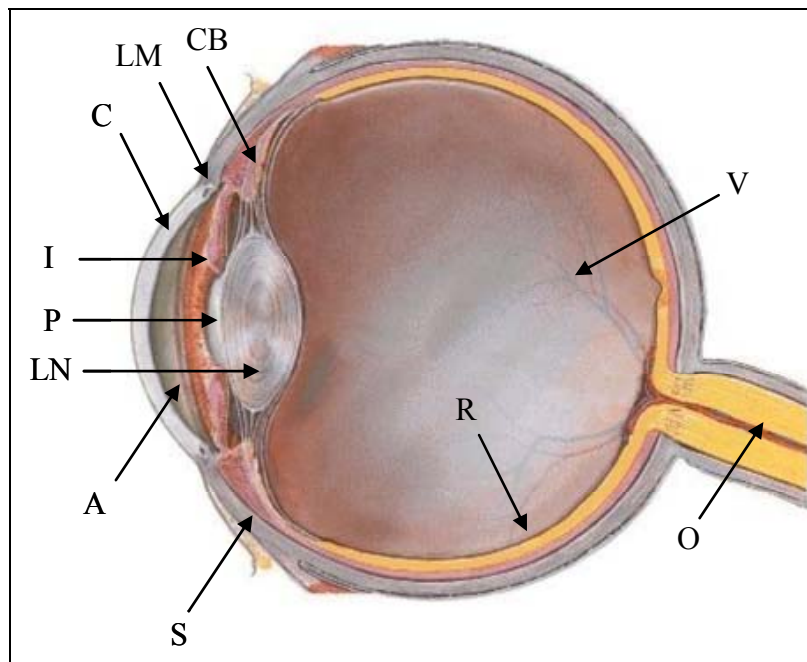


Figure 2. Basic ocular anatomy includes the A) anterior chamber: aqueous humor, CB) ciliary body, C) cornea, I) iris, LM) limbus, LN) lens, O) optic nerve, P) pupil, R) retina, S) sclera, and V) posterior chamber: vitreous humor.

The ocular orbit functions to protect and support the eye, as well as to serve as an attachment surface for the connective tissue and musculature of the eye. The orbit is shaped as a pyramid on its side with the base anterior of the eye. Seven bones join to form the ocular orbit: the frontal, maxillary, zygoma, sphenoid, ethmoid, lacrimal, and palatine (Figure 3). The orbital roof is formed by the frontal bone and the sphenoid. The maxillary bone joins with the zygoma and the palatine to form the floor. The medial orbital wall consists of the maxillary, the lacrimal, the sphenoid, and the ethmoid bones. The lateral wall is formed by the sphenoid and the zygoma.

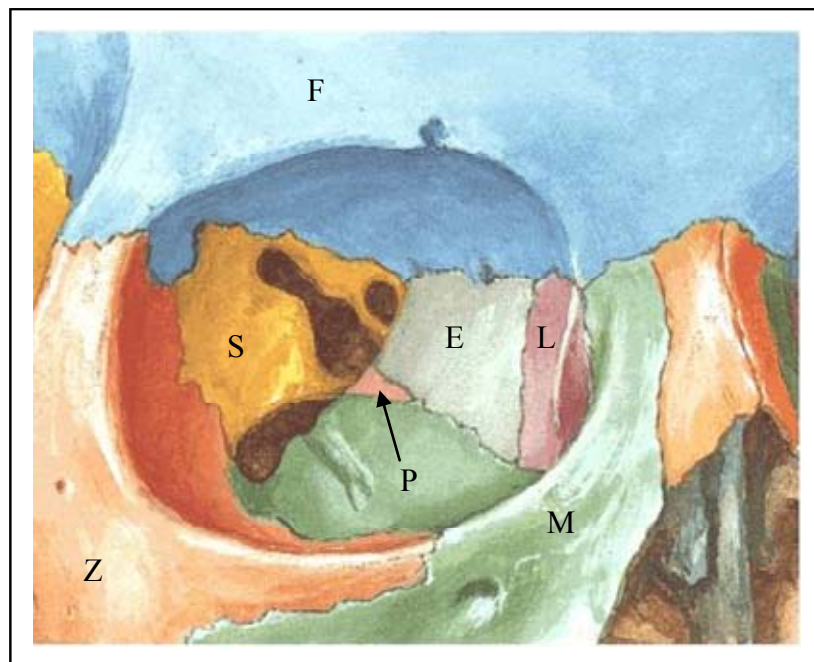


Figure 3. Seven bones form the ocular orbit: the (F) frontal, (M) maxillary, (Z) zygoma, (S) sphenoid, (E) ethmoid, (L) lacrimal, and (P) palatine.

The human eye is suspended within the orbit by three pairs of agonist-antagonist extraocular muscles (Figure 4). The superior rectus and inferior rectus muscles make up the first pair. They control the vertical rotations of the eye, and are attached just above and just below the periphery of the cornea respectively. The second pair of muscles are

the medial rectus and lateral rectus muscles which control the horizontal rotation of the eye. As suggested, they are attached to the medial and lateral sides of the eye respectively. The superior oblique and inferior oblique muscles are the final pair of extraocular muscles. They are responsible for the torsional rotations of the eye. Both of these muscles are attached to the lateral side of the eye, with the superior oblique muscle coming over the top of the eye to the medial side of the orbit, and the inferior oblique muscle going under the bottom of the eye to the medial side of the orbit. All of the rectus muscles run straight from their scleral attachment points to the posterior orbit near the optic nerve. The obliques however have a different orientation (Figure 5). The angle between the plane of action and the plane of vision for the obliques is approximately 51° (Records 1979). The superior oblique also runs through a pulley attached to the superior portion of the anterior orbit. This accounts for it being the longest of the extraocular muscles. All of the extraocular muscles are attached to eye, and their anchoring points at the posterior or anterior (inferior oblique only) orbit, with short lengths of tendon woven into the sclera tissue.

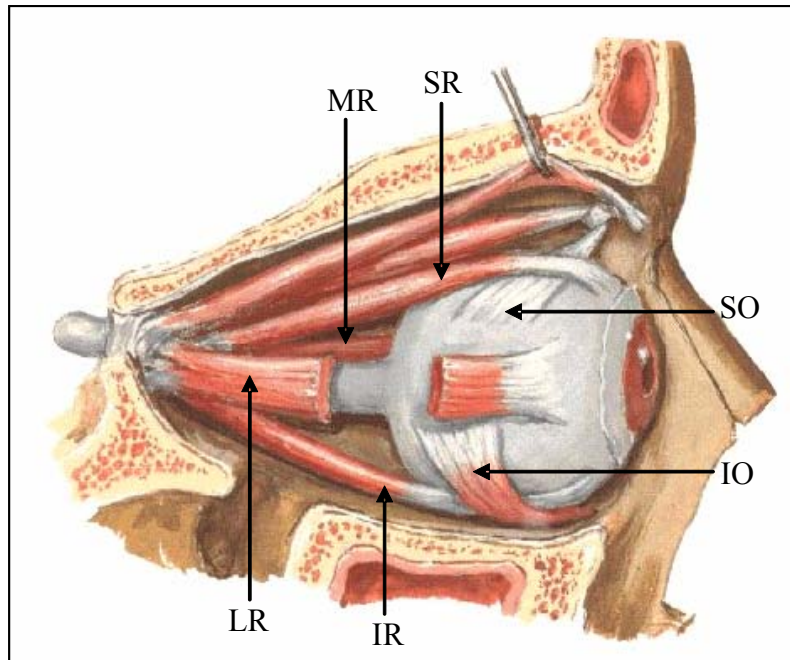


Figure 4. The extraocular muscles and their attachment points, shown on a right eye: (SR) superior rectus, (IR) inferior rectus, (MR) medial rectus, (LR) lateral rectus, (SO) superior oblique, and (IO) inferior oblique.

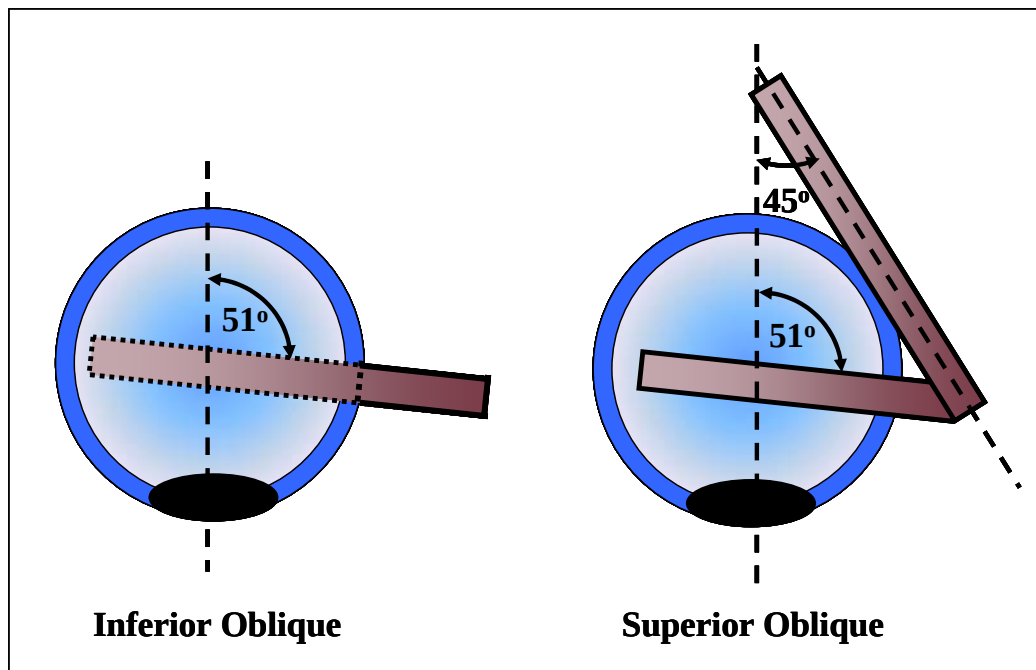


Figure 5. Schematic showing the orientation and attachment angles of the oblique extraocular muscles, viewed from above on a right eye.

1.3 Imaging Techniques

Three main imaging techniques have historically been employed to visualize the orbit and its contents *in vivo*. They are ophthalmic ultrasound, computed tomography, and magnetic resonance imaging. The three imaging modes each have their own distinct advantages and disadvantages. It is for this reason that they co-exist and are still considered common practice today.

1.3.1 Ophthalmic Ultrasound

The basic principle of ophthalmic ultrasound is the same as any other type of ultrasound used and that is to send a pulse of ultrasound into the body and to detect the echoes that reflect back from the different surfaces reached by the pulse. The more time that it takes for the pulse echo to return to the detector, the further away the reflecting surface is located. Ultrasound is high-frequency sound above 20 kHz, which is out of the range of human hearing. Diagnostic ophthalmic ultrasound uses frequencies of 5 MHz and greater (Hewick 2004).

During A-scan ultrasound, only one pulse is sent out, and the return echoes are measured by a detector. The differences in time between the echoes can easily be equated to distances since the speed of sound through both water and air is known. In A-scan ultrasound, a traditional image is not produced, only a plot of echo strength or distance vs. time. This type of imaging is useful in measuring the axial length of the eye, and is routinely used in measuring corneal thickness (Chau 2004, Oyster 1999). Ophthalmic ultrasound is also used to measure changes in the extraocular muscles in Graves' diseases, orbital myositis and other muscular disorders (Tian 2000).

B-scan ultrasound is the type of ultrasound that produces the images taken of a fetus in a pregnant mother's uterus. A B-scan planar image is created by adding numerous A-scans together. A fan of ultrasound pulses are sent out from a single point on the detector, and as the echoes return a black and white image is created (Figure 6). The white portions are the reflected ultrasound pulses, and the black parts are where the ultrasound was absorbed and not reflected. B-scan ultrasound is used to detect the presence of tumors, foreign objects present in the eye, and retinal detachment (Oyster 1999).

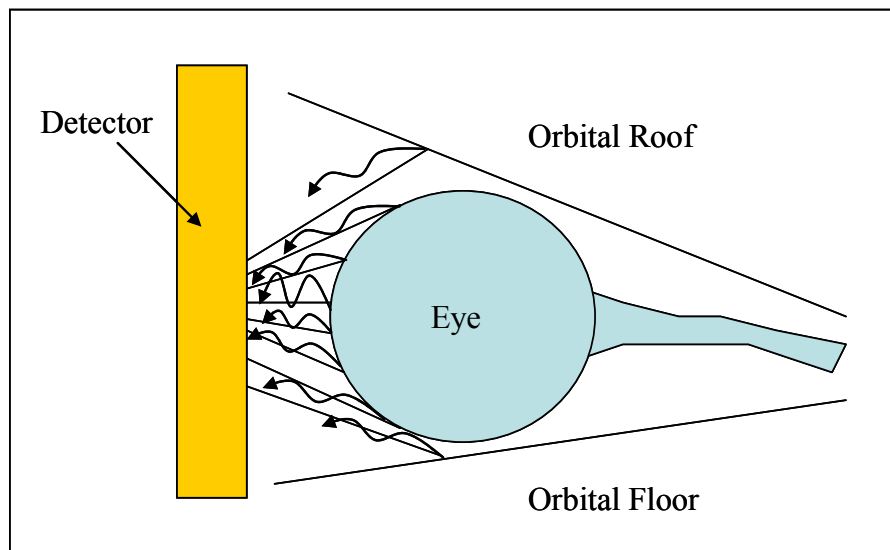


Figure 6. Diagram of B-scan ophthalmic ultrasound, where a fan of pulses are sent out, and the echoes return to form a black and white image.

Ophthalmic ultrasound is a very quick procedure for a patient, it is non invasive, and there is no discomfort to the patient. However, ophthalmic ultrasound does not produce detailed or precise images of the entire eye within its orbit and therefore there is a lack of soft tissue differentiation (Lee 2004). Ophthalmic ultrasound can yield detailed and high resolution images of a single location within the eye, and has been used to measure the volume of the extraocular muscles and corneal thickness, but imaging the whole eye and

its orbit in detail would be difficult (Phillips 2003). The detector used during ophthalmic ultrasound also blocks the orbit opening, preventing any direct impact with the eye.

1.3.2 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) uses magnetic energy and radio waves to create cross-sectional images. A relatively large magnetic field is constantly present in the MRI scanning area. During an MRI scan, a radio signal is turned on and off, and the energy which is absorbed by different atoms in the body is echoed or reflected back out of the body (Figure 7). These echoes are continuously measured by a scanner and a computer digitally reconstructs these echoes into images.

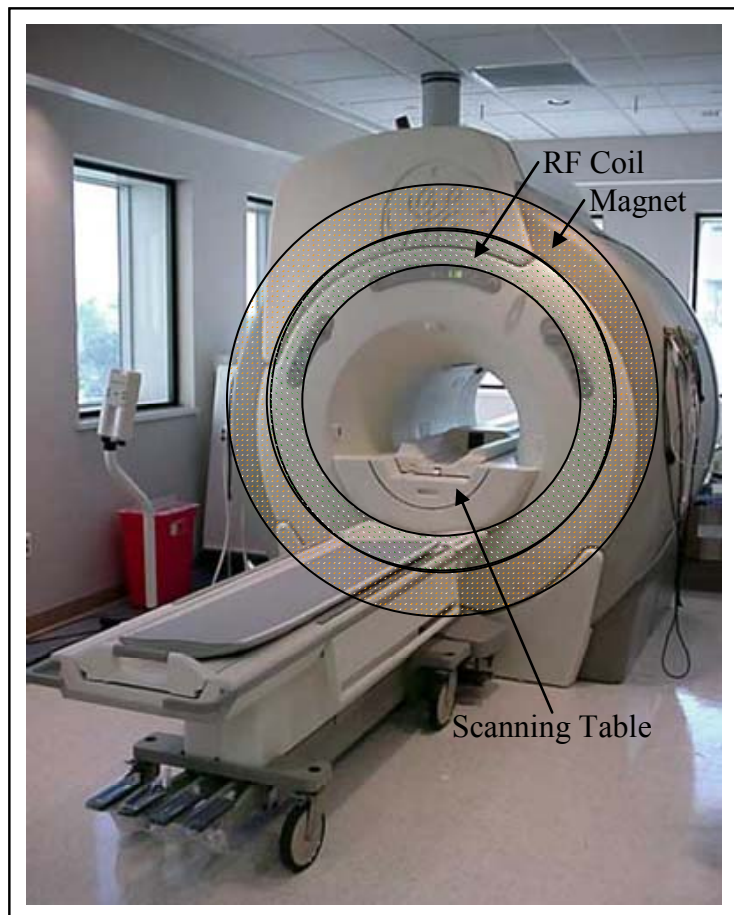


Figure 7. Diagram of an MRI scanner, showing the relative location of the RF coil and magnet to the scanning table.

The atomic nuclei which have odd-numbered atomic weights are affected the most, specifically hydrogen which is present in water. Since water makes up a large part of soft tissue, soft tissues are imaged quite easily. If there is not any hydrogen present in a material, it will produce a dark area in an MRI image. For this reason bone is difficult to image. If there is not a mucus membrane present on the surface of the bone, it will show up the same color, black, as air in an MRI image (Wichmann 2000b). Additionally, MRI does not image foreign bodies present in the orbit well, such as bone, wood, or glass fragments (Lee 2004).

Ferrous-metallic objects are a problem in MRI scanning because of the magnetic field that is constantly present. Patients that are scanned are asked to remove any metal in their pockets, glasses, and jewelry, especially piercings, because the magnetic field is strong enough to pull objects out of pockets and piercings out of the skin. During MRI scanning if there are any ferrous-metal foreign bodies present in the orbit, such as metal shavings, fishing hooks, or metal beads from welding, they could be drawn out by the magnetic field causing further injury and lacerations (Lee 2004). Metal in or near the volume to be scanned will cause artifacts to appear in the final scanned image. Even the small metal flakes present in eye shadow can cause these image artifacts. Carbon and titanium alloy needles have also been investigated as to their effect on creating artifacts MRI images (Reichenbach 2000).

Because of the scanning nature of MRI, a cross sectional image can be obtained at any angle to the sagittal plane. A typical MRI image is 512 x 512 pixels. The size of the

pixels depends on the size of the area to be scanned. An MRI image can have up to 0.25 mm in plane, or slice, resolution. The minimum slice thickness, the distance between the slices, recorded in the literature was 2 mm. A slice thickness of smaller than 2 mm can be achieved through signal averaging and interpolation. A single slice with the highest resolution possible can take anywhere from 2 to 15 minutes depending on the size and prescribed resolution of the prescribed scan volume, additional slices and small slice thicknesses can add to the scan time. The resolution of a scan of a small or concentrated volume can be achieved more quickly through the use of a surface coil. Surface coils come in several sizes that can be used depending on the size of the area that is being scanned (Figure 8). These coils act as a radio frequency receiver to improve the signal-to-noise ratio during the imaging procedure. Using surface coils to enhance the image quality and shorten scan time in orbital scans is common practice (Cheng 1992, Demer 2003a, 2003b, 2003c, Simon 2003, Tian 2000, 2003, Wichmann 2004b). A high resolution orbital scan utilizing a surface coil can be performed in three and a half minutes (Cheng 1992).



Figure 8. A medium to large size surface coil commonly used in orbital scans.

As there is no risk to a subject who undergoes an MRI scan, it has been frequently been used in ocular research conducted *in vivo*. As early as 1992, Cheng *et al* investigated the shape of myopic eyes in three dimensions using MRI scans. Tian *et al* (2000) used MRI to investigate the thickness, cross sectional area, and volume of the extraocular muscles in different positions of gaze, as well as the volume of the optic nerve, the globe, and the fatty tissue present in the orbit. In 2003, Tian *et al* went on to use MRI to assist in the investigation of eye muscle force development in thyroid-associated ophthalmopathy, a type of eye movement disorder. Kono *et al* (2003) also utilized MRI scanning to take measurements of the extraocular muscles. They were interested in the anatomy of the inferior oblique muscle in relation to superior oblique palsy. In 2003, Demer *et al* published several studies concerning the mechanics of the extraocular muscles using data

collected via MRI scanning. Detorakis *et al* (2003) and Wichmann *et al* (2004a) used MRI images in their studies of the anatomy of the visual system and its orbit, and Li *et al* (2003) used the results from similar scans to create a model of the human orbit. It was noted by several authors that motion during the scanning time caused image artifacts, and that during the long scanning times it was difficult to overcome (Li 2002, Simmon 2003, Wichmann 2004b).

1.3.3 Computed Tomography

Computed tomography (CT) uses x-ray beams in a similar manner to traditional x-rays.

A source produces x-rays and passes them through the subject and a detector collects the x-rays on the opposite side of the subject. The x-rays are attenuated, or weakened, at different levels depending on the matter's atomic number. The resulting matrix is a profile of x-ray beams of different strength used to create the CT image (Reddinger 1998). Regions with the greatest x-ray attenuation, like bone, will appear bright white in the image, while regions where the x-rays were not absorbed as much will appear darker. Air filled cavities will show-up as completely black, because there is little or no matter present to absorb the x-rays. CT scans can take anywhere from 5 seconds to a few minutes depending on the scanning volume selected, consisting of the total number of slices taken, the in-plane resolution of each slice, and the slice thickness. Like MRI images, CT scans have a maximum image size of 512 x 512 pixels and the resulting resolution depends on the scanning area. The larger the scanning area, the larger the area per pixel.

CT scanning techniques and equipment have greatly improved over the past couple of years. Multi-slice spiral, or helical, scanning has become the standard, replacing the old slice by slice method of acquiring images. During helical scanning the x-ray source and detectors rotate on a track, while a motorized scanning table moves the subject through the circling x-ray beam (Figure 9). The resulting scan is an unbroken high quality spiral image. The use of a multidetector-row during helical scanning can create higher resolution images in a shorter amount of time. Instead of a single detector rotating around the subject of the scan, a row of 4 or 16 detectors is employed.

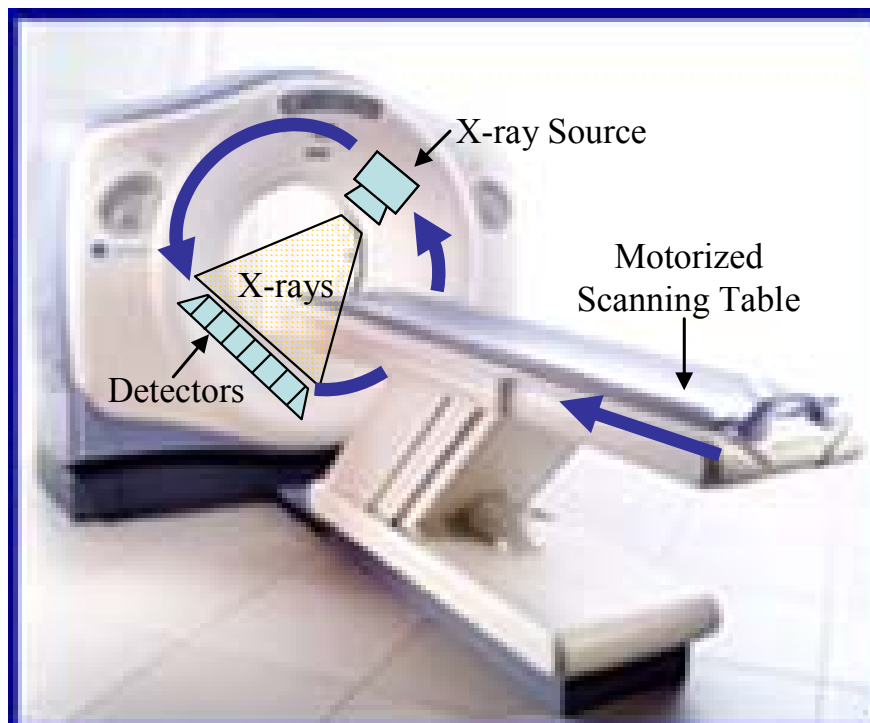


Figure 9. Diagram of the helical CT scanning technique. The blue arrows indicate synchronous movement of the x-ray source, detectors, and motorized scanning table.

CT scanning exposes the patient to undesirably high doses of radiation. When helical scanning is used with multiple detectors to image the orbit the radiation exposure can be increased by eight fold (Muller-Forell 2004). However, if the imaging procedure is

conducted on post mortem tissue, radiation no longer becomes a factor in choosing an imaging technique. Because of the nature of helical CT scanning, images can only be acquired in the coronal plane of the subject being scanned. If other planes are needed there is software available to reconstruct the images, even for planes at angles other than 90 degrees of the original scans. The resolution of these reconstructed images depend on the original slice thickness. Any points in between the slices can also be interpolated. Like MRI, metallic objects can create artifacts in CT images. These artifacts will appear as starbursts stemming from the metallic object (Reddinger 1998). During orbital scans, even dental work can show up (Figure 10).

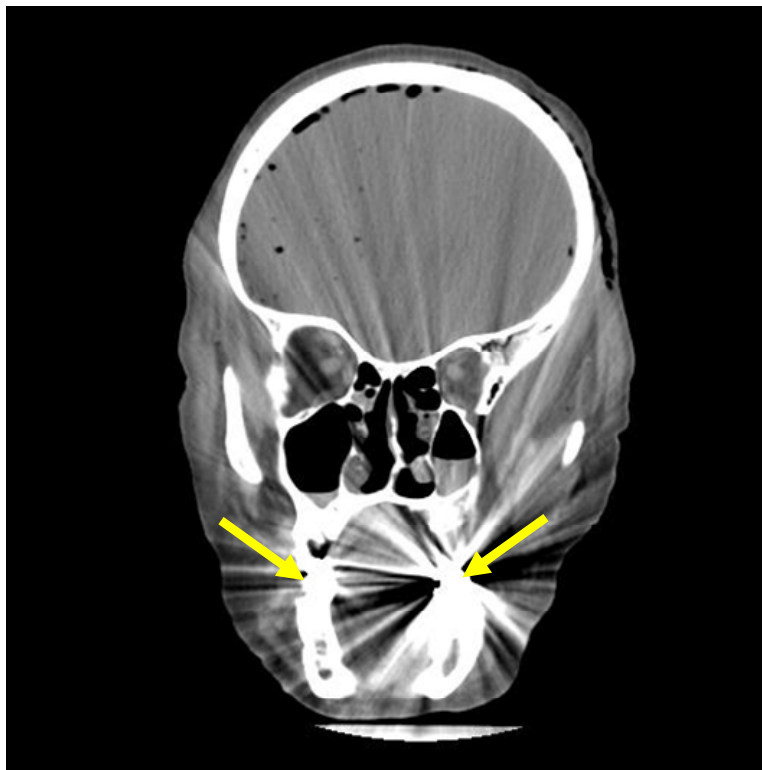


Figure 10. Coronal scan of the head containing starbursts from metal dental fillings (origins indicated with the arrows).

As reported by Muller-Forell (2004), the distinctly different X-ray absorption of bone, fat, muscles, the lens, and the vitreous body of the posterior globe, leads to an inherent contrast of the orbital tissue. Muller-Forell confirmed that a CT examination of the orbit is lower in cost and quicker than an equal quality image obtained using MRI. CT scanning is used by many investigators for *in vivo* orbital research. Wichmann *et al* (2004a) used CT images in their study of the anatomy of the visual system. The extraocular muscle volumes and their paths have been investigated using CT (Tian 2000). CT imaging was used by Lee *et al* (2004) to investigate orbital trauma.

1.3.4 MRI and CT Imaging Technique Comparison

Lee also pointed out that MRI was better at imaging soft tissue within the orbit than CT imaging, but that with CT there was an excellent contrast between bony structures and soft tissue, not present in MRI images. The difference in MRI and CT imaging characteristics can be seen in the sagittal images of the orbit in Figure 11. The MRI image has a resolution of 0.23 mm x 0.46 mm and is one of 13 slices that were collected with a slice thickness of 5 mm. It took five minutes to acquire. The CT image is a single reconstructed image from a scan of a volume that has a resolution of 0.625 mm x 0.625 mm x 0.625 mm. A total of 185 coronal images were collected in thirty seconds. It took an additional thirty seconds to reconstruct the sagittal CT image. The plastic indenter (outlined by the white dashed lines) cannot be seen in the MRI image because it is made of plastic, and does not have any water present in it, but it is very easily seen in the CT image. It is somewhat difficult to make out the bony structures of the orbit and skull in the MRI image, but they are readily seen in the CT image.

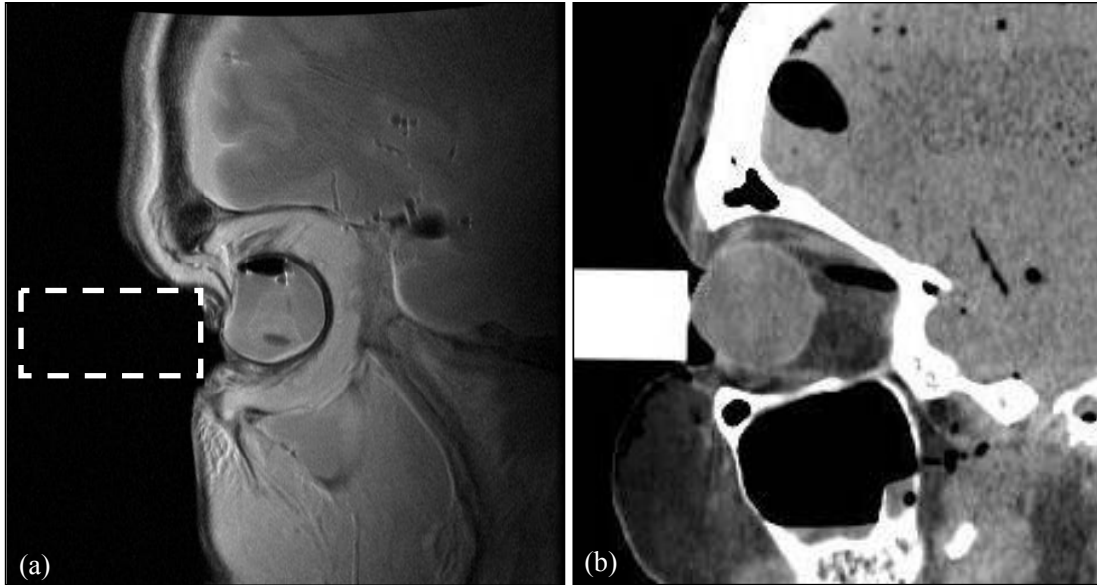


Figure 11. Comparison of sagittal (a) MRI and (b) CT images of the orbit.

1.4 Pressurization and Intraocular Pressure Measurement Technique

In order to conduct studies on human eyes *in situ*, a way of repressurizing the eyes to their anatomical intraocular pressure was needed. The intraocular pressure of the eyes also had to be measured during testing, so a way to perform this measurement also had to be considered.

In the thesis work of Voorhies, enucleated human and porcine eyes were pressurized through the optic nerve until rupture (Voorhies 2003). A no. 16 gauge needle was inserted through the optic nerve into the posterior chamber of the eye, and secured in place with wire. Connected to the needle was a pressurization system which both pressurized the eye and measured the resulting intraocular pressure. This approach was considered at first since there was only one point of penetration into the globe. There was also a valve present to prevent back flow of fluid into the saline holding area, and the pressure measurements were instantaneous. However, this procedure was found to be

much too difficult to perform *in situ*. This technique would require removing a portion of the skull as well as the entire brain to access the posterior orbit. The optic nerves are naturally positioned at an angle, so inserting a needle along the length of one into the globe of the eye without puncturing through the optic nerve itself would be difficult. Securing the needle in place and creating a watertight seal would also be a difficult procedure in such a small space. Also, the presence of a needle and tubing in the rear of the orbit was hypothesized to affect the linear displacement of the eye and surrounding tissue. Other methods of pressurization and measuring the intraocular pressure had to be investigated.

In a study to investigate myopia conducted by Akazawa *et al* (1993) the eyes of living New Zealand White rabbits were used. They changed the pressure in the eye by adjusting the height of a saline reservoir that was connected to the anterior chamber of the eye through a no. 30 gauge needle that was inserted through the limbus. The intraocular pressure was measured by using a semiconductor catheter pressure transducer inserted into the vitreous body by a no. 18 gauge needle placed 5 mm posterior to the limbus of the eye. This approach had promise in that the eye was penetrated on the anterior side; however, it was not mentioned how or if either of the needles were secured to the sclera of the globe. Even if the needles were held in place by sutures or adhesive, there were two points of entry, which leaves more room for error and leakage in the pressure measurements. If this technique was used to pressurize eyes which were impacted, the intraocular pressure collected by the pressure transducer would not be

correct, because the saline could return to the saline reservoir, and the intraocular pressure would be considerably lower.

Burnstein (1995) also pressurized eyes through the limbus in his study to assess corneal weakening after photorefractive keratectomy. Burnstein inserted a no. 25 gauge butterfly needle through the limbus into the anterior chamber of human cadaver eyes. The eyes were pressurized until rupture with nitrogen gas through a line of tubing. The intraocular pressure was determined from the gage inline with the nitrogen tank. This type of pressurization technique has promise because there is only one point of entry into the anterior chamber of the eye; but, it cannot measure instantaneous pressure, and would still have a problem with backflow. The study also did not report whether the butterfly needle was secured in place. Since the butterfly needles have rather large wings in comparison to the surface area of the globe of the eye, it does not seem that suturing them to the sclera is an option.

Eye cups are a common way of non-invasively measuring intraocular pressure on living patients (Bayraktar 2005, Chen 1993, Friling 2003, Muir 2004). These eye cups look similar to suction cups, and are placed over the cornea and sclera of the eye. To measure pressure, a vacuum is applied to the exterior of the globe, and through the measurement of changes in volume, the intraocular pressure can be determined. This type of measuring technique would not be possible in an impact setting for several reasons: the eye cup prevents direct contact with the eye, the pressure measurement is not instantaneous, and the eye cups can sometimes leak yielding erroneous pressure readings

(Chen 1993). In addition, a way of initially pressurizing the eye to physiological conditions would still need to be implemented.

For this project a novel method of pressurization was introduced. To date, this type of pressurization and intraocular pressure measurement technique have not been recorded in the literature. The method involves entering the globe of the eye from the lateral side and pressurizing using saline, IV tubing, and gravity, and measuring the intraocular pressure with a pressure transducer inline with the pressurization system.

An investigation was conducted to pressurize porcine and human eyes to physiological conditions using either a cannula or catheter in conjunction with a hanging saline IV bag. Since porcine eyes are viable surrogates for human eyes, they were used for the initial round of testing (Voorhies 2003, Duma 2000). First, customized footed-cannulas fabricated from Teflon (Plastics One, Roanoke, VA) were tested (Figure 12). The cannulas were made from Teflon because any metallic materials would create image artifacts in both Magnetic Resonance Imaging and Computed Tomography techniques. The cannula was inserted into the posterior chamber of the eye near the equator with the aid of a no. 22 gauge needle. The mating surfaces were superglued together after being cleaned with alcohol swabs and 6-0 sutures (DEXON “S”) were placed through the holes in the cannula’s base and secured to the sclera. Intravenous (IV) tubing was connected to the cannula that ran to a saline IV bag which was secured at a height which pressurized the eye to physiological conditions. A pressure transducer (Kulite, 6380-3-75, Leonia, NJ) and plug shut-off valve (Swagelok, SS-2T4T4, Solon, OH) were included in the line

of pressurization (Figure 13). The pressure transducer measured intraocular pressure and the valve was used to cut off the possibility of back flow from the eye when the eye was impacted, so an accurate pressure measurement could be made.

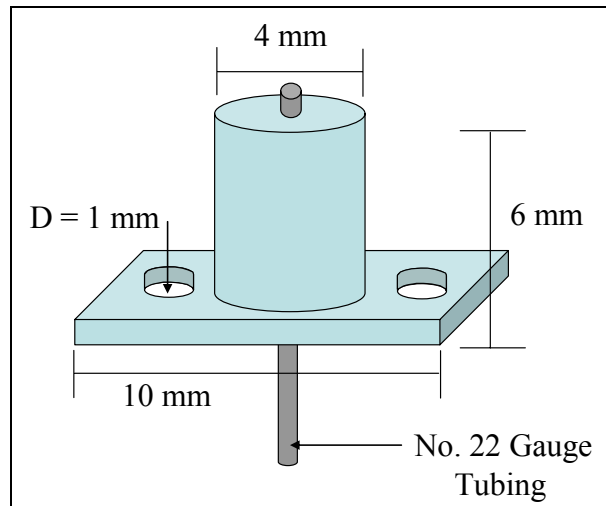


Figure 12. Schematic of the Teflon footed-cannula evaluated in this study.

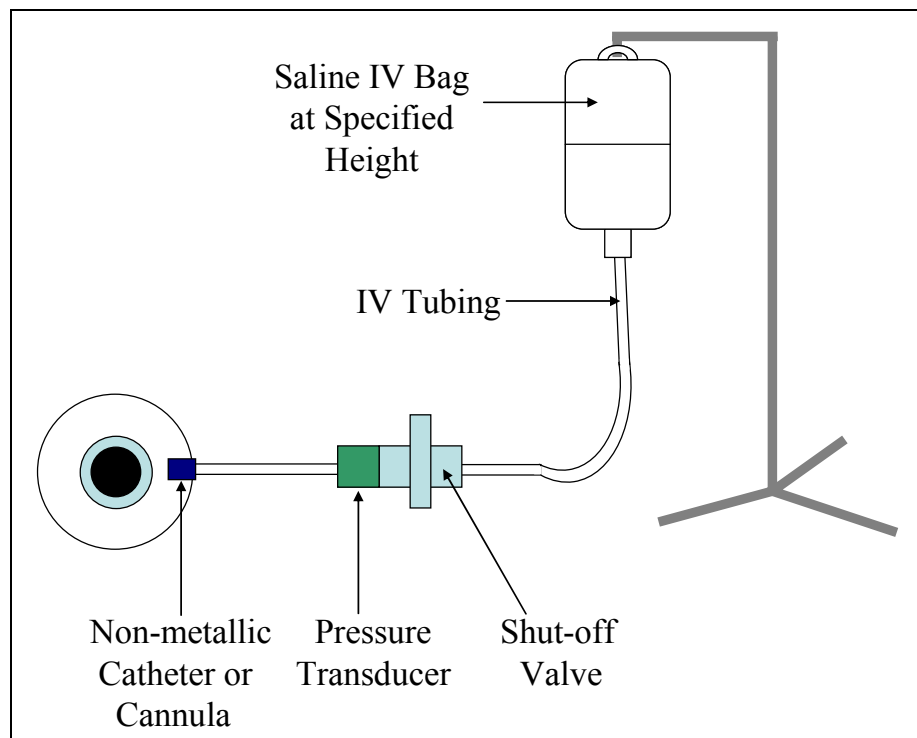


Figure 13. Schematic of the pressurization and pressure measurement technique.

The cannula set up was tested first under static conditions. The eye held pressure without any leaks when no load was imposed. However, once a distributed load, was placed on the eye, a small leak appeared at the interface between the base of the cannula and the sclera. When the set up was tested under dynamic conditions, the eye deformed and the sutures were ripped out of the sclera, creating a leak of fluid and a lower pressure (Figure 14). It was hypothesized that the cannula base was acting as a lever, and once enough curvature was created the sutures could not hold, and the scleral tissue failed.



Figure 14. The arrow indicates the location where the sutures ripped through the sclera during a dynamic test utilizing a non-metallic catheter, which caused a leak.

The next scleral interface investigated was a non-metallic catheter. Several variations of no. 20 gauge IV catheters with nylon tips (Jelco - Johnson & Johnson Medical Inc., New Brunswick, NJ) were tested: (1) as is with superglue, (2) beveled tip and a cut length of 12 mm with super glue, and (3) beveled tip and a cut length of 12 mm with super glue and sutures (Figure 15). For all of the options tested, a needle (that comes with the catheter) was used to insert the catheter and the surface of the sclera was cleaned with alcohol prior to applying the superglue. When the catheter at its original length, 32 mm, was tested, it held pressure and did not leak; however, binding and twisting of the tip was

observed. This blocked the backflow from the eye to the pressure transducer when the eye was impacted, and the intraocular pressure could not be accurately measured. When a catheter with a beveled tip and a cut length of 12 mm with super glue was tested, it held pressure under static conditions, and the intraocular pressure could be measured. When this set up was tested under dynamic conditions (the cornea was hit with a rubber mallet) 50% of the time the superglue failed, the catheter became loose, and a leak was observed. It was hypothesized that by adding the sutures to the existing combination, this percentage could be reduced. The hypothesis proved correct, and the catheter with a beveled tip and a cut length of 12 mm with super glue and sutures proved to be the best option (Figure 16).



Figure 15. A (A) no. 20 gauge catheter with a beveled tip and a cut length of 12 mm and (B) an uncut no. 20 gauge catheter.



Figure 16. Final catheter method in place, with sutures and superglue.

1.5 Preliminary Study

To visualize the quasi-static loading of the human eye in the ocular orbit, MRI was used.

Several different indenters were investigated to determine which type produced the largest forces in the eye when the extraocular muscles were present. The results from this test determined the methodology for the following tests.

1.5.1 Preliminary Test Methodology

A rigid testing device had to be created which could be used in the MRI scanner while keeping all metallic objects away from the scanning area, and allowing a force to be measured while displacing the eye. A post mortem human head was mounted in a fiberglass box using expandable foam (Figure 17). The box, the screws that hold it together, and the rest of the testing apparatus all were made of fiberglass or plastic so they would not interfere with the MRI imaging system. Stainless steel could be used, but not within the area of the mounting box scanned by the surface coil, otherwise image artifacts would be induced into the scanned images. A 5-inch surface coil was secured next to the eye that was to be scanned. By using the surface coil, the scan time was lowered and the MRI image resolution was improved. The eye was pressurized to physiologic intraocular conditions using a saline IV bag and a non-metallic catheter. The catheter was inserted into the posterior chamber of the eye and super glued and sutured into place. The saline IV bag was secured at a height which pressurized the eye to physiological conditions. A pressure transducer (Kulite, 6380-3-75, Leonia, NJ) and plug shut-off valve (Swagelok, SS-2T4T4, Solon, OH) were included in the line of pressurization. The pressure transducer measured intraocular pressure and the valve was used to eliminate the possibility of back flow from the eye when the eye was impacted.

The eyelids of the eye were sutured open to allow a greater impact area of the eye without the inclusion of the surrounding tissue.

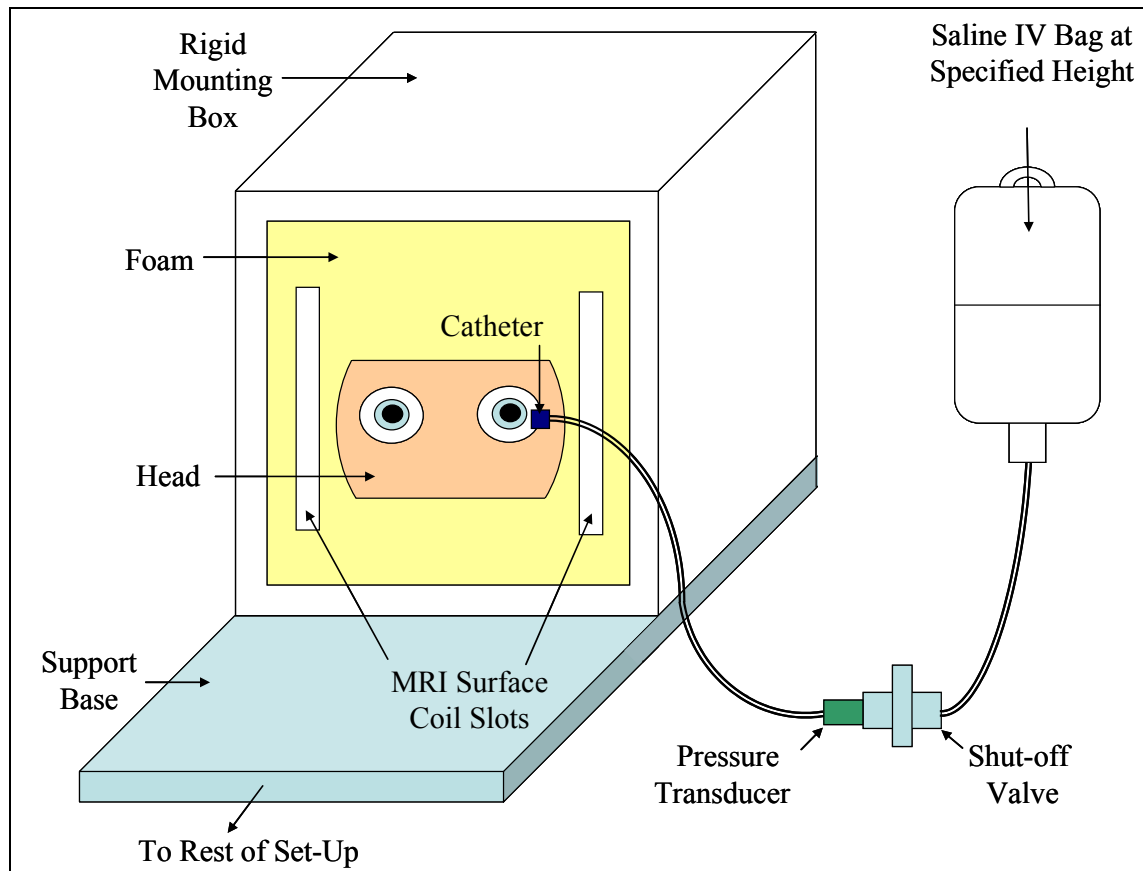


Figure 17. Set up of the head box and pressurization system for the preliminary test.

The head mount was secured to a support base, which was then placed on the table of the MRI scanner (Figure 18). At a distance of 0.8 meters from the head, a load cell (Interface, 147319, Scottsdale, AZ) was mounted to a support stand. Threaded through the load cell was a fiberglass rod which was used to indent the eye. The distance of 0.8 meters was used because this was the distance required to minimize any effects that the metal in the load cell might have on the MRI image quality. The rod was aligned both horizontally and vertically at the opening of the head mount to displace the eye.

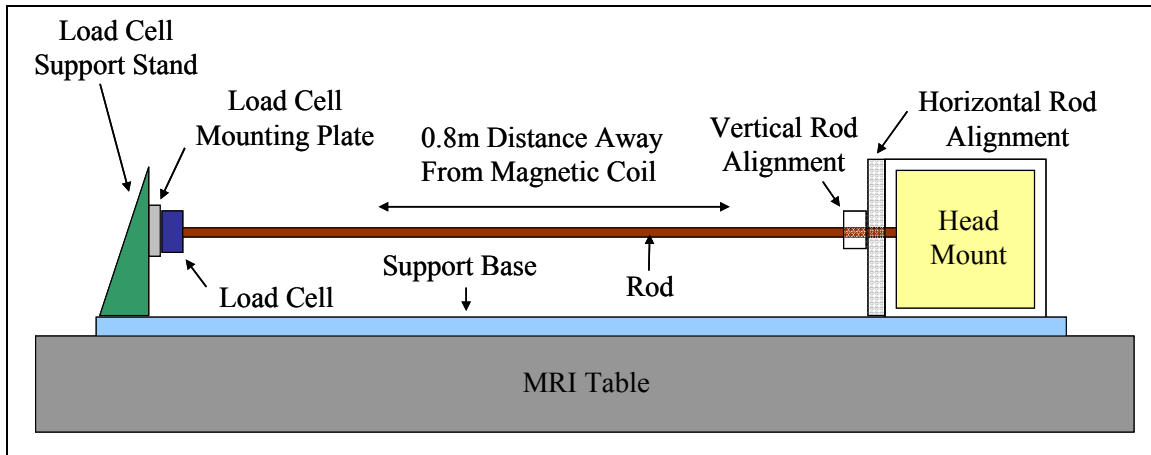


Figure 18. Side view of the MRI test apparatus.

To evaluate the effect of surface area and shape, three different indenters were used to indent the eye: a spherical indenter, a BB sized indenter, and a flat cylindrical indenter (Figure 19). The indenters were machined out of Delrin, an acetyl resin which is MRI safe. To adjust the displacement of the indenter, the rod was screwed through the load cell with 0.25 mm precision. MRI markers were placed on the edge of the indenter so that the sagittal slices could be properly prescribed by the MRI technician.

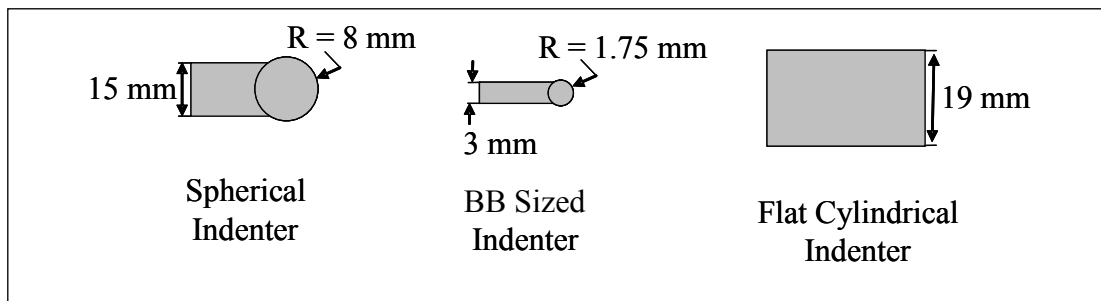


Figure 19. Dimensions of the indenters used to displace the eye.

With each indenter the eye was displaced in 5 mm increments up to a final indentation of 15 mm. An MRI scan was taken at the zero position and following each indentation. Immediately prior to and following each indentation, load and pressure data were

collected (Iotech WBK16, Cleveland, OH). Data was also collected following the MRI scan to determine the relaxation experienced by the eye. After each indentation, the load was removed from the eye and another set of data was collected in order to determine if the eye had experienced a loss of pressure. The field of view in each MRI image was 12 cm square with a resolution of 0.23 mm in the x-direction and 0.47 in the y-direction. Sagittal slices of the eye were taken every 5 mm across the diameter of the eye. Following testing, the force and pressure data was filtered and averaged over each 3 second data collection period. The MRI images were converted to jpegs and digitally analyzed to determine the displacement of the globe that took place for each series of tests utilizing the distance formula.

1.5.2 Preliminary Test Results

The BB shaped indenter produced the greatest posterior horizontal displacement followed by the flat indenter (Table 1, Figure 20 - Figure 38). Most of the displacement that the eye experienced from the spherical indenter was in the superior vertical direction. The flat indenter generated the greatest horizontal compression of the eye, followed closely by the BB shaped indenter. The BB shaped indenter also generated the largest pressures experienced in the eye, while the flat cylindrical indenter generated the largest forces.

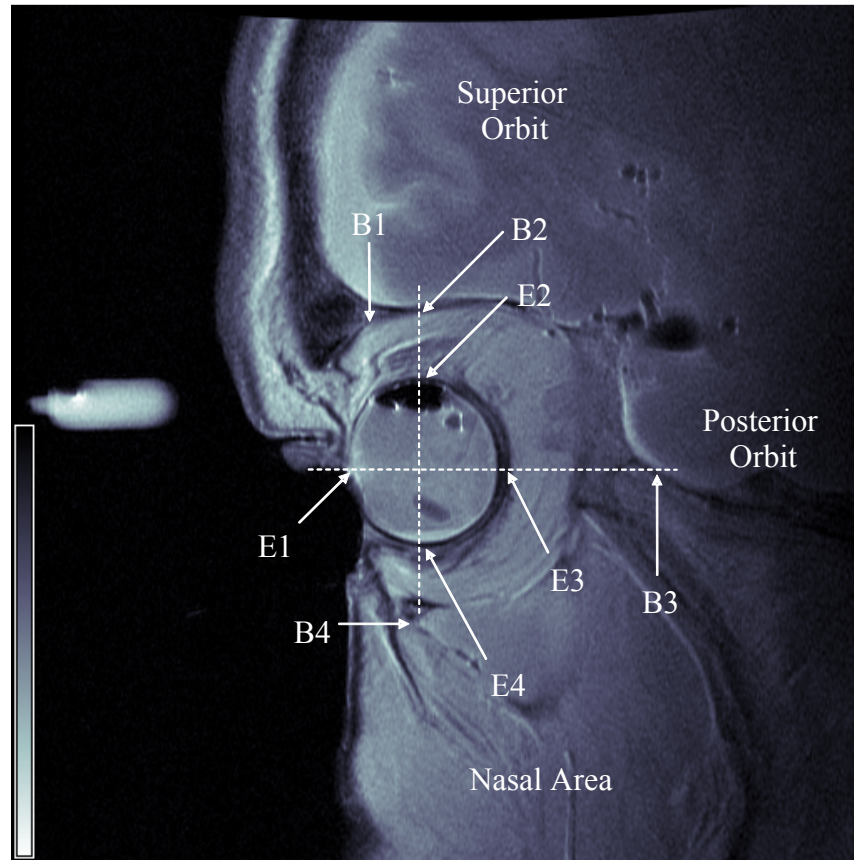


Figure 20. Location of the points recorded from digital analysis of the MRI images.

Table 1. Displacements measured from the MRI images at each step with different indenters.

Indenter Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
Spherical Indenter						
0 mm	21.54	8.91	19.69	10.31	16.03	16.78
5 mm	21.61	8.22	19.24	11.57	15.21	15.91
10 mm	21.96	6.09	19.16	15.56	15.70	14.58
15 mm	22.16	4.74	19.22	22.76	16.72	13.86
BB Indenter						
0 mm	20.73	7.28	19.02	11.51	16.84	17.09
5 mm	20.89	7.09	18.14	12.50	16.89	17.26
10 mm	20.41	7.22	16.57	20.16	15.83	16.66
15 mm	21.42	7.45	14.88	20.12	15.72	15.58
Flat Indenter						
0 mm	19.45	8.26	15.94	12.69	14.83	18.20
5 mm	19.86	8.93	15.00	11.26	13.64	18.49
10 mm	20.64	9.25	14.30	11.27	12.76	18.28
15 mm	22.22	8.32	12.71	14.22	13.36	17.97

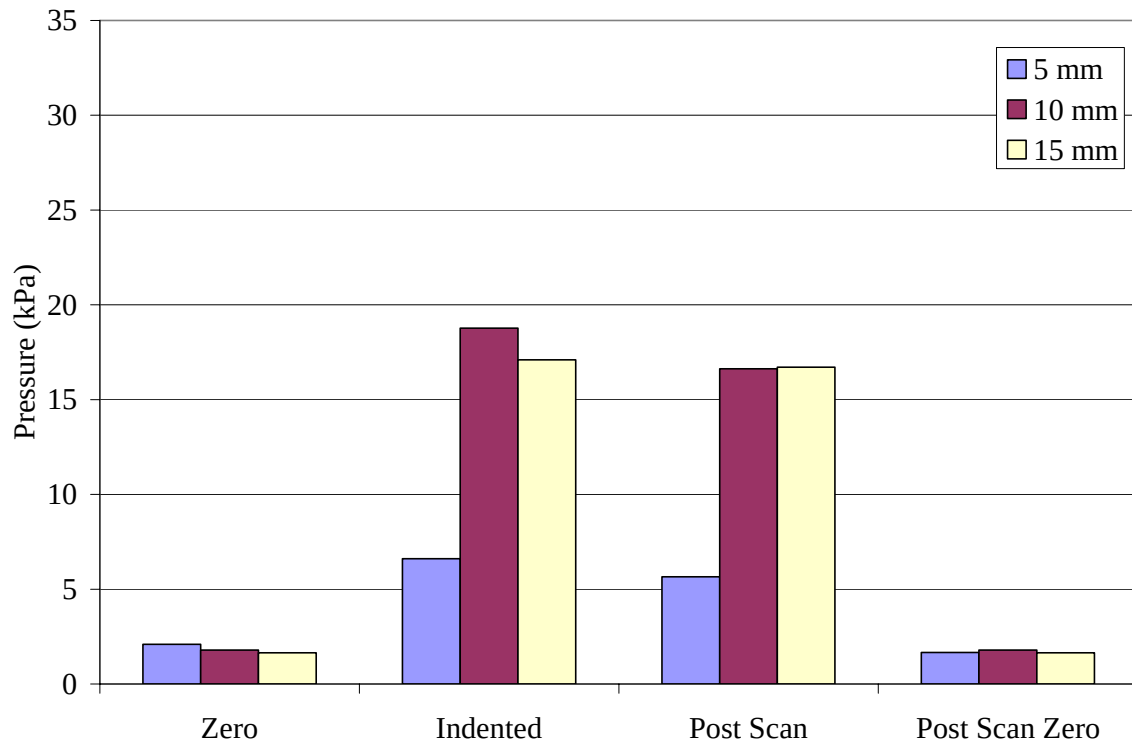


Figure 1. Pressures measured at each indentation step for the eye with muscles using the spherical indenter.

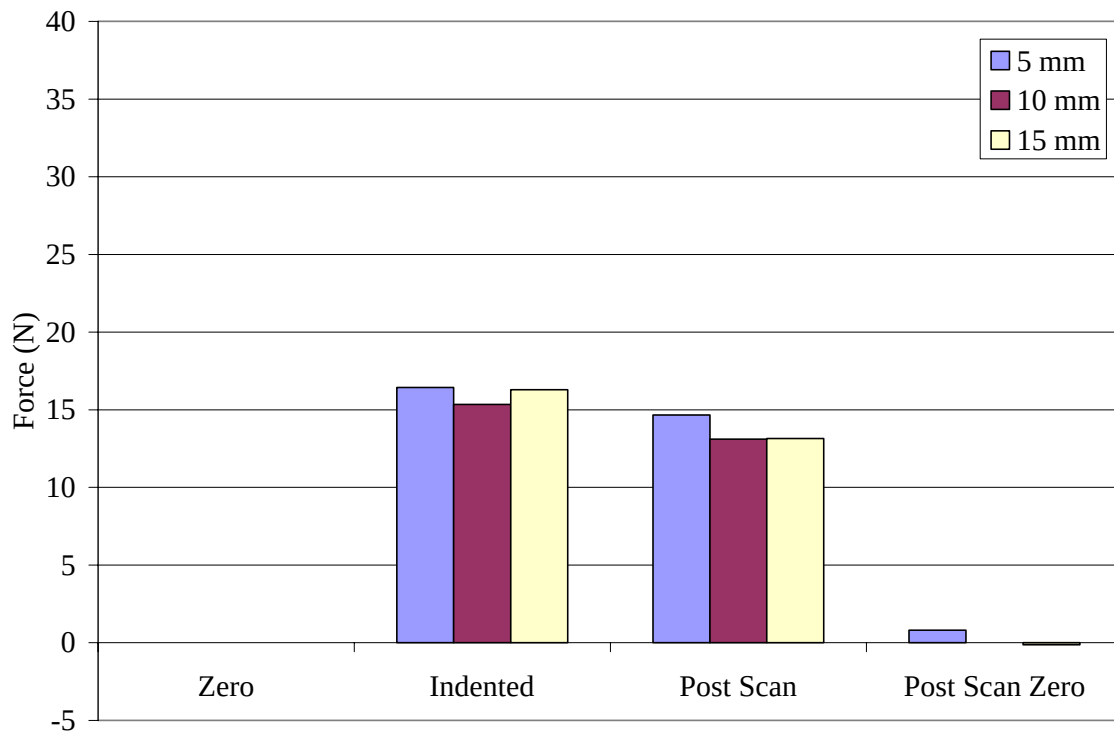


Figure 2. Forces measured at each indentation step for the eye with muscles using the spherical indenter.

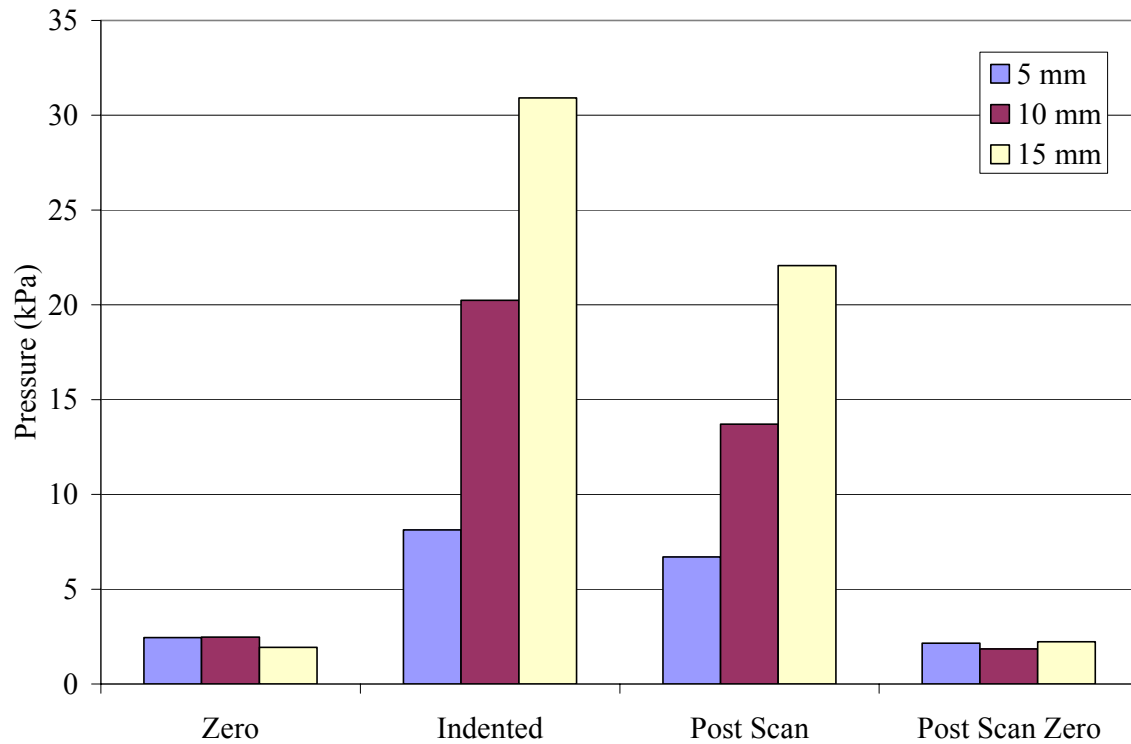


Figure 23. Pressures measured at each indentation step for the eye with muscles using the BB shaped indenter.

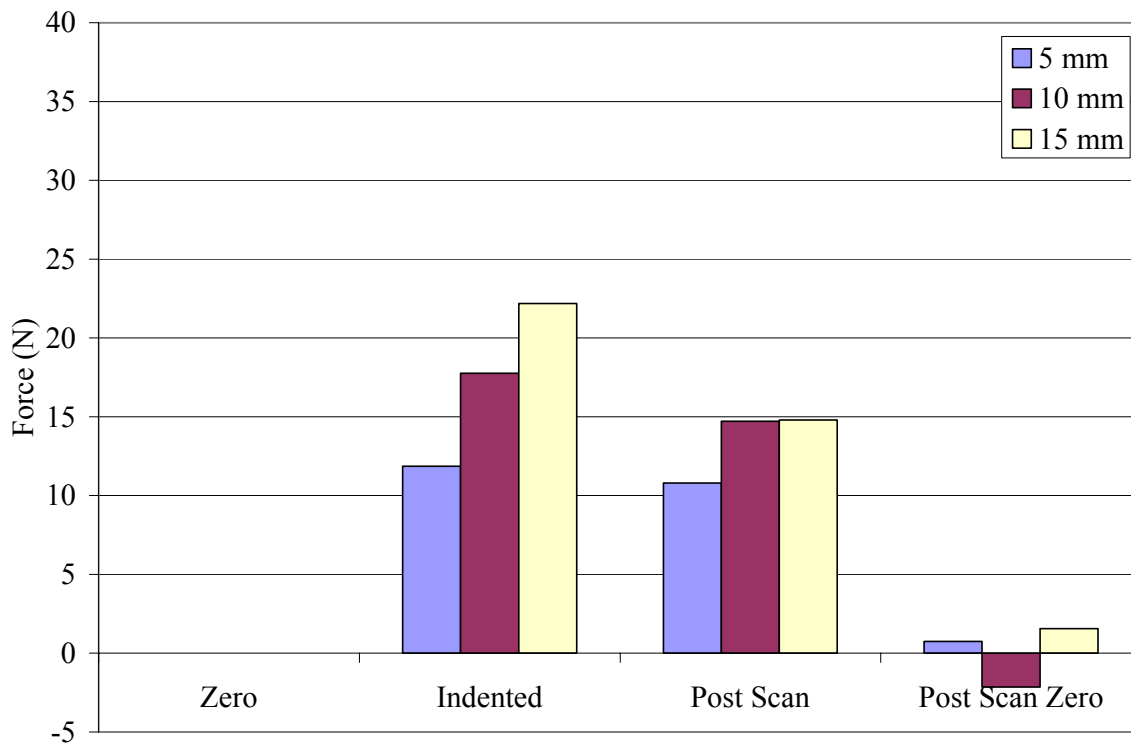


Figure 24. Forces measured at each indentation step for the eye with muscles using the BB shaped indenter.

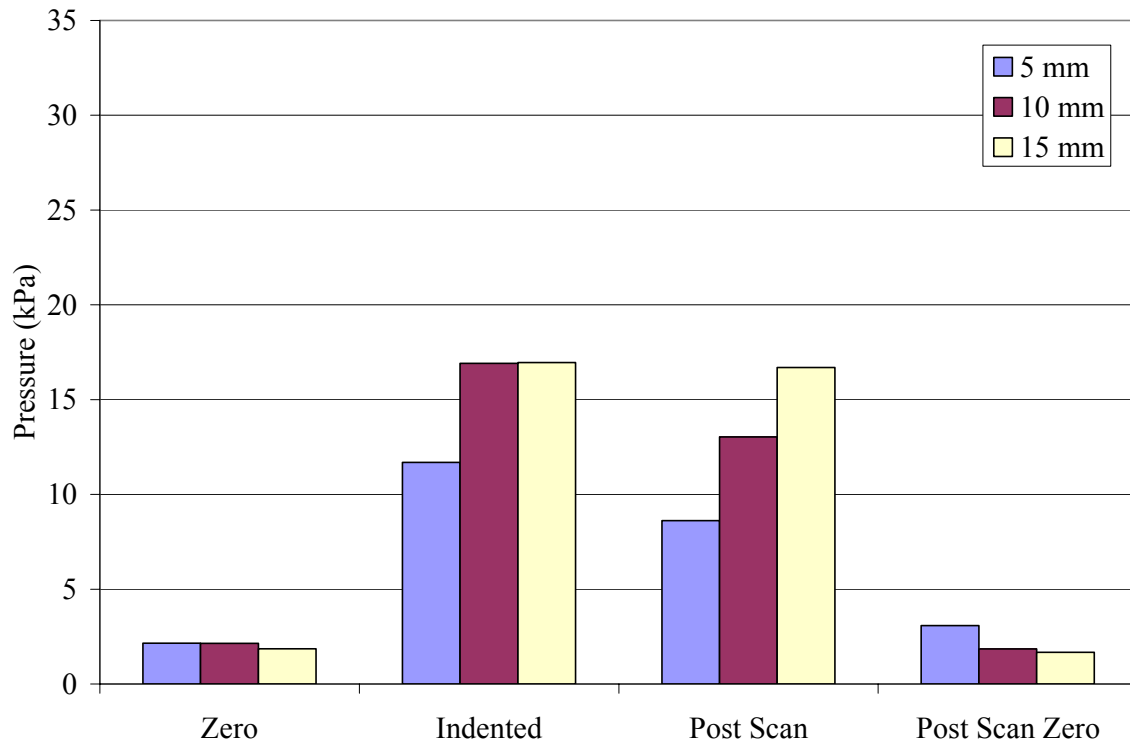


Figure 25. Pressures measured at each indentation step for the eye with muscles using the flat cylindrical indenter.

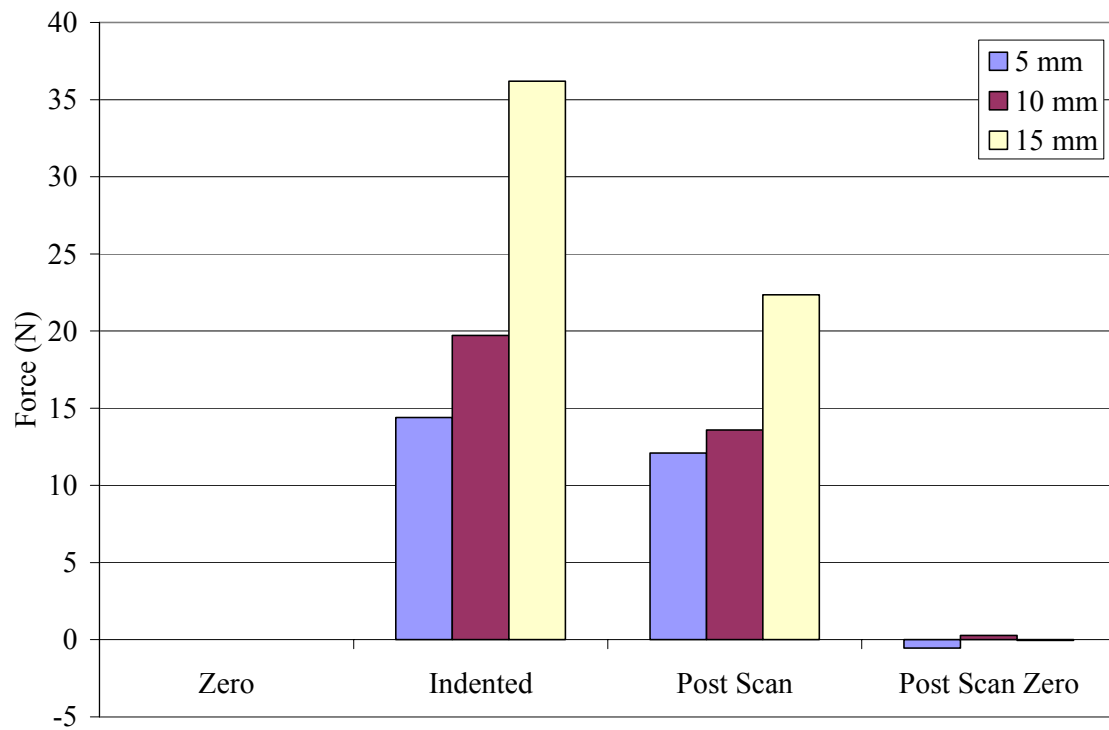


Figure 26. Forces measured at each indentation step for the eye with muscles using the flat cylindrical indenter.

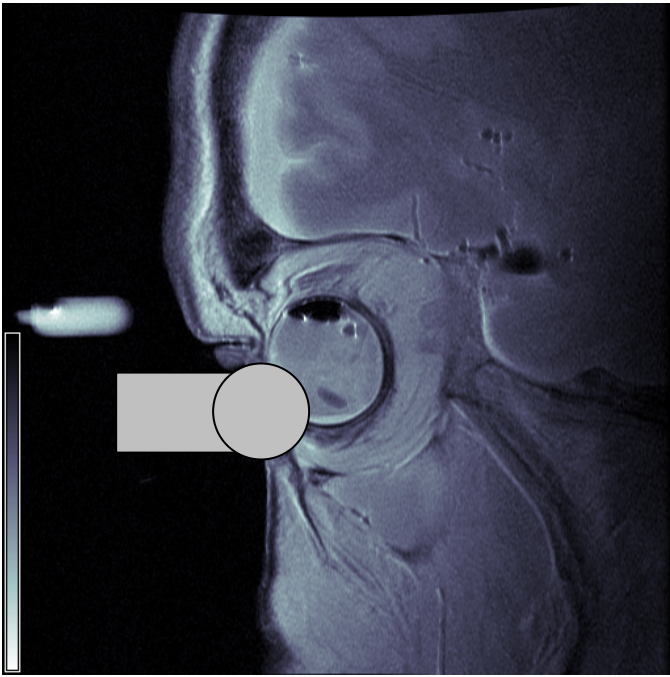


Figure 27. MRI taken of the eye at an indentation of 0 mm with the spherical indenter.

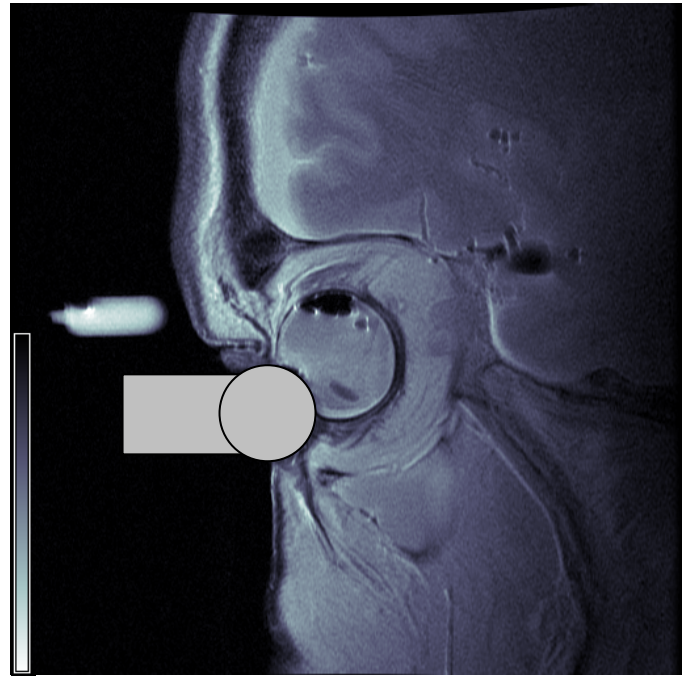


Figure 28. MRI taken of the eye at an indentation of 5 mm with the spherical indenter.

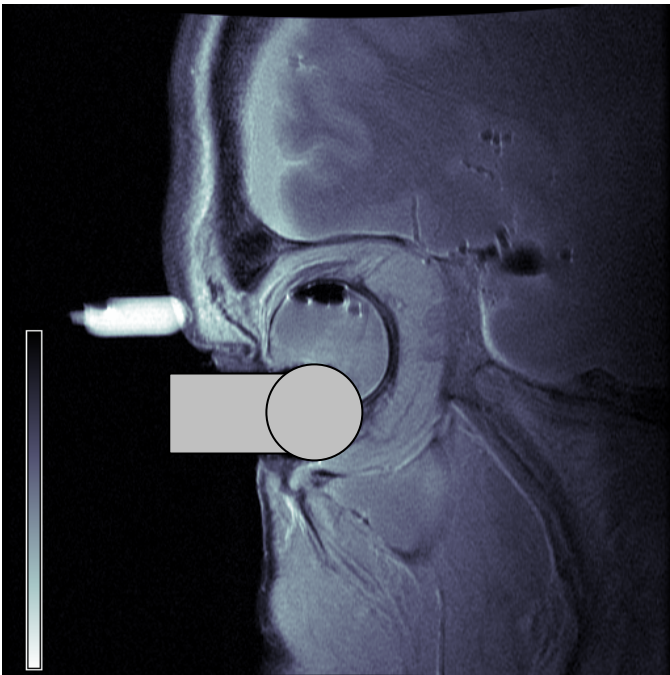


Figure 29. MRI taken of the eye at an indentation of 10 mm with the spherical indenter.

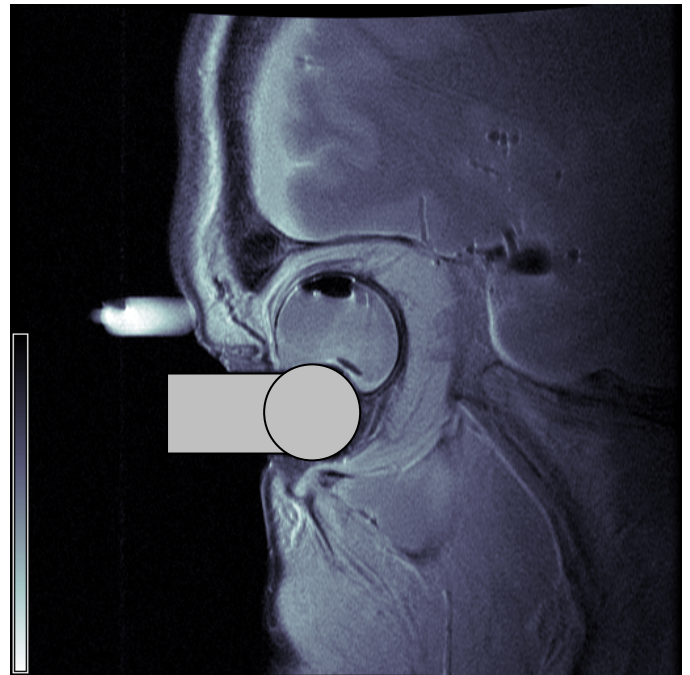


Figure 30. MRI taken of the eye at an indentation of 15 mm with the spherical indenter.

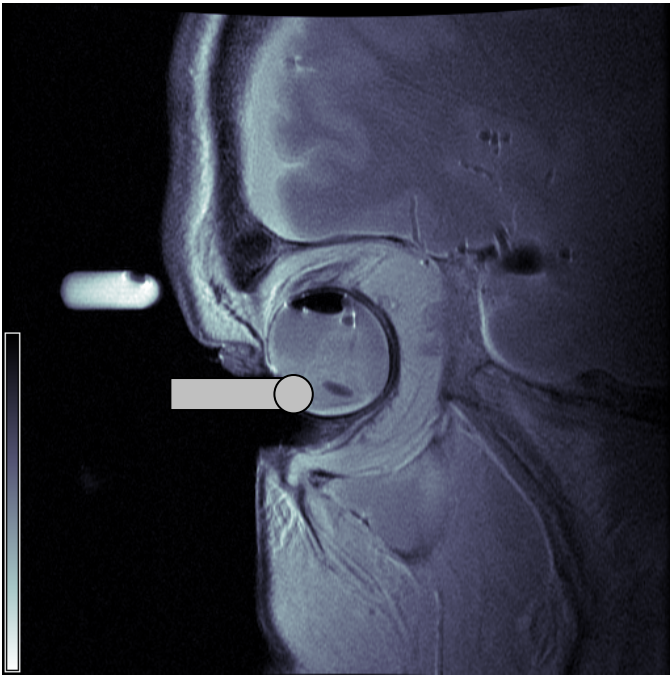


Figure 31. MRI taken of the eye at an indentation of 0 mm with the BB shaped indenter.

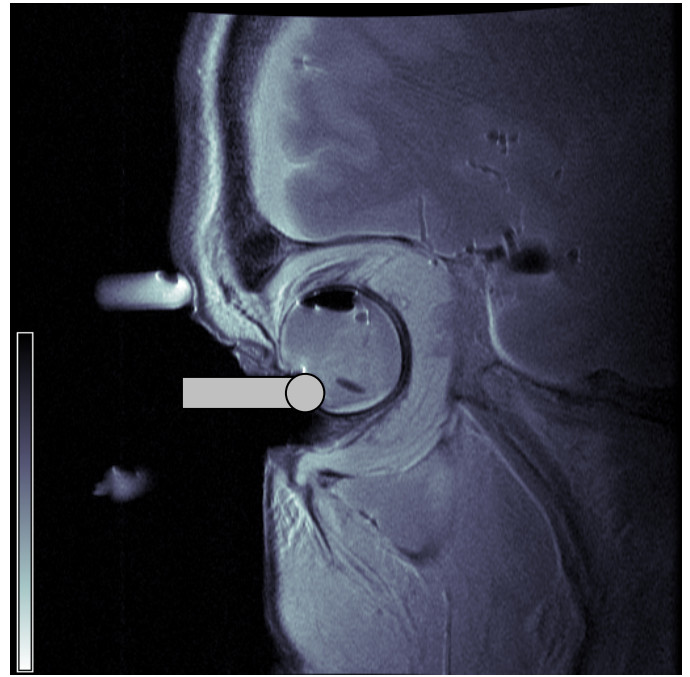


Figure 32. MRI taken of the eye at an indentation of 5 mm with the BB shaped indenter.

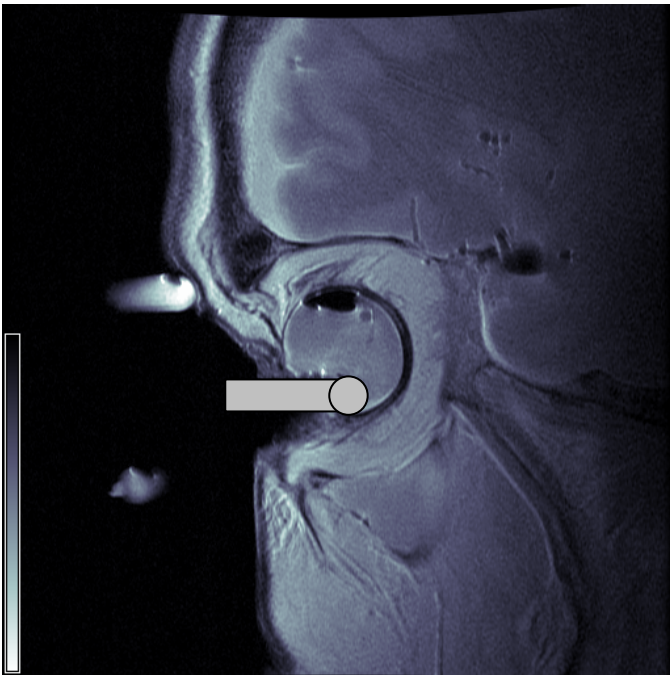


Figure 33. MRI taken of the eye at an indentation of 10 mm with the BB shaped indenter.

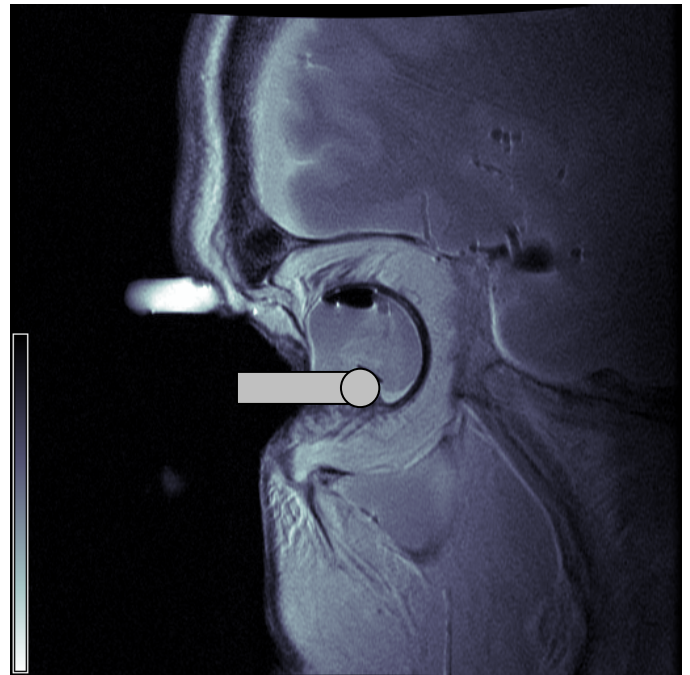


Figure 34. MRI taken of the eye at an indentation of 15 mm with the BB shaped indenter.

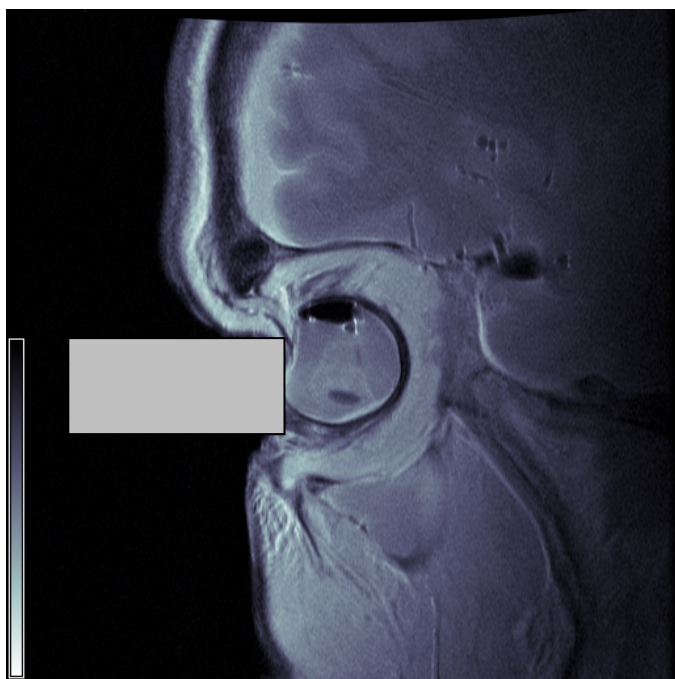


Figure 35. MRI taken of the eye at an indentation of 0 mm with the flat cylindrical indenter.

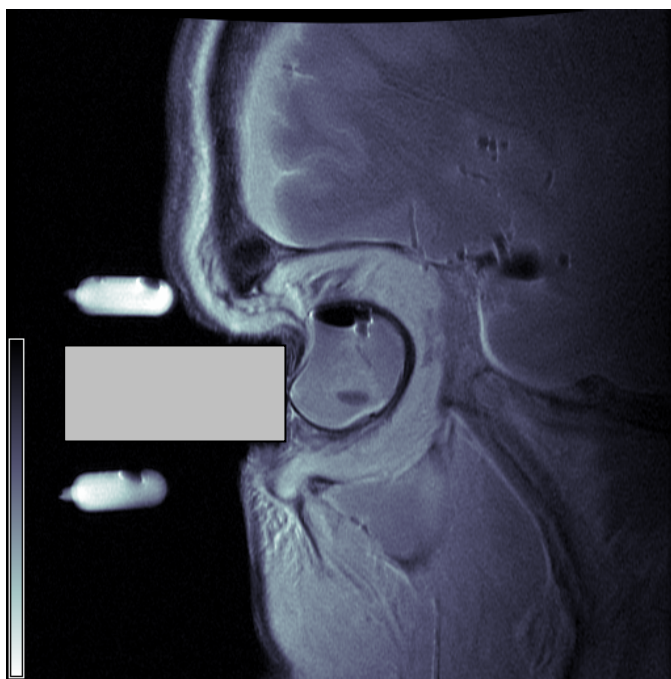


Figure 36. MRI taken of the eye at an indentation of 5 mm with the flat cylindrical indenter.

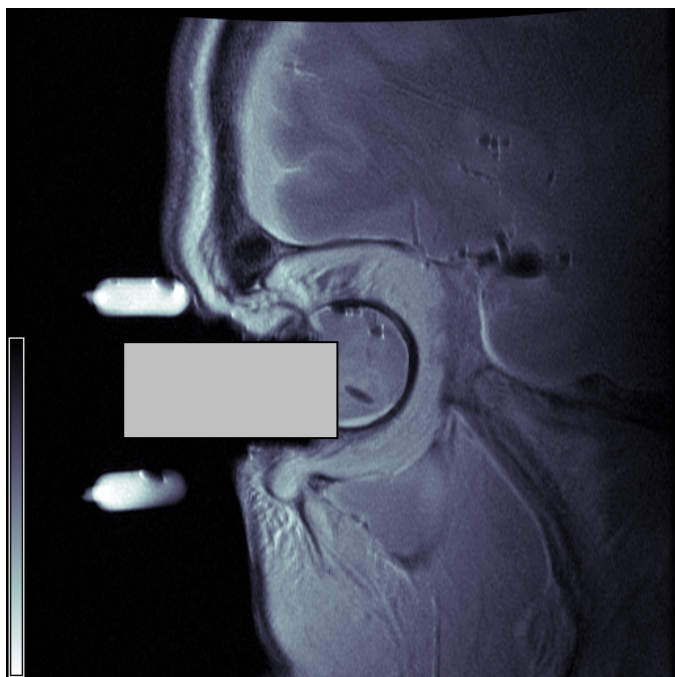


Figure 37. MRI taken of the eye at an indentation of 10 mm with the flat cylindrical indenter.

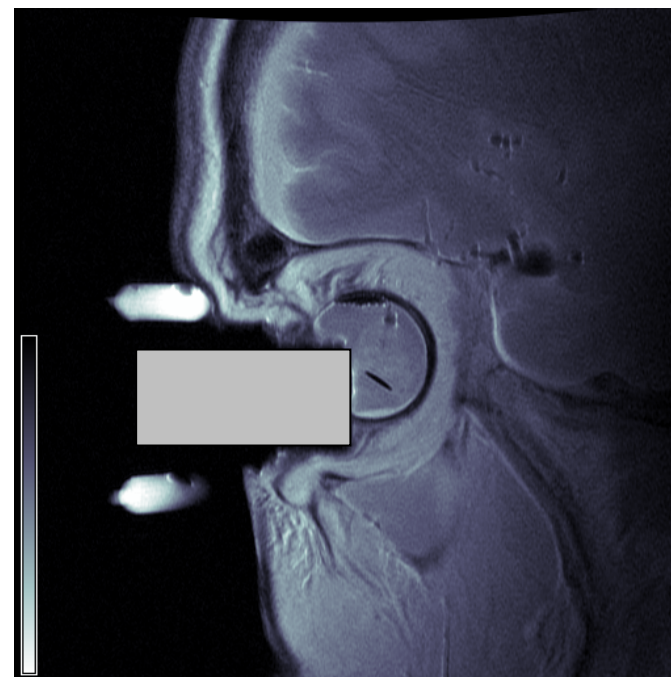


Figure 38. MRI taken of the eye at an indentation of 15 mm with the flat cylindrical indenter.

1.5.3 Preliminary Test Discussion

The preliminary MRI test provided some insight to the test set up used to indent the eye:

- It was determined that the eye lids needed to be removed to enable the indenter to be aligned with the center of the eye, rather than the center of the eye opening.
- The rod alignment and force measurement set up also needed to be modified in order to reduce the effects of residual friction that were seen in the force results.
- Since it was determined that the flat cylindrical indenter created the largest forces in the eye, only that indenter would need to be used in subsequent tests.

This preliminary MRI technique was also found to have some drawbacks in collecting data for this type of testing:

- The MRI images are of high quality, but it is not easy to determine the bone from the fatty masses and was therefore difficult to take position measurements of the globe within the orbit.
- The MRI tests were costly because each scan took approximately five minutes to conduct, and there was a long set up time to start collecting the images.
- The indenter could not be seen in the MRI images, and therefore the alignment of the indenter could not be verified in the images prior to impacting the eye.
- The thinnest image slices that could be taken through MRI while keeping both the in-plane resolution at least 0.5 mm x 0.5 mm and a scan time below 5 minutes, was a 5 mm thickness. While this thickness is acceptable when only one image in the sagittal plane is required, it is unacceptable for any reconstructions that would be needed in the coronal or transverse planes.

The preliminary test provided a good starting point for the following tests. It was found that using MRI to collect sagittal images of the eye being quasi-statically impacted was not feasible, and that utilizing CT scanning would be a better alternative. CT scanning at a resolution equal to that used in this preliminary study would take seconds instead of minutes. Images obtained from CT scans would also show a better contrast between bone and soft tissue and allow displacement measurements of the eye in relation to its orbit to be made with greater accuracy. No changes would have to be made to the indenter for it to appear in the CT images, and during testing CT images would verify the placement of the indenter.

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CHAPTER 2

Quasi Static Response of the Human Eye with Extraocular Muscles

Tested *In Situ* Using Computed Tomography Imaging

2.1 Matched-Pair *In Situ* Human Eye Tests

The purpose of the Computed Tomography (CT) quasi-static tests was to investigate the effect of the presence of the extraocular muscles on the biomechanical response of the human eye *in situ*. The role of the extraocular muscles in relation to eye injuries has yet to be quantified in the literature. Without considering the forces and stresses induced in the sclera from the presence of these muscles, the current eye injury criteria may significantly underestimate the risk of serious eye injuries. In this research, the effect of the extraocular muscles was determined in relation to the force, pressure, and displacement experienced by the eye under loading similar to that experienced during a blunt impact, which is believed to cause the most serious eye injuries (Parver 1986).

2.1.1 Testing Methodology

The rigid testing device created for the preliminary testing was also used in these tests; however, changes in the alignment and advancement method of the rod were made to alleviate the friction forces present in preliminary results. A post mortem human head was mounted in a fiberglass box using expandable foam (Figure 39). The box, the screws that held it together, and the rest of the testing apparatus were all made of fiberglass or plastic so that they would not interfere with the CT imaging system. Image artifacts appearing as starbursts would be induced into the collected images if metal were present in the scanning area. The eye was pressurized to physiologic intraocular conditions using a saline IV bag and a non-metallic catheter. The catheter was inserted into the posterior chamber of the eye and super glued and sutured into place. The saline IV bag was secured at a height which pressurized the eye to physiological conditions. A pressure

transducer (Kulite, 6380-3-75, Leonia, NJ) and plug shut-off valve (Swagelok, SS-2T4T4, Solon, OH) were included in the line of pressurization. The pressure transducer measured intraocular pressure and the valve was used to cut off the possibility of back flow from the eye when the eye was impacted. The eyelids of both eyes were removed to allow a direct impact on the cornea of the eye, and aid in aligning the indenter with the eye. The extraocular muscles were transected from the left eye, leaving the eye held in place by solely the optic nerve, while the muscles of the right eye were left intact.

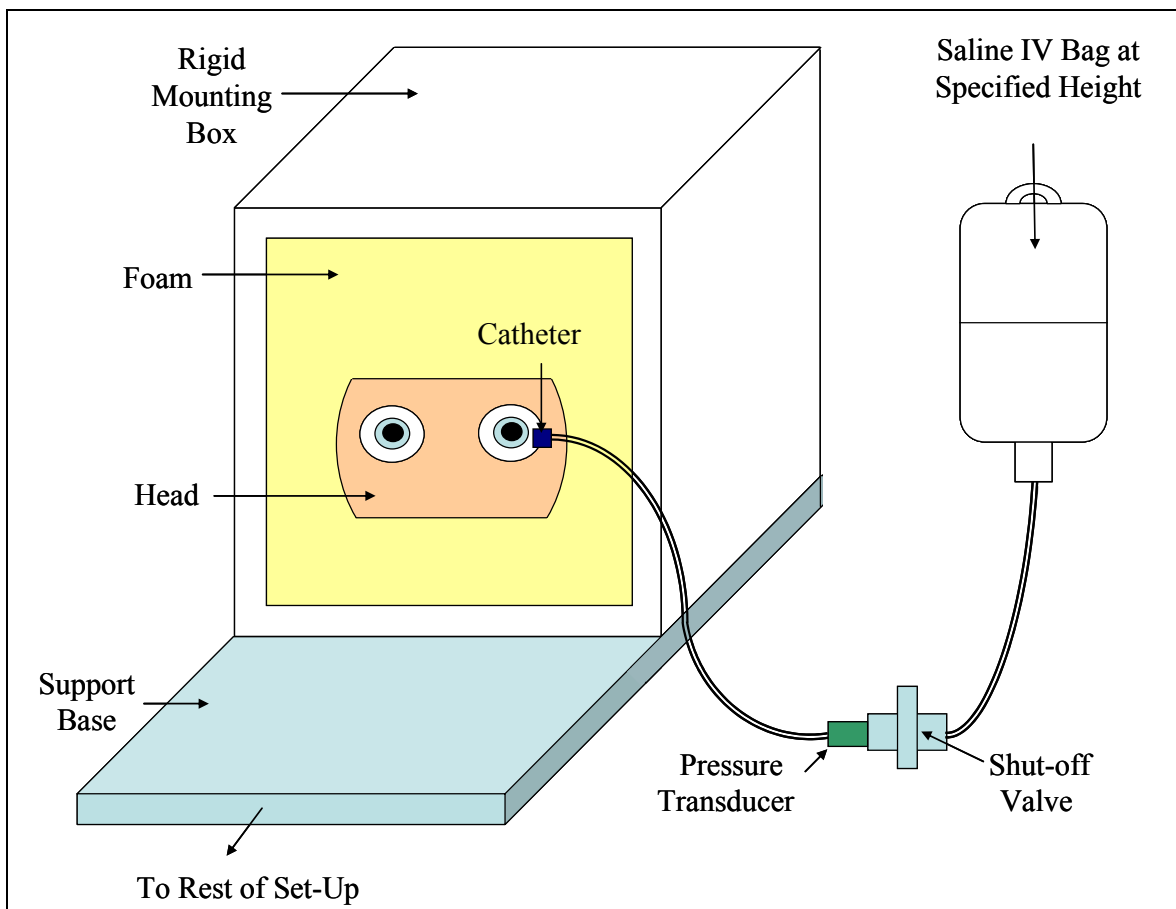


Figure 39. Set up of the head box and pressurization system.

The head mount was secured to a support base, which was then placed on the table of the CT scanner. At a distance of 0.8 meters from the head, a load cell (Interface, 147319,

Scottsdale, AZ) was mounted to a support stand. Threaded through the load cell was a fiberglass rod which was used to indent the eye. The distance of 0.8 meters was used because this was the distance required to minimize any effects that the metal in the load cell might have on the MRI image quality, since the testing apparatus worked well for the preliminary test, this distance was not changed. The rod was aligned both horizontally and vertically at the opening of the head mount to displace the eye (Figure 40).

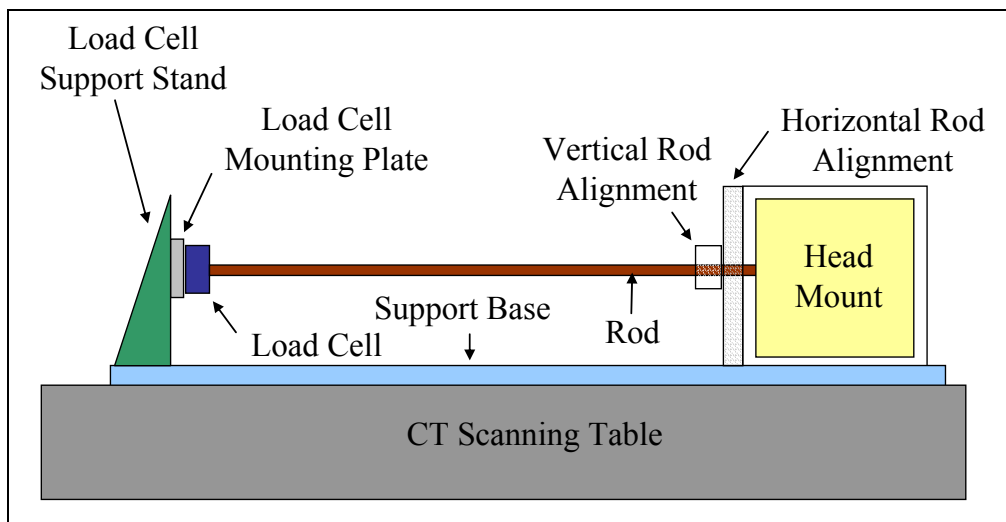


Figure 40. Side view of the test apparatus.

The eye was indented with the flat cylindrical indenter with a diameter of 19 mm, which was the indenter that created the largest forces in the eye during preliminary tests. The eye was displaced in 5 mm increments up to a final indentation of 30 mm. A CT scan was taken immediately after each 5 mm indentation. The indentation and scan start and end times were recorded for each step, which correlated to the time stamp on the force data that was collected. Force and pressure data was continually collected using a high speed data acquisition system (Iotech WBK16, Cleveland, OH) at a sampling rate of 10 Hz for the duration of the test on each eye (Figure 41).

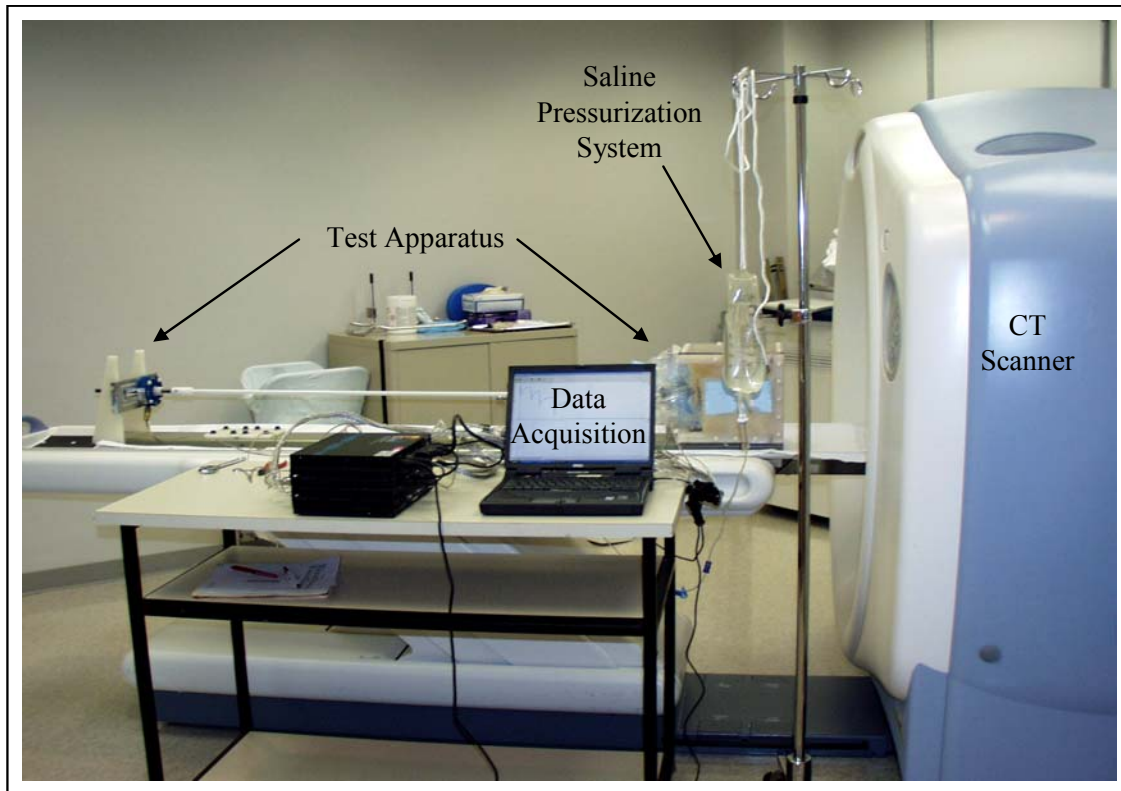


Figure 41. Labeled photograph of the test set up.

Following testing, the force and pressure data were averaged over each 30 second CT scan period (Figure 42). The field of view for each CT scan was 25 cm square with a resolution of 0.488 mm in the x-direction and the y-direction. There were 180 frontal or coronal slices taken of the eye, which were then reconstructed into sagittal slices of the same in-plane resolution using ImageJ software (ImageJ 1.33u, Wayne Rasband, National Institutes of Health) (Appendix A). The CT images were converted from Dicom images to jpegs and digitally analyzed to determine the relative displacement of the globe that took place for each series of tests using the same software. Following testing, the force and pressure data were averaged over each 30 second scan period, so there was one resulting average force value and one resulting average pressure value for each displacement step.

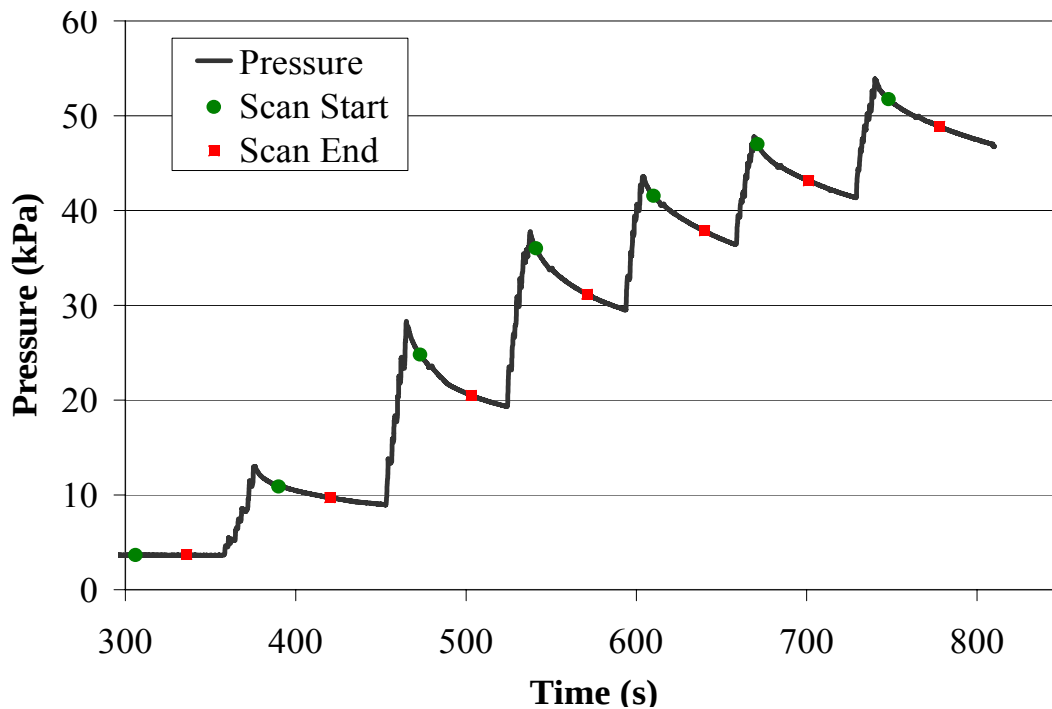


Figure 42. Pressure trace collected for series 4 with CT scan start and end times labeled.

A total of three post mortem human heads were used for the matched pair tests (Table 2). A pre-test OsteoGram was obtained for the cadavers used in this test (Compumed, Inc., Los Angeles, CA). The OsteoGram was used to examine the Bone Mineral Density (BMD) of the test subject to identify if there was a pre-existing osteoporotic condition. BMD is the measured density of calcium in regions of the bones. The BMD index is the readout from the x-ray in normalized units and results are reported with respect to the normal population. A t-score can be used to compare the subject's bone mineral density with that of the general population whereas a z-score can be used to compare the bone mineral density of a subject with the average score for their age. The t-score is generally low for elderly subjects. A t-score of -1 corresponds to one standard deviation below the mean for a 30-year old subject, meaning the individual is at the 37th percentile for bone mineral density, or close to normal. T-scores of 2 and 3 correspond to 97th and 99th percentiles, respectively.

Table 2. Tissue matrix for the matched pair tests.

Test Series IDs	Gender	Age	Body Mass	Body Height	Race	Cause of Death	Osteogram		
	M/F	(years)	(kg)	(cm)			BMD	t-score	z-score
1,2	F	46	115.91	177.80	Caucasian	muscular dystrophy	93.7	-1.6	-1.6
3,4	M	42	85.91	170.18	Caucasian	cirrhosis of the liver	92.1	-1.7	-1.3
5,6	M	66	66.22	177.80	Caucasian	gun shot	79.4	-2.9	-1.4

2.1.2 Test Results and Discussion

Each indentation of each test was recorded and assigned a Test ID number within each test series. The odd test series numbers correspond to the left eye which has the extraocular muscles transected, while the even series numbers correspond to the right eye which has the extraocular muscles attached (Table 3). Aside from series 1 and 2, there are matched displacements at 5 mm increments up until a final indentation of 30 mm. There are a total of 37 scanned CT images from which displacement measurements were collected. There are a total of 30 force measurements. The pressure measurement system was not as reliable during the test as it was in the lab environment; a total of seven pressure measurements were collected for a single eye. For this reason, each eye was also visually inspected for signs of globe rupture after each 5 mm indentation. On series 3, the data acquisition system crashed, and all of the collected force and pressure data were lost, however the CT scans were still collected. Once a test was completed on one eye, another test could not be repeated on the same eye. Once an eye was translated back into the orbit, it would not return back to its original position, causing the eye to become permanently recessed in the orbit. This phenomenon was even more prevalent in the eye that had the extraocular muscles transected.

Table 3. Test matrix for the matched pair tests, and data collected.

Test ID	Muscles	Displacement	CT Measurements from Image	Force	Pressure
1.1	No	0 mm	Yes	Yes	No
1.2	No	10 mm	Yes	Yes	No
1.3	No	20 mm	Yes	Yes	No
1.4	No	30 mm	Yes	Yes	No
2.1	Yes	0 mm	Yes	Yes	No
2.2	Yes	5 mm	Yes	Yes	No
2.3	Yes	10 mm	Yes	Yes	No
2.4	Yes	15 mm	Yes	Yes	No
2.5	Yes	20 mm	Yes	Yes	No
3.1	No	0 mm	Yes	No	No
3.2	No	5 mm	Yes	No	No
3.3	No	10 mm	Yes	No	No
3.4	No	15 mm	Yes	No	No
3.5	No	20 mm	Yes	No	No
3.6	No	25 mm	Yes	No	No
3.7	No	30 mm	Yes	No	No
4.1	Yes	0 mm	Yes	Yes	Yes
4.2	Yes	5 mm	Yes	Yes	Yes
4.3	Yes	10 mm	Yes	Yes	Yes
4.4	Yes	15 mm	Yes	Yes	Yes
4.5	Yes	20 mm	Yes	Yes	Yes
4.6	Yes	25 mm	Yes	Yes	Yes
4.7	Yes	30 mm	Yes	Yes	Yes
5.1	No	0 mm	Yes	Yes	No
5.2	No	5 mm	Yes	Yes	No
5.3	No	10 mm	Yes	Yes	No
5.4	No	15 mm	Yes	Yes	No
5.5	No	20 mm	Yes	Yes	No
5.6	No	25 mm	Yes	Yes	No
5.7	No	30 mm	Yes	Yes	No
6.1	Yes	0 mm	Yes	Yes	No
6.2	Yes	5 mm	Yes	Yes	No
6.3	Yes	10 mm	Yes	Yes	No
6.4	Yes	15 mm	Yes	Yes	No
6.5	Yes	20 mm	Yes	Yes	No
6.6	Yes	25 mm	Yes	Yes	No
6.7	Yes	30 mm	Yes	Yes	No

The force versus displacement measurements for a matched pair of human eyes, series 5 and 6, tested *in situ* can be seen in Figure 43. A trend can be seen that a greater amount of force is created in the eye with the extraocular muscles intact. The greatest force measured in the eye with the extraocular muscles intact was 92 N, while the greatest force measured in the eye with the extraocular muscles transected was 80 N.

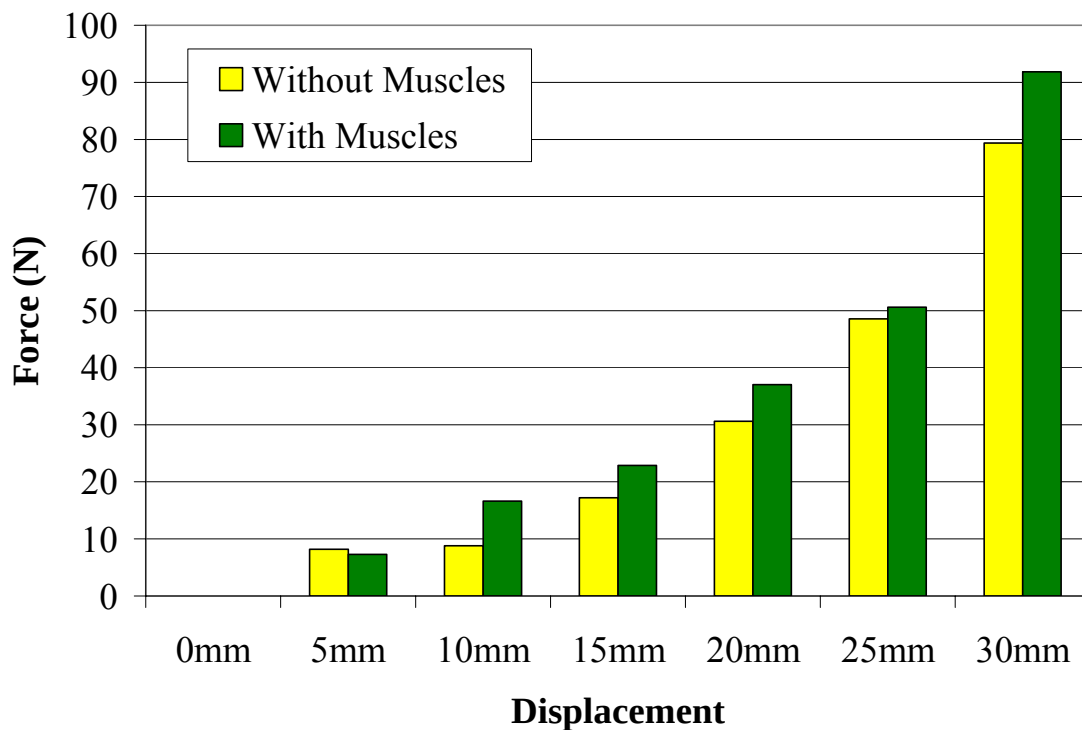


Figure 43. Force versus displacement measurements for a matched pair of human eyes tested *in situ*, series 5 and 6.

The force versus displacement measurements for the matched pair of human eyes, series 1 and 2, tested *in situ* can be seen in Figure 44. The same trend can be seen that a greater amount of force is created in the eye with the extraocular muscles intact; however, the eye with the extraocular muscles transected ruptured sometime during the 20 mm indentation leading to lower force measurements.

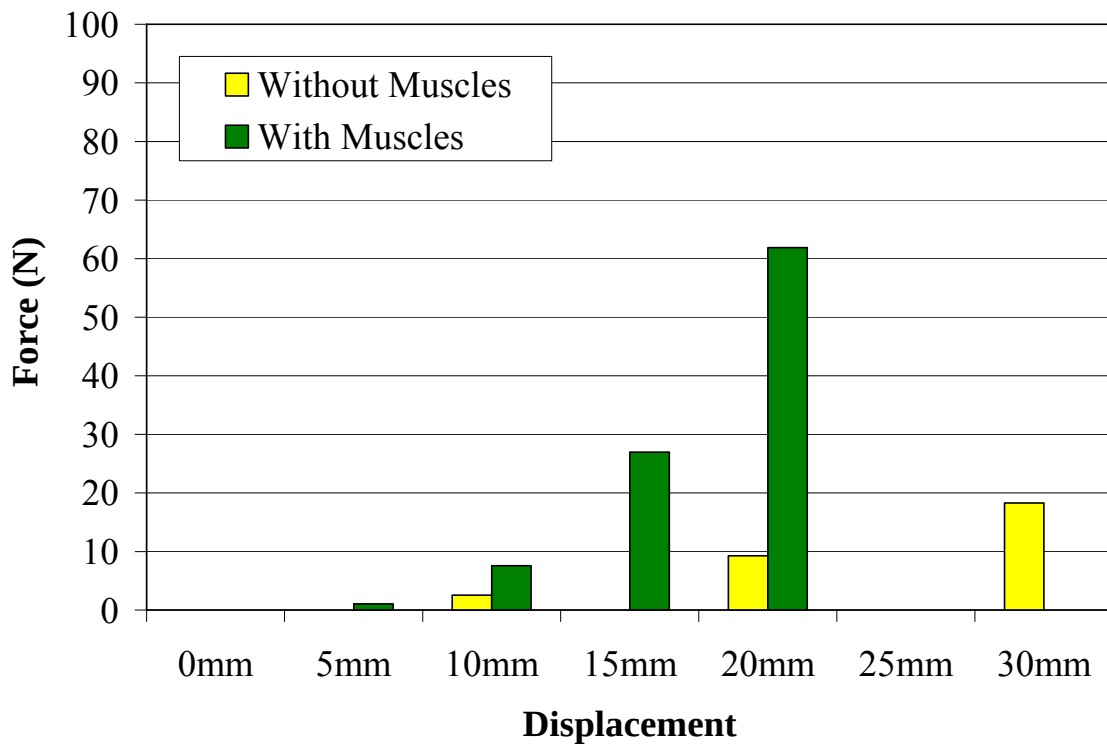


Figure 44. Force versus displacement measurements for a matched pair of human eyes tested in situ, series 1 and 2.

The average force per 5 mm displacement for the eyes with the extraocular muscles attached and the eyes with the extraocular muscles transected was calculated (Figure 45). The standard deviation was also calculated for the displacement steps that had more than one measurement. The same overall trend seen in the matched pair test can also be observed here when it is taken into consideration that the 25 mm displacement step for the eye without muscles only has one sample.

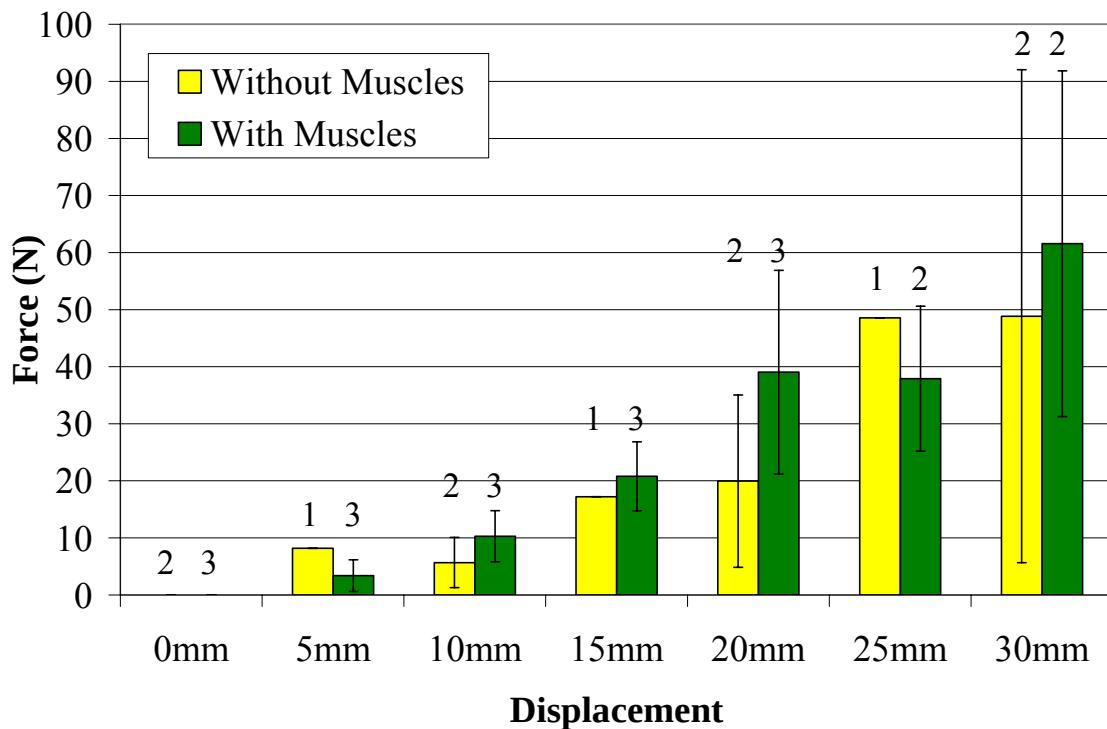


Figure 45. Average force measured per 5 mm displacement for the eyes with the extraocular muscles attached versus the eyes with the extraocular muscles transected. Error bars indicate the standard deviation, while the numbers above each bar correspond to the number of samples.

An additional comparison was completed for the forces measured in eyes with the extraocular muscles intact and the forces measured in the eyes with the extraocular muscles transected. These forces were examined to see if there was a linear correlation. Since there is only one set of complete force measurements for a matched pair of human eyes, series 5 and 6, this data was used (Figure 46). A linear relationship was observed between the two force measurements. The forces measured in the eye with the extraocular muscles transected can be scaled by a factor of 1.1 to achieve the correlating forces in the eye with the extraocular muscles intact, with an R-squared value of 0.985. This scaling factor could be amplified or reduced if there were more data points available to chart.

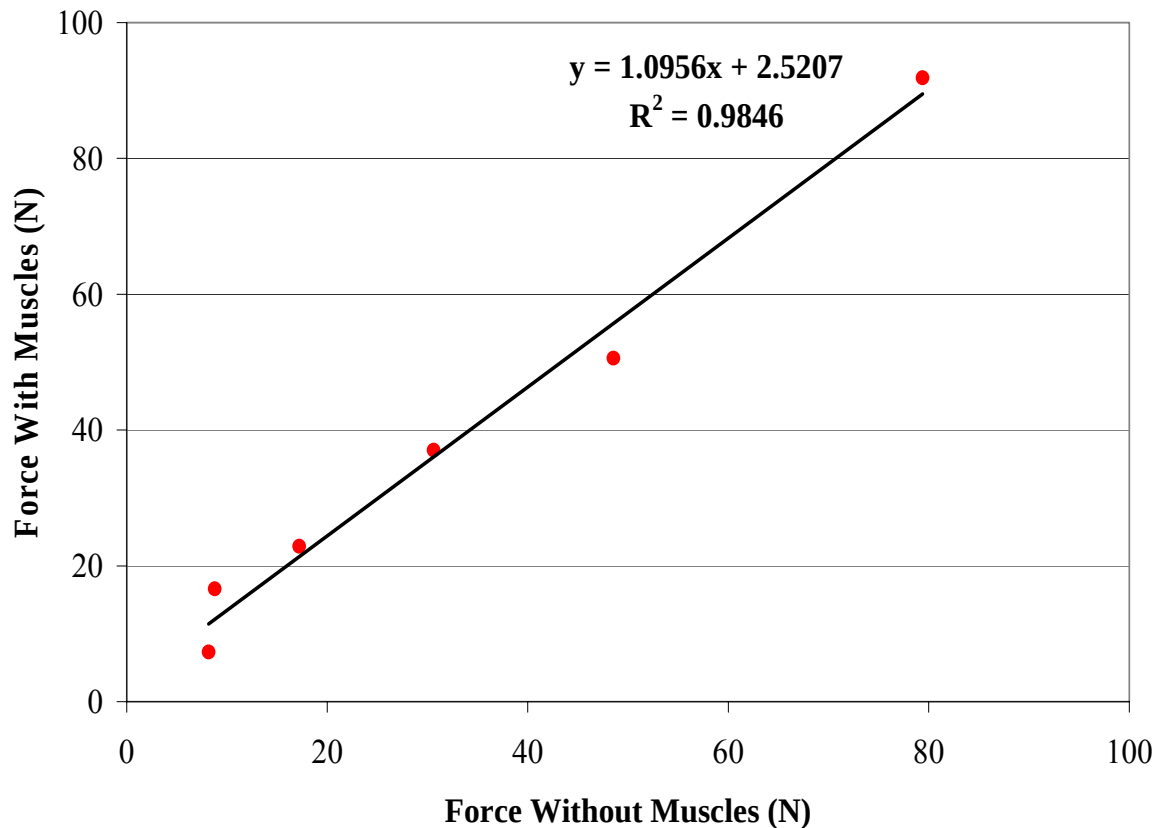


Figure 46. Linear correlation between the forces measured in an eye with the extraocular muscles intact and those measured in an eye with the extraocular muscles transected.

The measured intraocular pressure for an eye with the extraocular muscles attached can be seen to increase at each of the 5 mm indenter displacements (Figure 47). As there was only one complete data set for the pressure measurements, a direct comparison to an eye without the muscles attached could not be made. The physiological intraocular pressure is approximately 2 kPa (0.3 psi, 15 mmHg) and was observed in the eye at zero displacement. The pressure measured in the eye at a 30 mm impactor displacement was 50 kPa, approximately 25 times the normal physiological intraocular pressure.

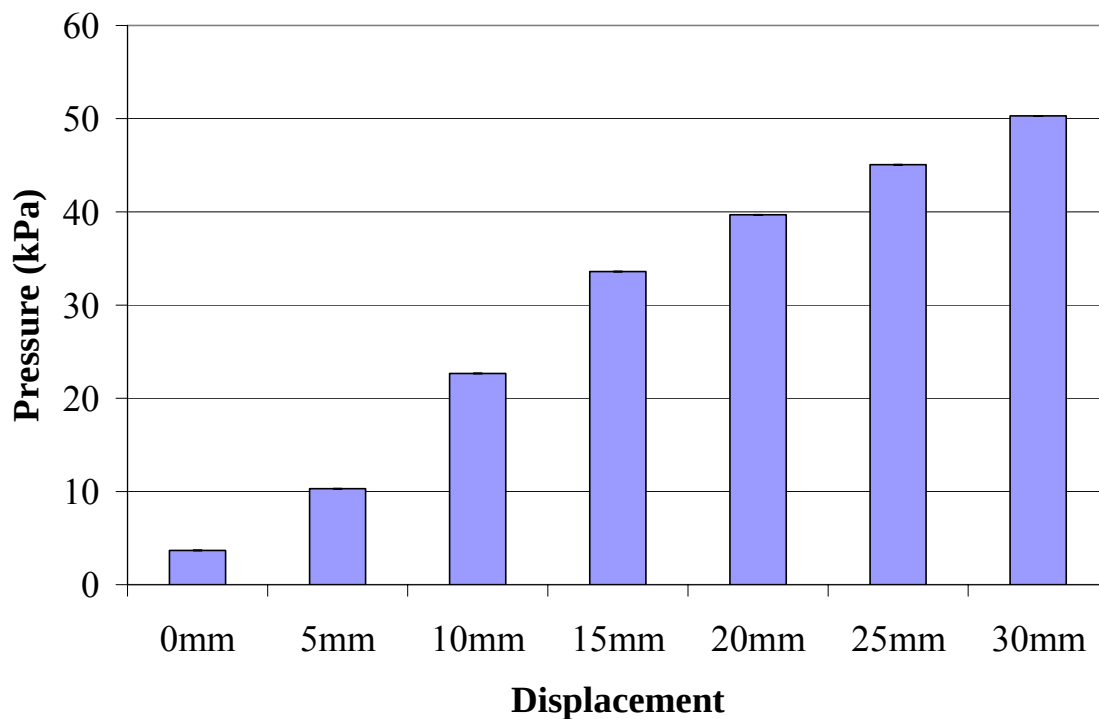


Figure 47. Measured intraocular pressure of an eye with the extraocular muscles attached collected at 5 mm indenter displacements.

Measurements were completed on each of the 37 CT scans to quantify the compression and translation of the eye within the orbit in the sagittal plane (Figure 48). The points were recorded for each scan and the distances between the eye and the orbital walls were then calculated using the distance formula. The first matched pair tested, series 1 and 2, both experienced similar horizontal displacements and compressions at a maximum comparable deflection of 20 mm (Table 4, Table 5). It can be seen in the images, that the eye is displaced steadily in the posterior direction (Figure 49 - Figure 57). It is known that the eye ruptured sometime during series 1. It is hypothesized that the rupture occurred during test ID 1.4, since the eye gets compressed drastically in the anterior to posterior direction.

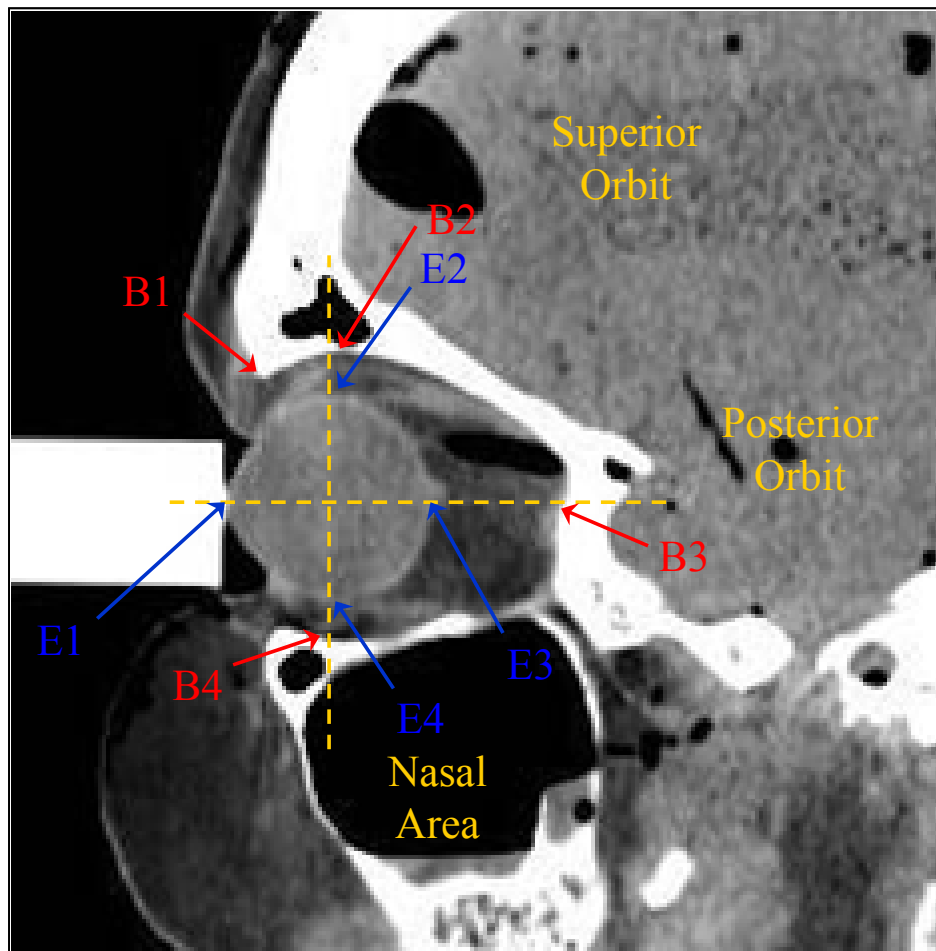


Figure 48. Location of the points recorded during the digital analysis of the CT images in the sagittal plane for the large flat cylindrical indenter.

Table 4. Distance measurements for Series 1, an eye with the extraocular muscles transected, impacted using the flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	13.99	8.59	16.43	4.43	24.02	24.08
10	11.68	6.31	12.52	4.55	18.73	24.52
20	16.63	7.74	6.24	9.66	14.89	27.03
30	24.29	10.54	5.62	12.24	7.22	24.98

Table 5. Distance measurements for Series 2, an eye with the extraocular muscles intact, impacted using the flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	16.70	5.30	16.86	5.17	24.96	24.98
5	16.35	6.15	15.96	6.15	21.61	25.00
10	17.15	8.26	11.68	8.26	19.70	25.03
15	18.93	11.69	7.81	10.53	18.73	25.94
20	19.12	11.08	5.17	10.31	17.34	26.92

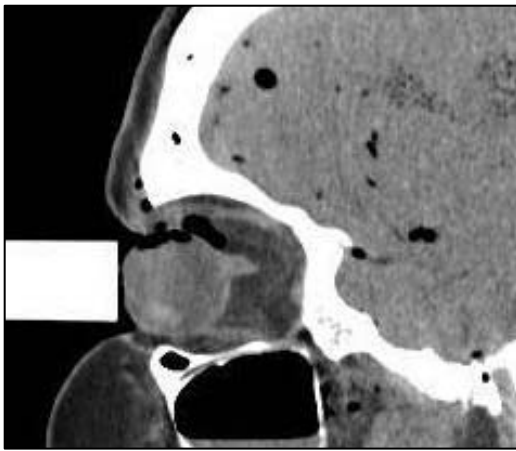


Figure 49. Sagittal CT image of Series 1.1, with the muscles transected, at an indentation of 0 mm.

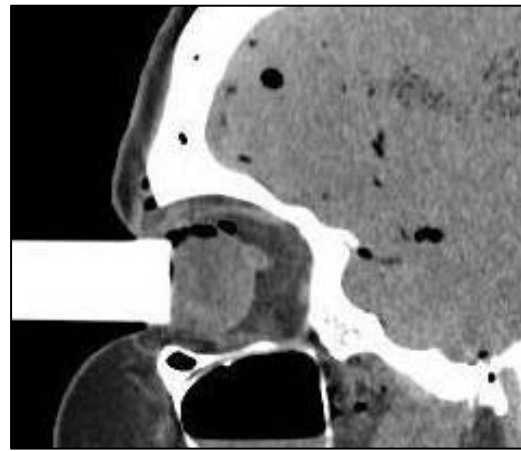


Figure 50. Sagittal CT image of Series 1.2, with the muscles transected, at an indentation of 10 mm.

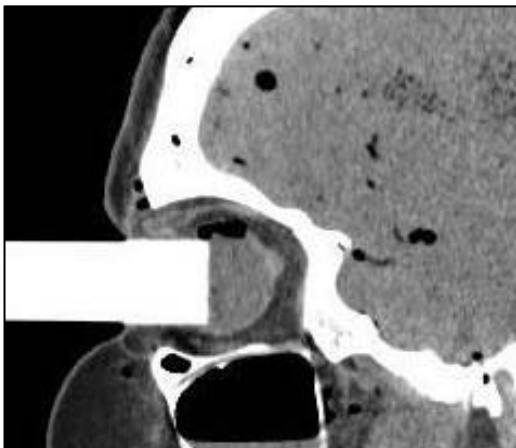


Figure 51. Sagittal CT image of Series 1.3, with the muscles transected, at an indentation of 20 mm.

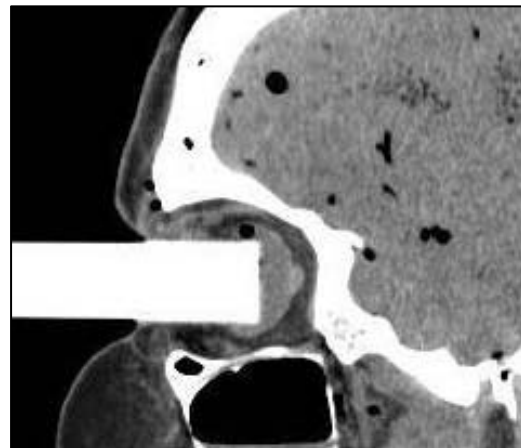


Figure 52. Sagittal CT image of Series 1.4, with the muscles transected, at an indentation of 30 mm.

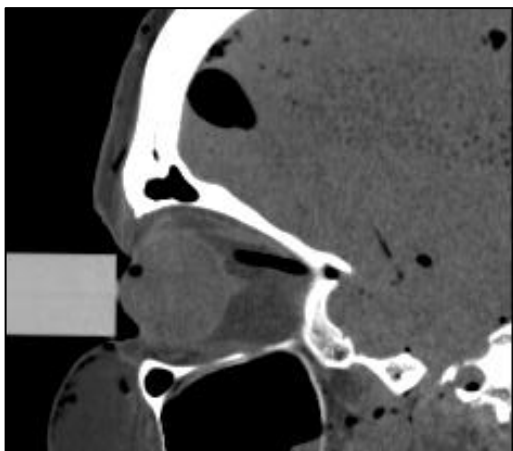


Figure 53. Sagittal CT image of Series 2.1, with muscles attached, at an indentation of 0 mm.

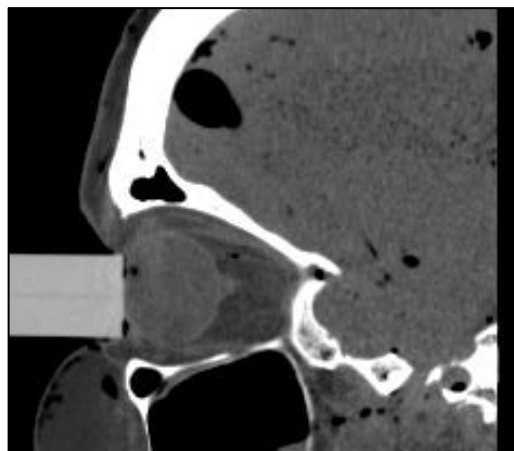


Figure 54. Sagittal CT image of Series 2.2, with muscles attached, at an indentation of 5 mm.

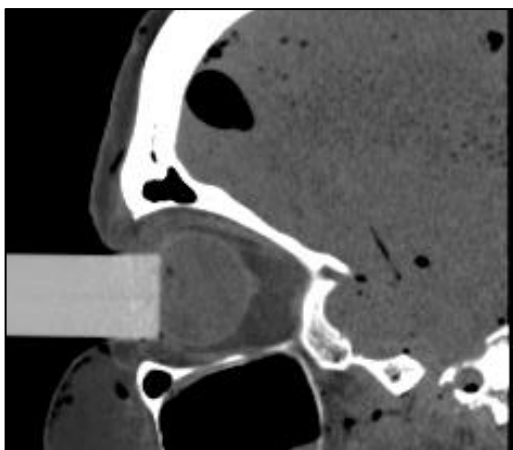


Figure 55. Sagittal CT image of Series 2.3, with muscles attached, at an indentation of 10 mm.

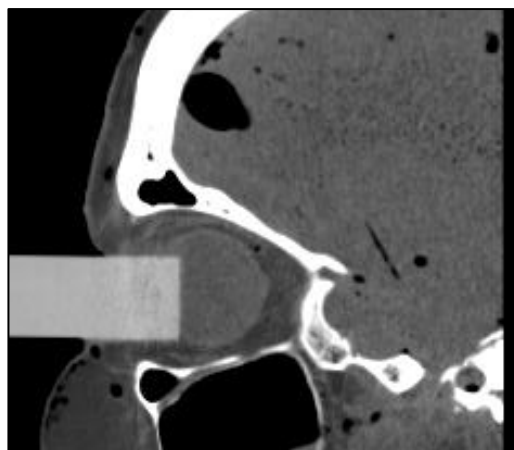


Figure 56. Sagittal CT image of Series 2.4, with muscles attached, at an indentation of 15 mm.

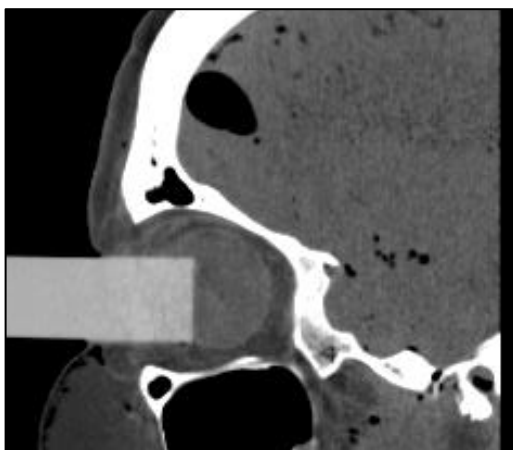


Figure 57. Sagittal CT image of Series 2.5, with muscles attached, at an indentation of 20 mm.

During the second matched pair test, series 3 and 4, the impactor displacement steps were matched throughout the test, enabling a point to point comparison to be made between the two conditions. This matched pair of eyes behaved similarly in some ways within the orbit. Both eyes translated vertically towards the roof of the orbit upon being impacted (Figure 58 - Figure 73, Table 6 - Table 7). Both eyes also compressed along the vertical axis during the vertical movement. One noticeable difference in the way that the eyes reacted to the impact was in the horizontal compression of the eye. The eye with extraocular muscles compressed along its horizontal axis longer and in a greater distance than the eye with the extraocular muscles transected.

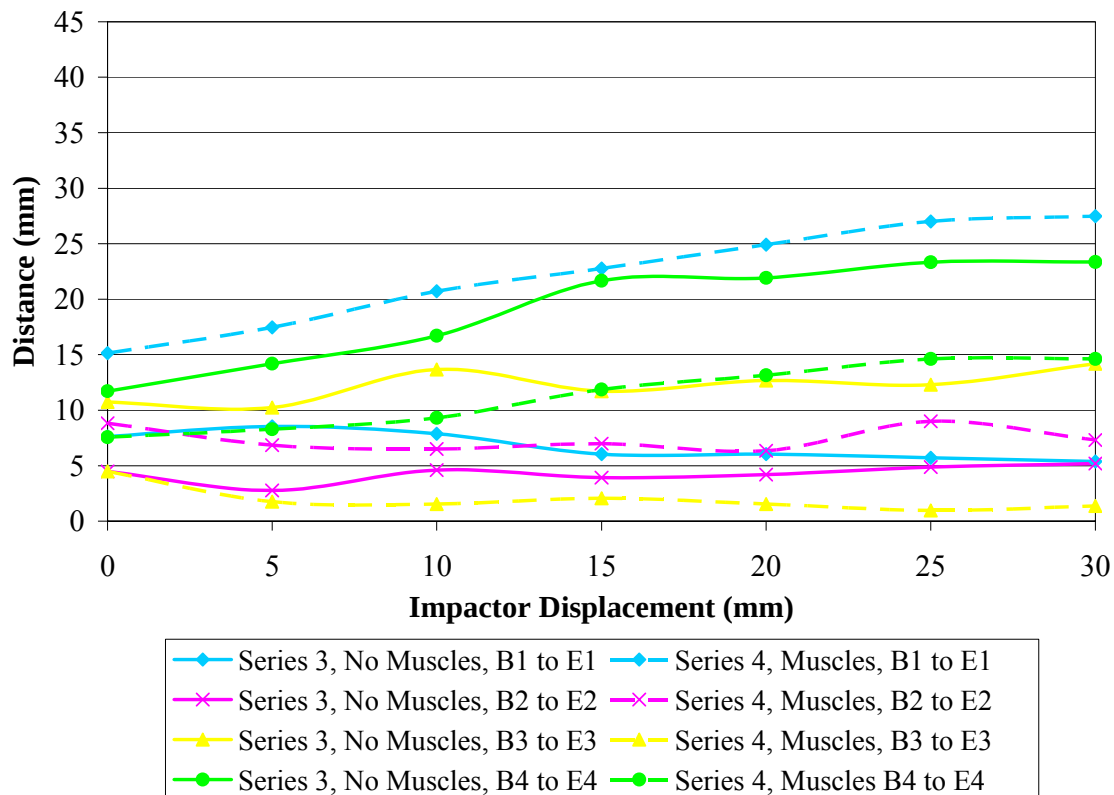


Figure 58. Displacement measurement comparisons of the eye in the orbit for the matched pair of series 3 and series 4 (solid line = no muscles, dashed line = muscles).

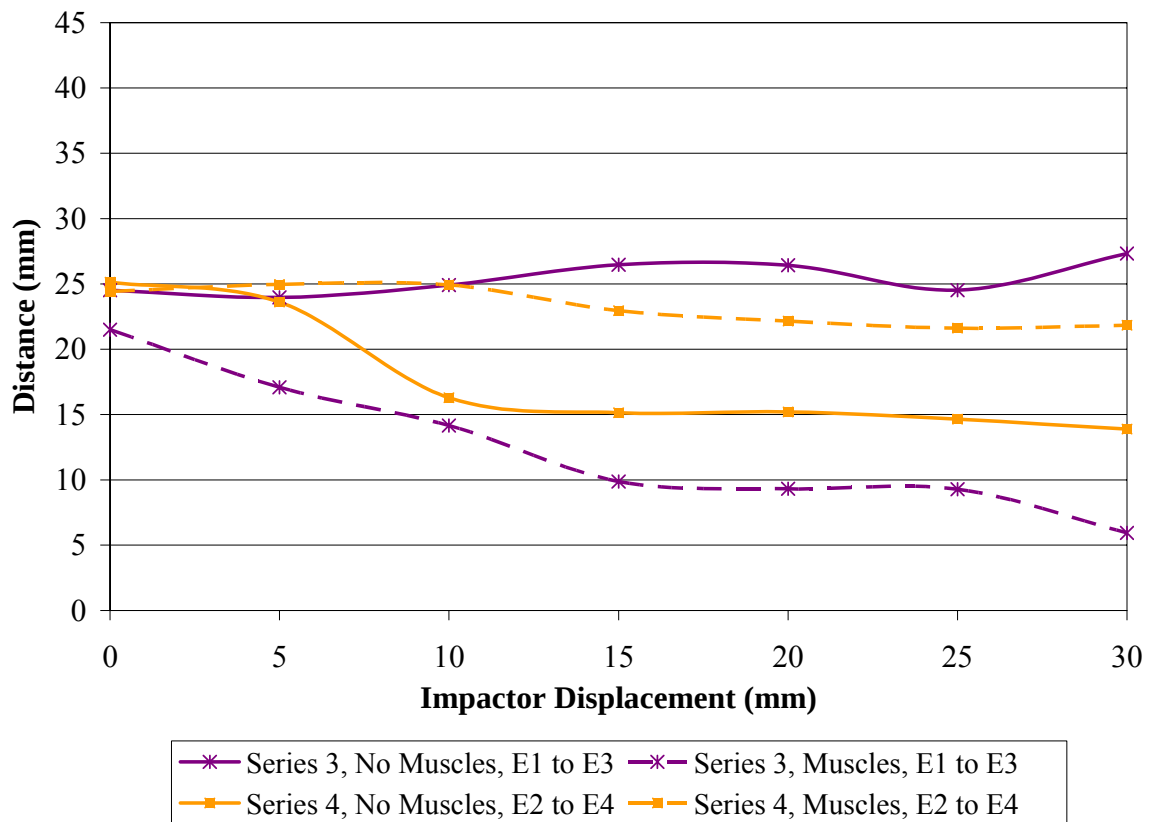


Figure 59. Compression and expansion measurements of the eye in the orbit for the matched pair of series 3 and series 4 (solid line = no muscles, dashed line = muscles).

Table 6. Distance measurements for Series 3, an eye with the extraocular muscles transected, impacted using the flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	7.64	4.50	10.75	11.71	24.52	25.12
5	8.54	2.76	10.25	14.19	23.96	23.61
10	7.88	4.60	13.66	16.71	24.91	16.29
15	6.04	3.93	11.71	21.66	26.46	15.13
20	6.04	4.20	12.69	21.92	26.42	15.20
25	5.71	4.88	12.29	23.33	24.52	14.64
30	5.39	5.19	14.19	23.35	27.33	13.89

Table 7. Distance measurements for Series 4, an eye with the extraocular muscles intact, impacted using the flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	15.14	8.84	4.50	7.58	21.49	24.42
5	17.47	6.85	1.76	8.30	17.09	24.96
10	20.72	6.51	1.54	9.32	14.15	24.93
15	22.76	6.99	2.07	11.87	9.87	22.94
20	24.93	6.34	1.54	13.14	9.32	22.15
25	27.02	9.00	0.98	14.62	9.28	21.61
30	27.48	7.32	1.38	14.62	5.94	21.82



Figure 60. Sagittal CT image of Series 3.1.

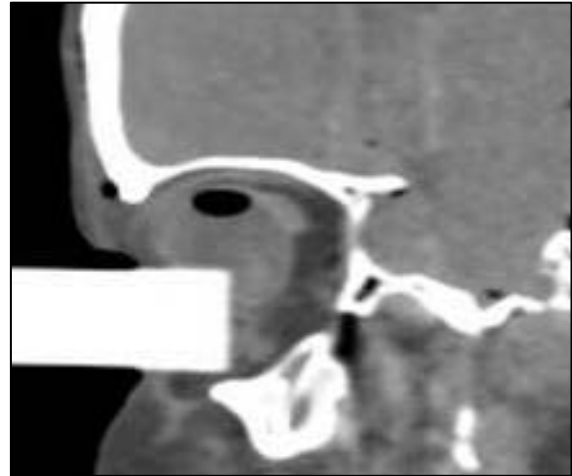


Figure 61. Sagittal CT image of Series 3.2.



Figure 62. Sagittal CT image of Series 3.3.



Figure 63. Sagittal CT image of Series 3.4.

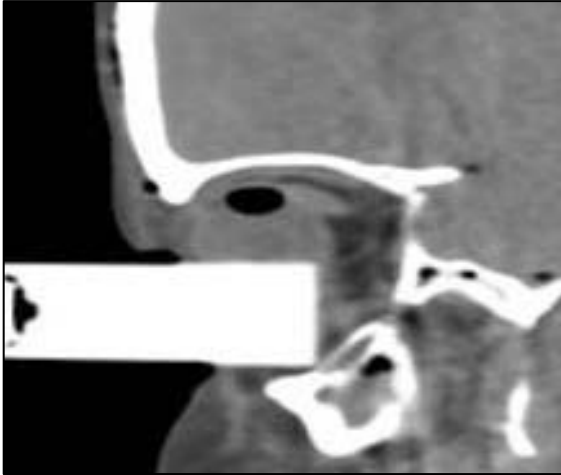


Figure 64. Sagittal CT image of Series 3.5.

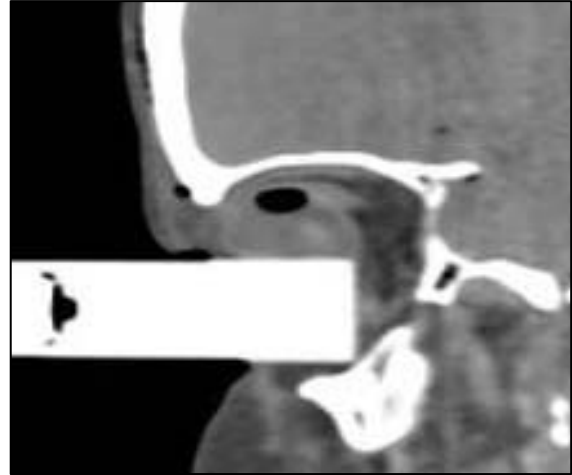


Figure 65. Sagittal CT image of Series 3.6.

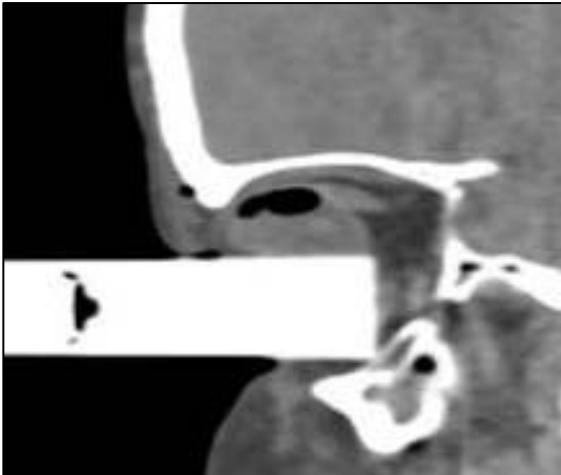


Figure 66. Sagittal CT image of Series 3.7.

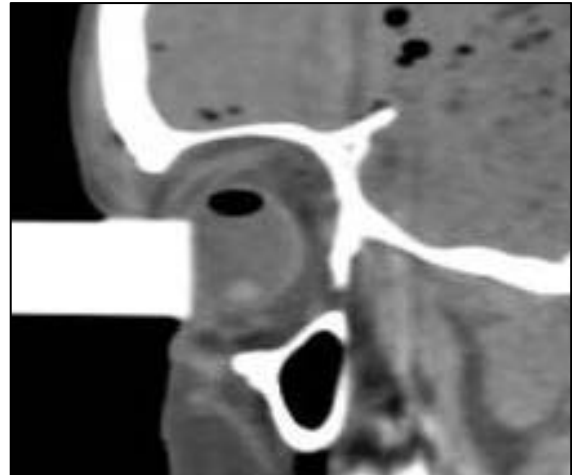


Figure 67. Sagittal CT image of Series 4.1.

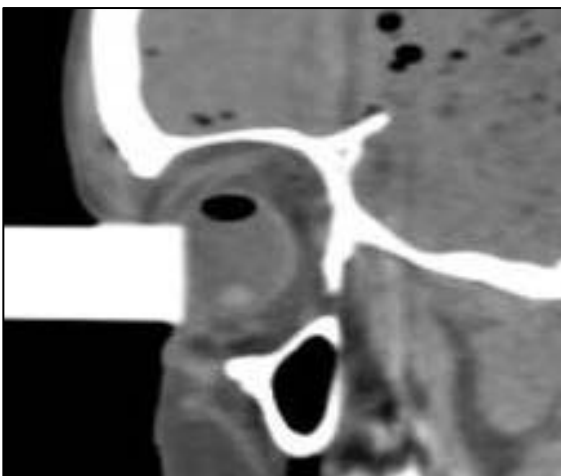


Figure 68. Sagittal CT image of Series 4.2.

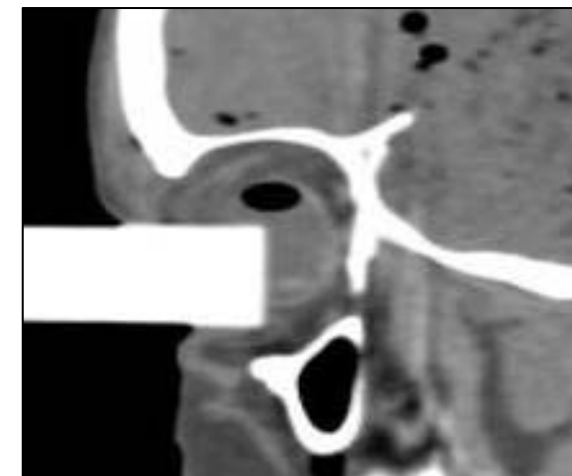


Figure 69. Sagittal CT image of Series 4.3.

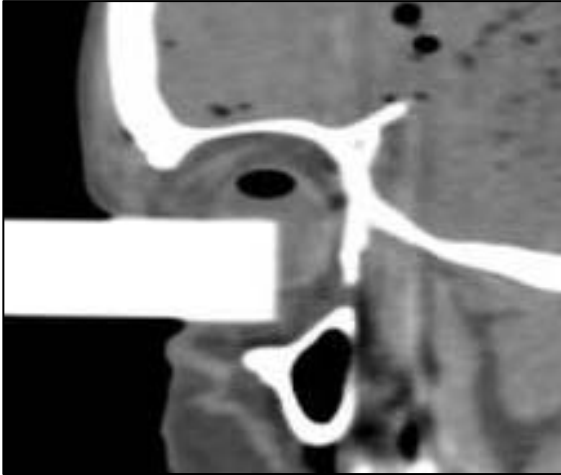


Figure 70. Sagittal CT image of Series 4.4.

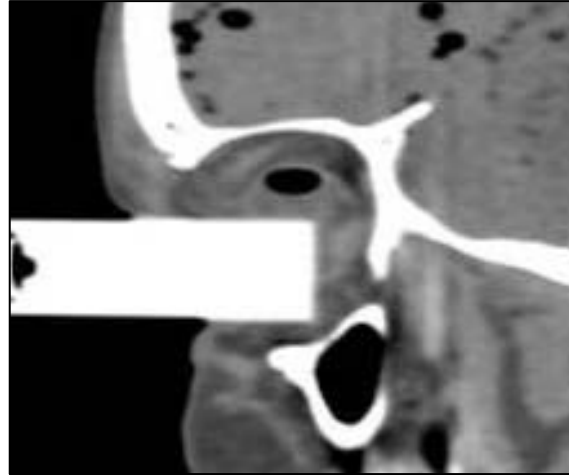


Figure 71. Sagittal CT image of Series 4.5.

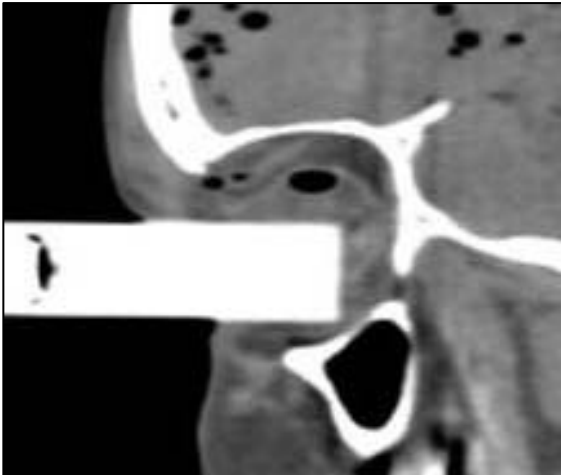


Figure 72. Sagittal CT image of Series 4.6.

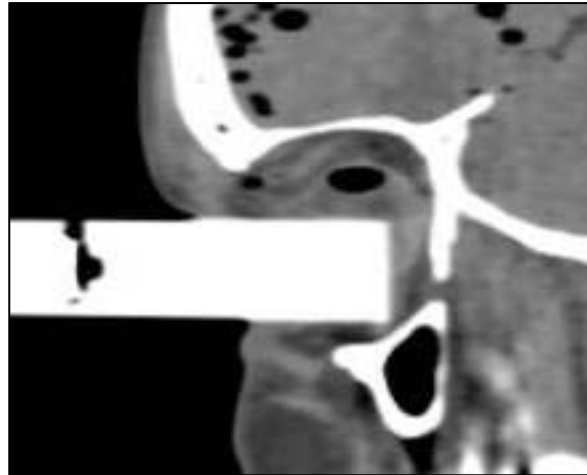


Figure 73. Sagittal CT image of Series 4.7.

During the third and final matched pair test using the large flat cylindrical indenter, consisting of series 5 and 6, the impactor displacement steps were once again matched throughout the test, enabling a point to point comparison to be made between the two conditions. During this matched pair test, a similar amount of posterior displacement along the horizontal axis for each testing condition was observed (Figure 74 - Figure 89, Table 8 - Table 9). Both eyes also experienced amounts of horizontal compression; however it was measured to be greater in the eye with the extraocular muscles intact.

The eye with the extraocular muscles either appears to move lateral to the indenter in the final steps of the impact, or rupture. Following each series of tests, the eyes were examined for signs of globe rupture but nothing to indicate rupture was found on this eye, so the eye must have moved lateral to the indenter. The pressure measurements would have also been useful here, as an immediate drop in pressure could signify a globe rupture, but none were received for this matched pair test.

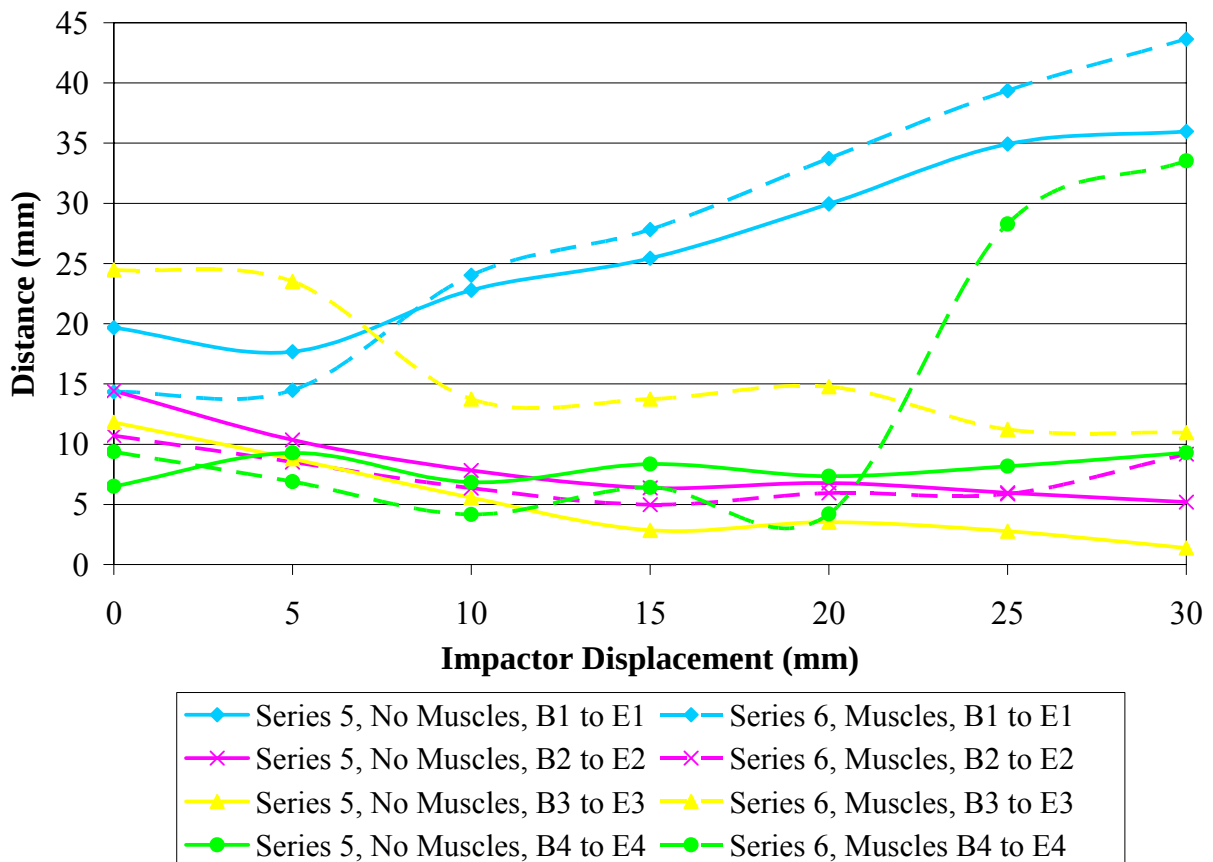


Figure 74. Displacement measurement comparisons of the eye in the orbit for the matched pair of series 5 and series 6 (solid line = no muscles, dashed line = muscles).

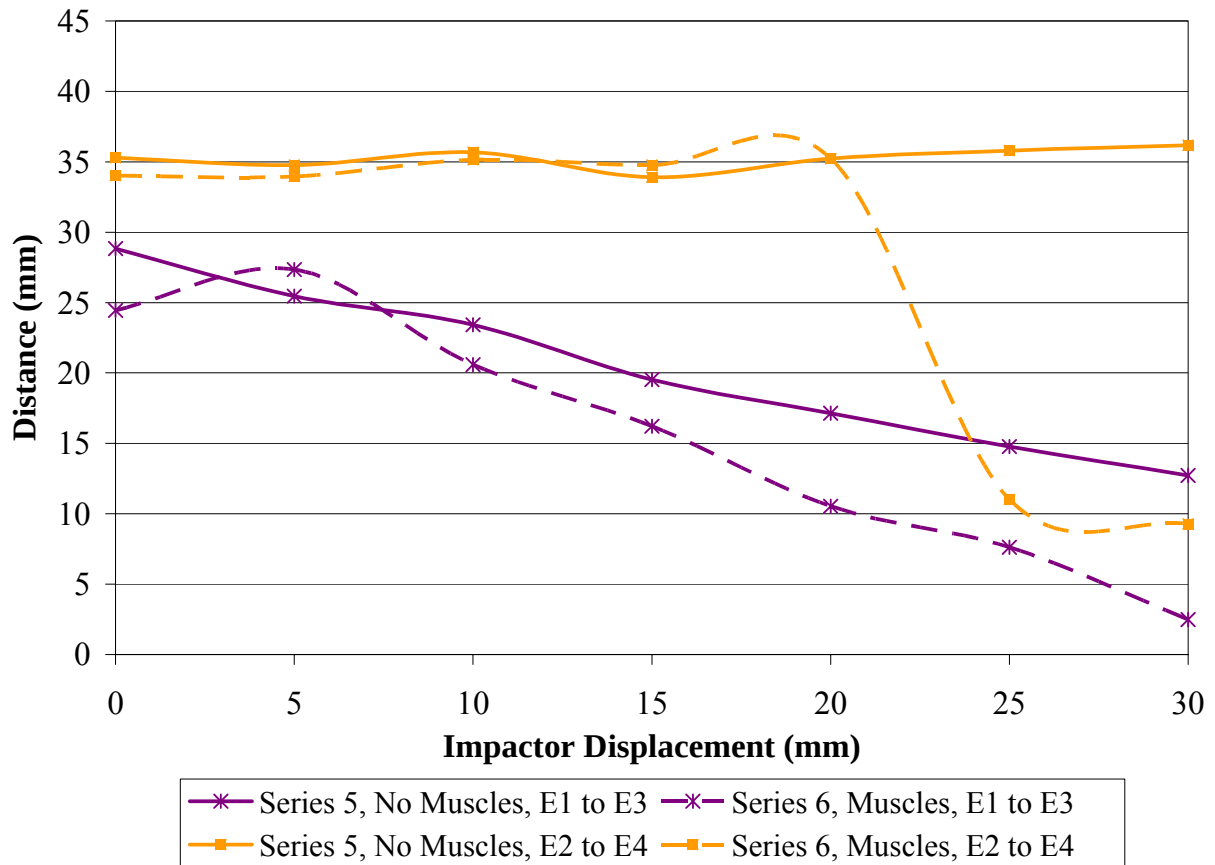


Figure 75. Compression and expansion measurements of the eye in the orbit for the matched pair of series 5 and series 6 (solid line = no muscles, dashed line = muscles).

Table 8. Distance measurements for Series 5, an eye with the extraocular muscles transected, impacted using the flat cylindrical indenter.

Impactor Displacement (mm)	Distance B1 to E1 (mm)	Distance B2 to E2 (mm)	Distance B3 to E3 (mm)	Distance B4 to E4 (mm)	Thickness E1 to E3 (mm)	Thickness E2 to E4 (mm)
0	19.67	14.42	11.80	6.51	28.83	35.30
5	17.68	10.35	8.78	9.27	25.45	34.77
10	22.78	7.82	5.56	6.83	23.42	35.68
15	25.45	6.36	2.85	8.35	19.52	33.90
20	29.96	6.78	3.52	7.34	17.14	35.22
25	34.94	5.96	2.76	8.18	14.77	35.79
30	35.98	5.19	1.38	9.28	12.73	36.16

Table 9. Distance measurements for Series 6, an eye with the extraocular muscles intact, impacted using the flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	14.35	10.70	24.48	9.37	24.44	34.02
5	14.49	8.52	23.51	6.90	27.35	33.96
10	24.03	6.34	13.74	4.17	20.59	35.14
15	27.82	4.98	13.74	6.42	16.22	34.77
20	33.73	5.94	14.77	4.20	10.53	35.22
25	39.36	5.88	11.23	28.29	7.62	11.01
30	43.65	9.17	10.97	33.54	2.49	9.27

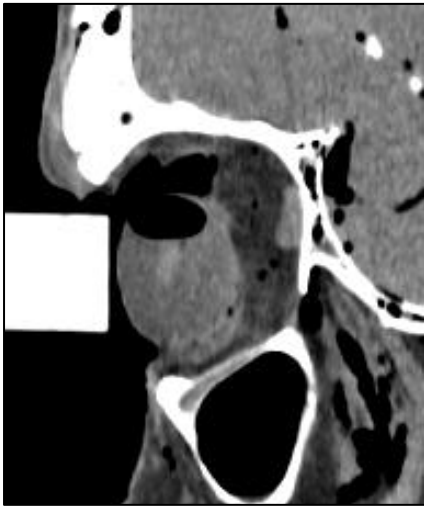


Figure 76. Sagittal CT image of Series 5.1.

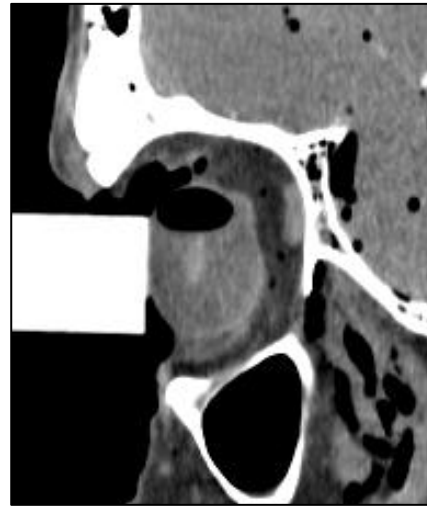


Figure 77. Sagittal CT image of Series 5.2.

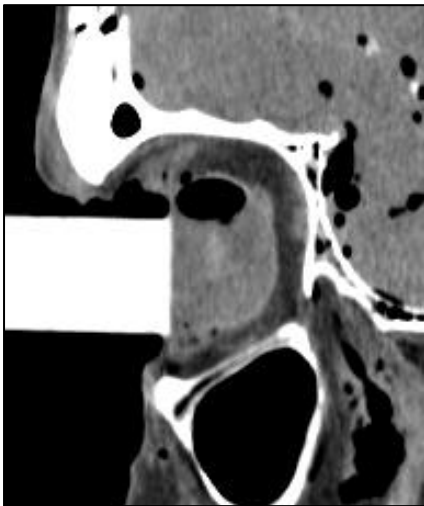


Figure 78. Sagittal CT image of Series 5.3.

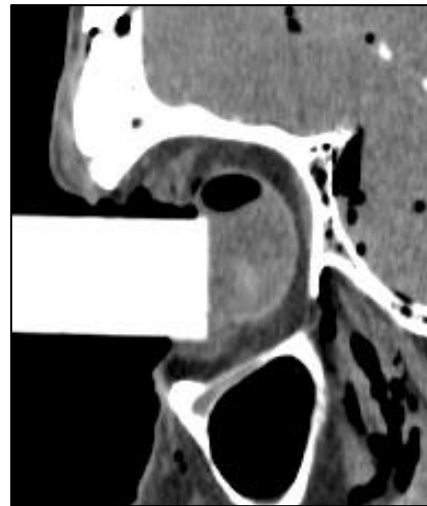


Figure 79. Sagittal CT image of Series 5.4.

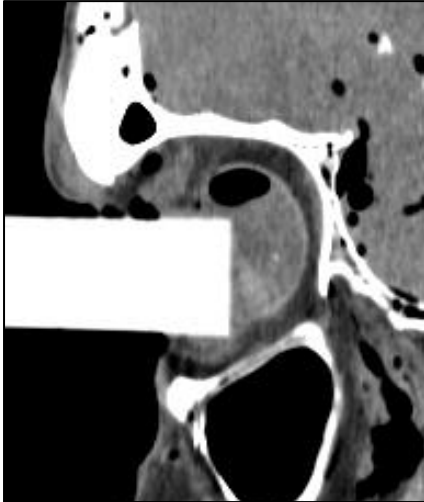


Figure 80. Sagittal CT image of Series 5.5.

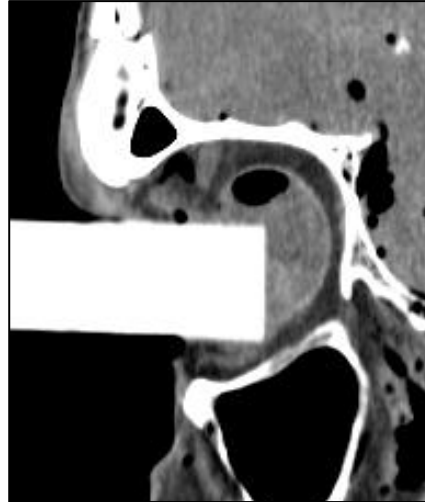


Figure 81. Sagittal CT image of Series 5.6.

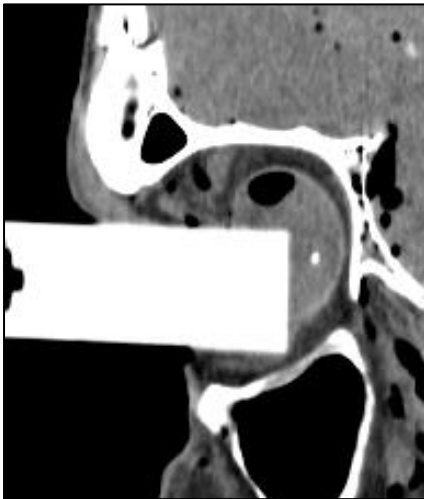


Figure 82. Sagittal CT image of Series 5.7.



Figure 83. Sagittal CT image of Series 6.1.



Figure 84. Sagittal CT image of Series 6.2.

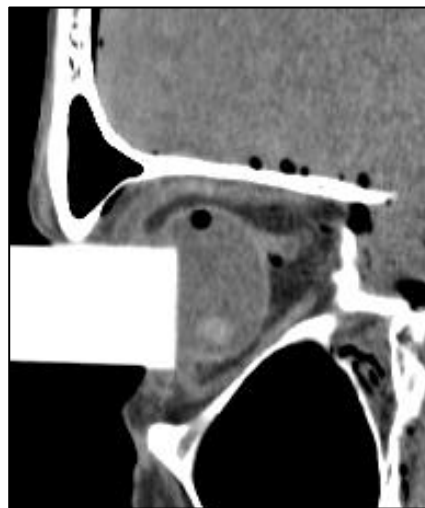


Figure 85. Sagittal CT image of Series 6.3.

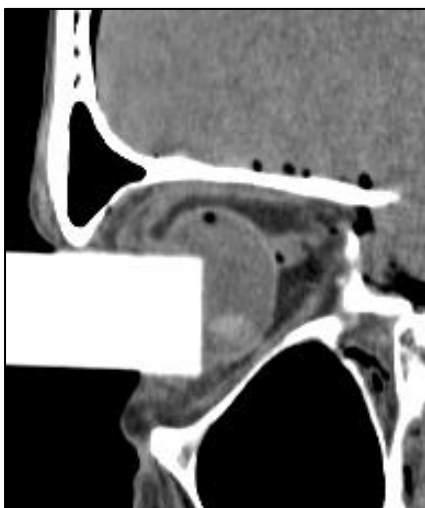


Figure 86. Sagittal CT image of Series 6.4.

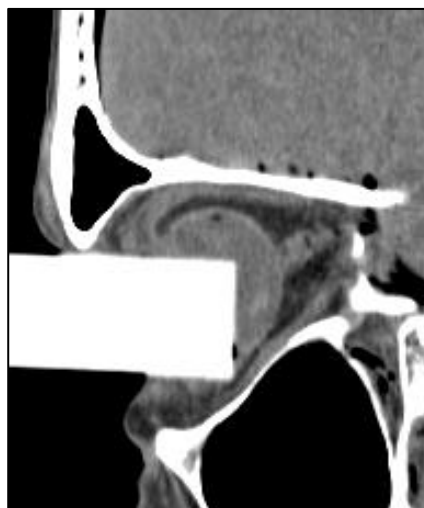


Figure 87. Sagittal CT image of Series 6.5.

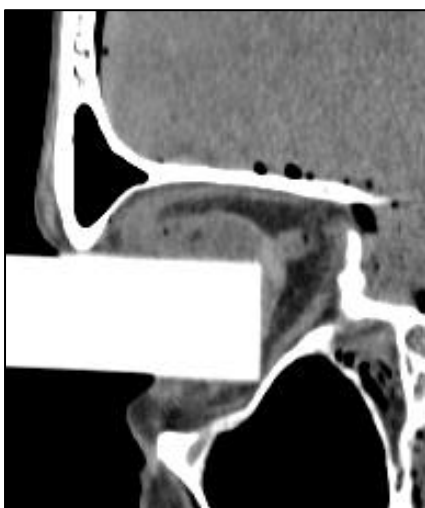


Figure 88. Sagittal CT image of Series 6.6.

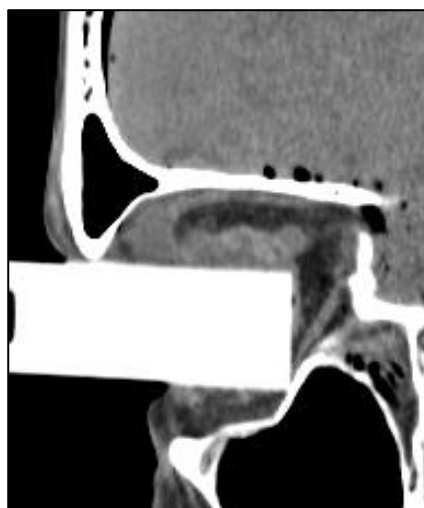


Figure 89. Sagittal CT image of Series 6.7.

2.2 Horizontal Translation of the Eye

In the literature, there have not been any studies of the movement of the eye under quasi-static loading conditions, let alone collected images of the eye in the orbit while it was being impacted. There are a multitude of studies that have impacted the eyes under dynamic conditions, but they were *in vitro* and without the extraocular muscles attached. This section looks at the horizontal translation of the eye under quasi-static loading conditions.

2.2.1 Testing Methodology

The rigid testing device described in section 2.1.1 was also used for this series of tests. The same testing protocol was also followed. The only difference was that this test was conducted on only the right eye that had the extraocular muscles intact and a small flat cylindrical indenter was used. The small cylindrical indenter was 4.5 mm in diameter, and meant to represent a BB. As previously mentioned the eye was indented in 5 mm increments up to a final indentation of 30 mm. A 25 mm step is not included in this test series.

2.2.2 Test Results

Force measurements at each step of the displacement are reported in Figure 90. A large increase in force, 27 N, was observed between the 20 mm and 30 mm displacements of the eye. By looking at the sagittal and transverse CT scans, it can be seen that the eye moved lateral to the indenter in the final displacement steps (Table 10 -

Table 11, Figure 91 - Figure 104). The force measured by the load cell is most likely the contact force and resistance induced on the side of the indenter, rather than the contact force on the initial contact area on the face of the indenter as in the initial displacement steps. The forces measured in this test were almost half of those measured for the eyes with muscles impacted using the large flat cylindrical indenter.

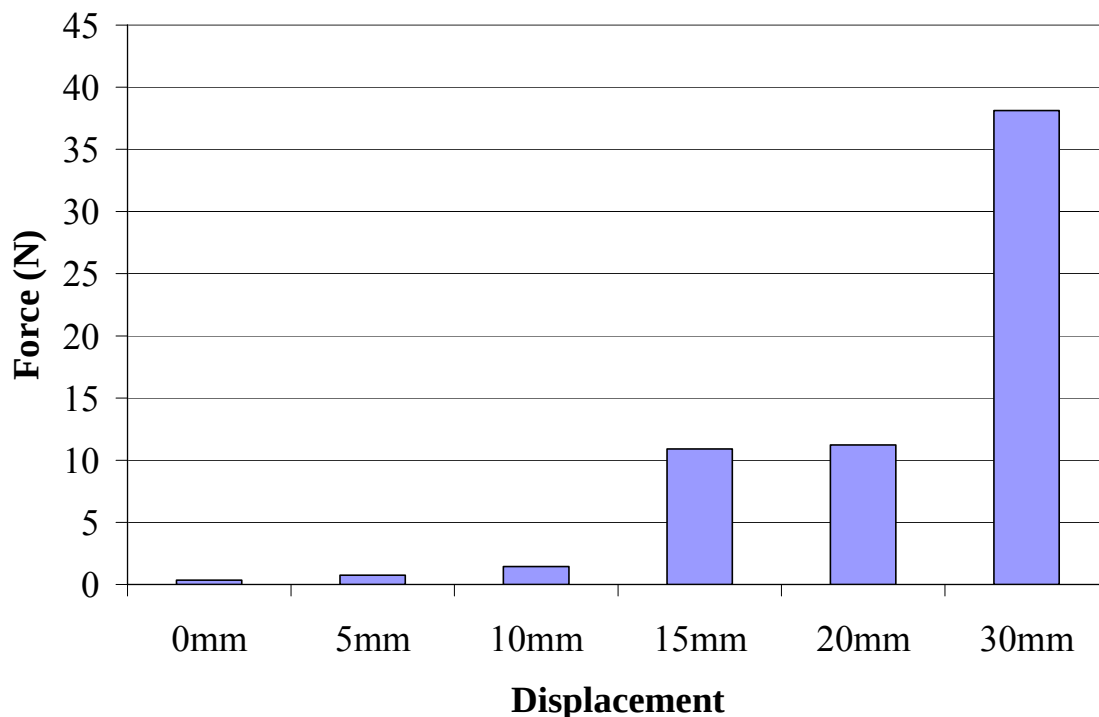


Figure 90. Force measurements from the displacement of a human eye *in situ* with the extraocular muscles intact using a small flat cylindrical indenter.

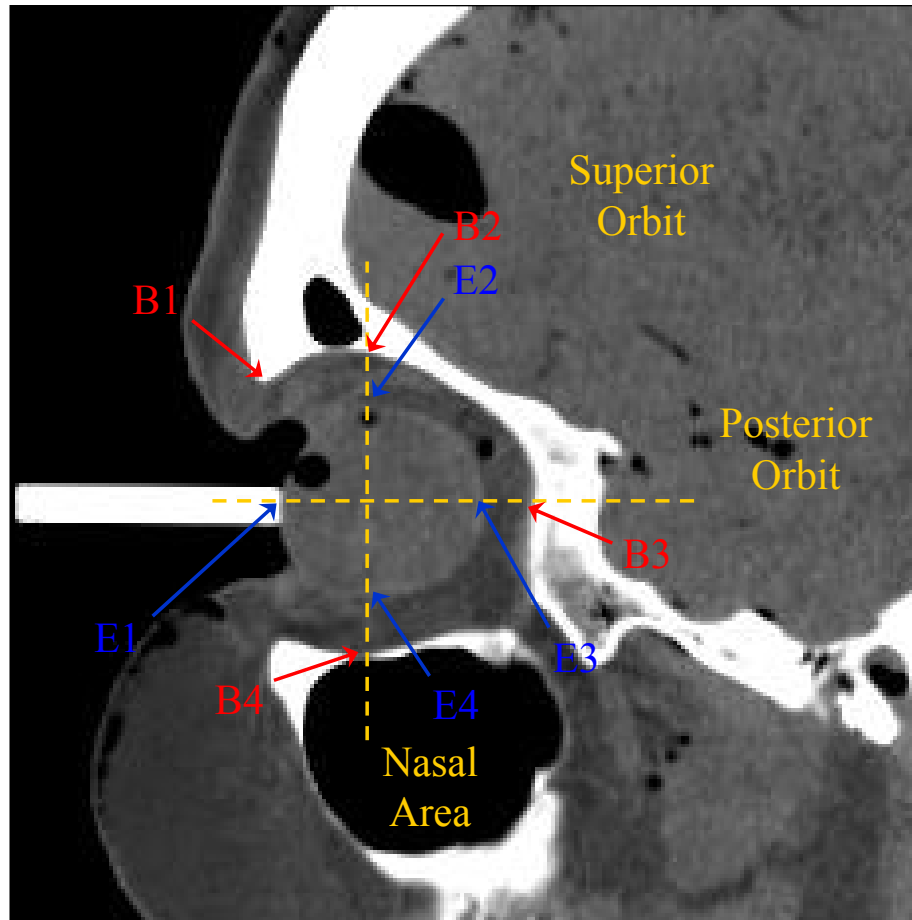


Figure 91. Location of the points recorded during the digital analysis of the CT images in the sagittal plane for the small flat cylindrical indenter investigation.

Table 10. Measurements from the sagittal CT images, for a human eye with the extraocular muscles intact *in situ*, impacted with a small flat cylindrical indenter.

Impactor Displacement	Distance B1 to E1	Distance B2 to E2	Distance B3 to E3	Distance B4 to E4	Thickness E1 to E3	Thickness E2 to E4
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	14.47	11.05	5.37	8.55	24.96	22.56
5	15.69	9.47	5.30	10.38	19.21	24.48
10	18.82	10.53	5.84	7.87	14.89	26.42
15	17.97	12.00	5.01	10.97	18.25	27.36
20	14.57	10.31	2.40	9.66	24.00	26.42
30	14.13	11.60	3.87	11.81	25.44	24.56

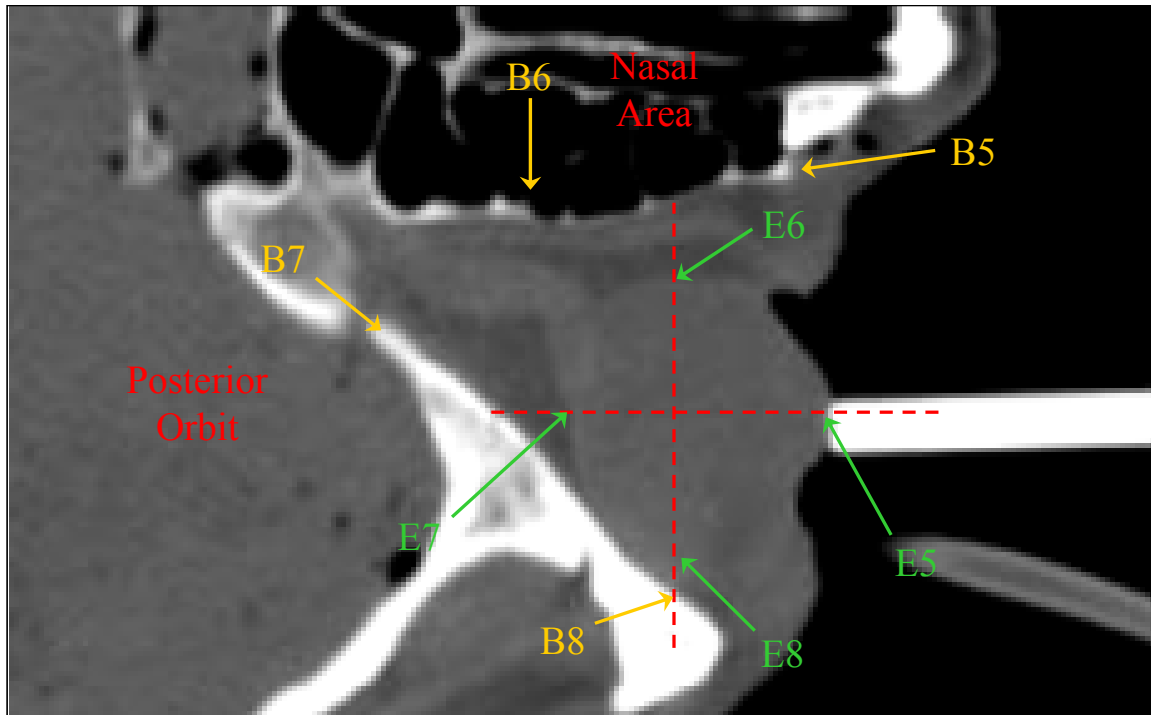


Figure 92. Location of the points recorded during the digital analysis of the CT images in the transverse plane for the small flat cylindrical indenter investigation.

Table 11. Measurements from the transverse CT images, for a human eye with the extraocular muscles intact *in situ*, impacted with a small flat cylindrical indenter.

Impactor Displacement	Distance B5 to E5	Distance B6 to E6	Distance B7 to E7	Distance B8 to E8	Thickness E5 to E7	Thickness E6 to E8
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
0	23.76	15.06	21.26	3.07	25.46	27.94
5	24.04	15.96	22.76	2.58	20.18	29.30
10	25.62	15.25	22.13	2.15	15.07	30.27
15	27.54	15.39	20.84	5.17	11.68	30.96
20	30.54	17.79	22.24	7.59	7.59	29.47
30	22.13	15.87	20.42	17.45	28.32	19.20

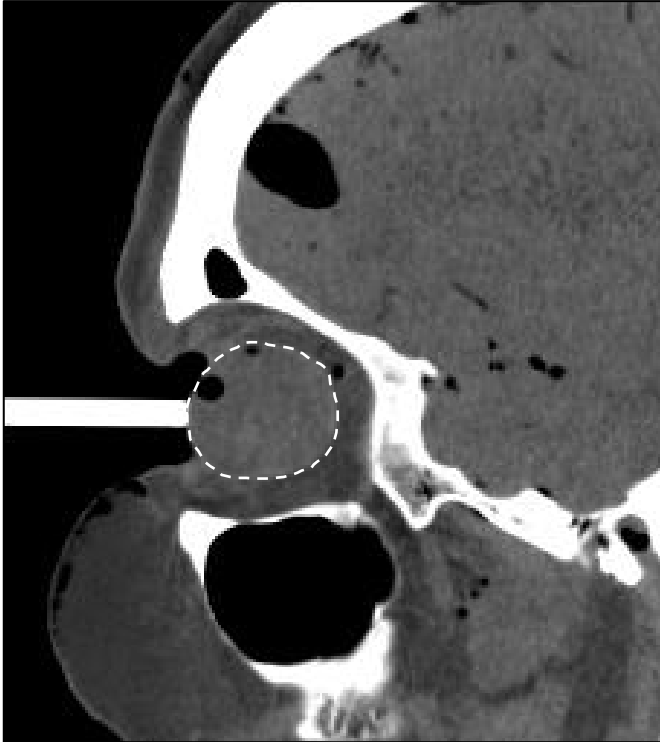


Figure 93. Sagittal CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 0 mm.



Figure 94. Sagittal CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 5 mm.

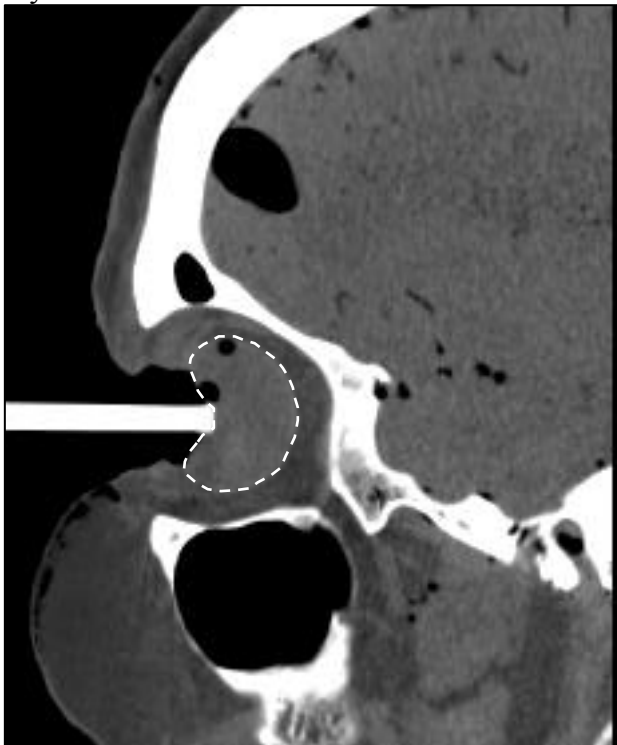


Figure 95. Sagittal CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 10 mm.



Figure 96. Sagittal CT image of the right eye, with the intraocular muscles, using the large flat cylindrical indenter at an indentation of 15 mm.

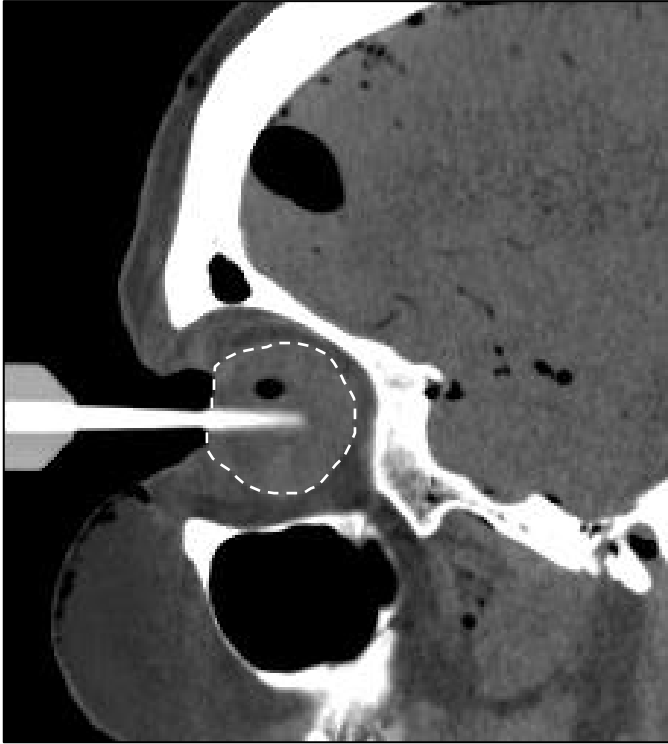


Figure 97. Sagittal CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 20 mm.



Figure 98. Sagittal CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 30 mm.

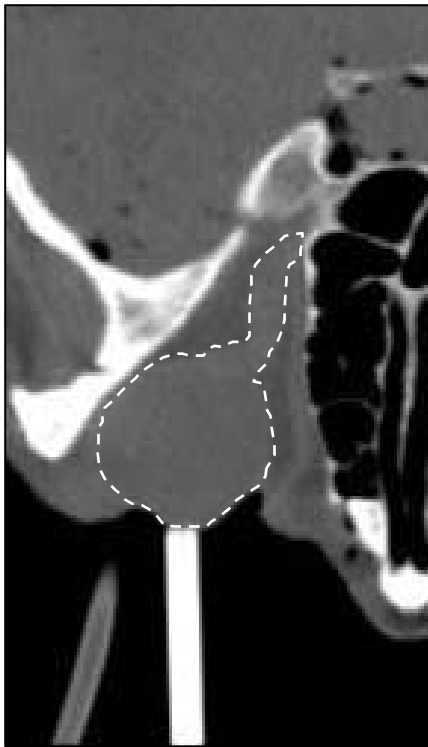


Figure 99. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 0 mm.

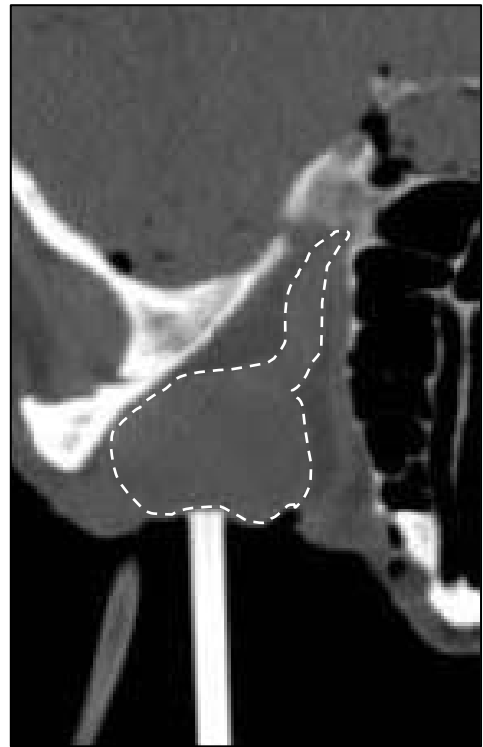


Figure 100. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 5 mm.

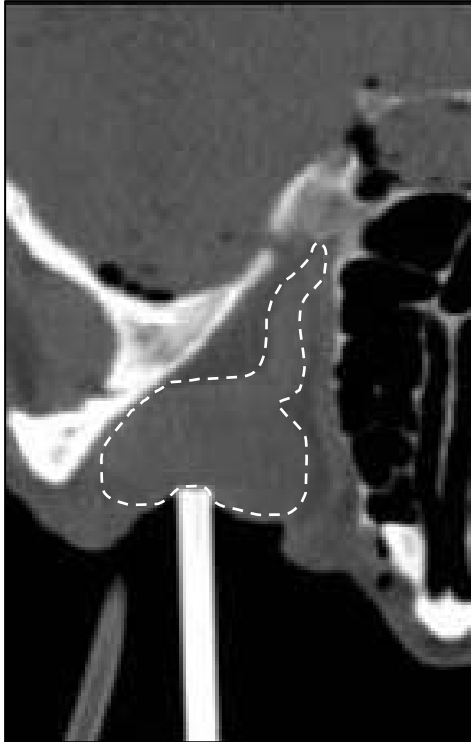


Figure 101. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 10 mm.

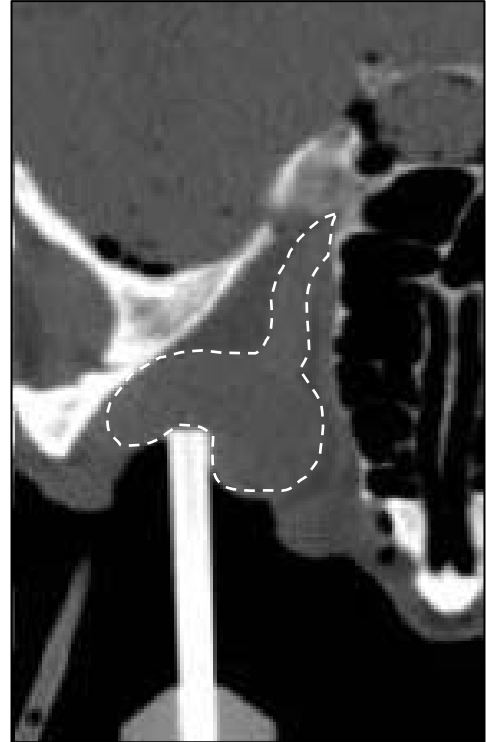


Figure 102. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 15 mm.

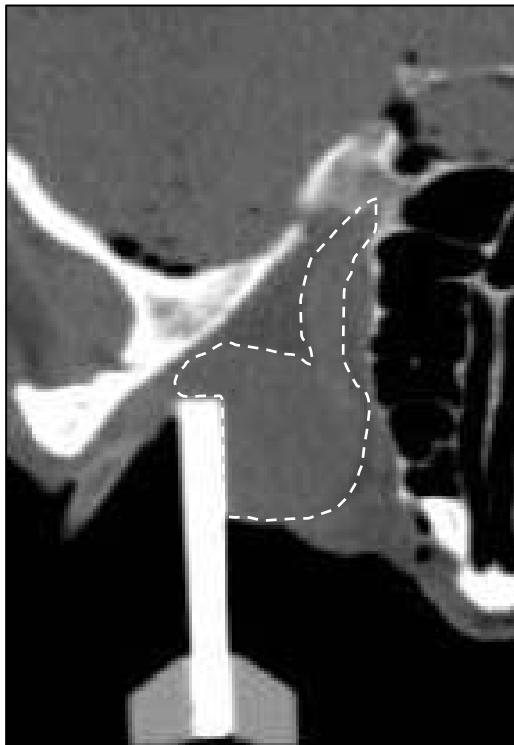


Figure 103. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 20 mm.

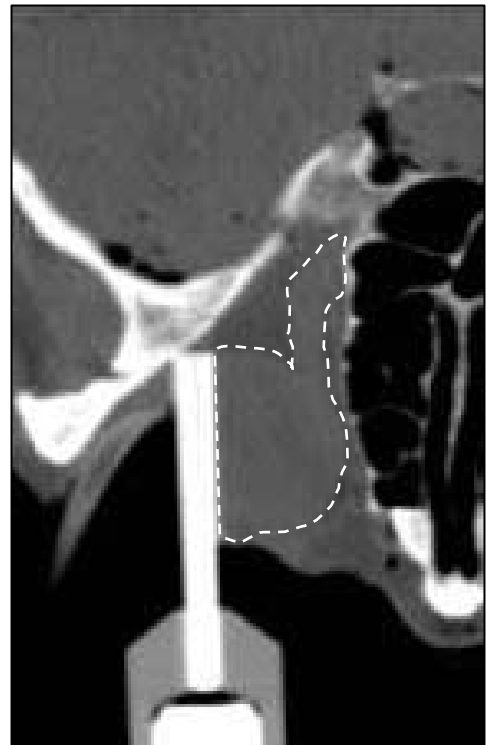


Figure 104. Transverse CT image of the right eye, with the intraocular muscles, using the small flat cylindrical indenter at an indentation of 30 mm.

2.2.3 Discussion

There is a definite difference in the response of the human eye to a blunt impact which is dependent upon the loading rate. During a quasi-static impact the eye appears to move out of the way of the imposing force. However, during a dynamic impact with a contacting area of the same size, the eye does not have time to move. The eye will absorb the force, and depending on the impacting energy, rupture (Stitzel 2002).

2.3 Conclusion

Computed Tomography (CT) quasi-static tests were conducted in order to investigate the effect of the presence of the extraocular muscles on the biomechanical response of the human eye *in situ*. Three matched pairs of human eyes were displaced in 5 mm increments using a large flat cylindrical indenter. The sample set is not large enough to say that these results are significant; however, a trend was seen in that a greater amount of force was created in the eye with the extraocular muscles intact than in the eye with the muscles transected, and a correlation between them was made. The greatest force measured in an eye with the extraocular muscles intact was 92 N, while the greatest force measured in an eye with the extraocular muscles transected was 80 N. An increase in intraocular pressure was also noticed for an eye with the extraocular muscles attached, rising steadily from 2 kPa to a maximum pressure of just over 50 kPa. It was also noted that during a quasi-static impact the eye can move out of the way of the imposing force. Since this test data set is small, analytical calculations need to be conducted.

References

Parver LM (1986) Eye Trauma: The Neglected Disorder. *Archives of Ophthalmology* 104: 1452-1453.

Stitzel JD, Duma SM, Cormier JM, Herring IP (2002) A Nonlinear Finite Element Model of the Eye With Experimental Validation for the Prediction of Globe Rupture. *The Proceedings of the 46th Stapp Car Crash Conference*. Society of Automotive Engineers, Key Biscayne, Florida.

CHAPTER 3

Analytical Effects of the Extraocular Muscles on Scleral Stress

3.1 Introduction

In order to quantify the stresses induced by the extraocular muscles in the scleral wall analytical calculations had to be made. There are physical ways of conducting these measurements which would include tension tests and the use of video point analysis, but these applications risk creating areas of increased stress at the attachment points of the gauges. Also it would be rather difficult to apply these techniques *in situ* and would have to be conducted *in vitro*, which would contradict the point of completing the matched pair tests *in situ*. This chapter attempts to analytically quantify the scleral stresses due to intraocular pressure and the additional stresses due the presence of the extraocular muscles.

3.2 Methods

For the case of a spherical shell under internal pressure, such as the eye, the material is under biaxial tensile stress. Since the ratio of the shell thickness to the shell radius for the eye is very small, the human eye can be considered a thin walled pressure vessel. In the wall of a thin walled pressure vessel, the tensile stresses are equal in all directions. The magnitude of the scleral stress due to internal pressure, σ_p , is therefore given by Laplace's Law (Gere 2001):

$$\sigma_p = \frac{(P_i - P_o)r}{2t} \quad (1)$$

Where P_i is the internal pressure of the sphere, P_o is the outside pressure on the sphere, r is the radius of the sphere, and t is the thickness of the spherical shell wall (Figure 105).

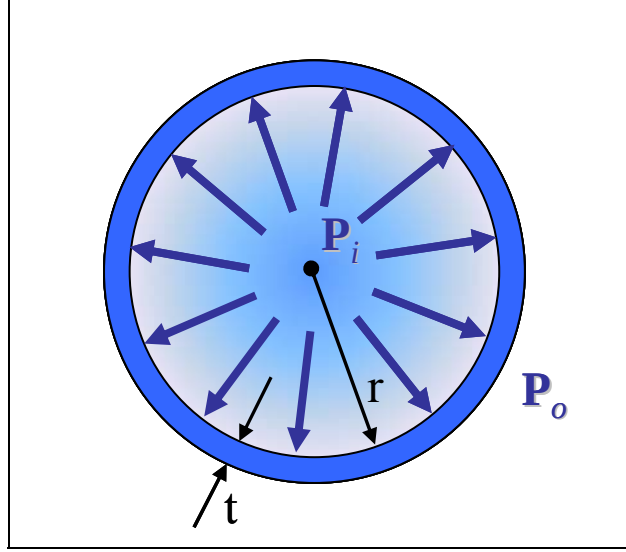


Figure 105. Cross section of a pressure vessel, also the human eye.

The difference in P_i and P_o is known as the transmural pressure drop, or the pressure drop across the shell wall. Since these experiments are all conducted with the external pressure equal to atmospheric pressure, and P_i is measured using gauge pressure, P_o can be removed from the equation, reducing equation 1 to the following equation:

$$\sigma_p = \frac{P_i r}{2t} \quad (2)$$

The radius of the sphere, r , can easily be determined from the results of the CT scans, and the value for P_i is collected during the experiment by the pressure transducer. That leaves the thickness of the spherical shell wall, the sclera, as the only unknown. There are a multitude of values for the sclera thickness of humans and various animals in the literature. It is also known that the thickness of the sclera varies by ocular region and from individual to individual. The ranges of values for human scleral thickness found in the literature are recorded in Table 12.

Table 12. Average human eye site thicknesses were collected from the literature. Standard deviations are shown in parenthesis if they were given. The number of eyes are also shown if they were reported. A dash (-) represents data that was not reported.

		Cornea	Sclera - Equator	Sclera - Posterior	Sclera - Limbus
Study	No. of Eyes	Thickness (mm)	Thickness (mm)	Thickness (mm)	Thickness (mm)
Bron <i>et al</i>	-	0.52 - 0.67	0.6	0.8	0.4 - 0.6
Duma <i>et al</i>	-	0.7	0.45	1.2	0.83
Fine <i>et al</i>	-	0.5 - 1.0	0.4 - 0.5	1	0.6
Hogan <i>et al</i>	-	0.52 - 0.67	0.4 - 0.6	1	0.8
Martola <i>et al</i>	209	0.66 (.076)	-	-	-
Olsen <i>et al</i>	25	-	0.39 (0.17)	.95 (.05)	0.53 (0.14)
Voorhies	2	0.725 (.025)	0.425 (.075)	1.275 (.025)	-
Woo <i>et al</i> (1972a)	-	0.52 - 0.66	0.55	1	0.8
Maximum Value	209	1.0	0.6	1.275	0.83
Minimum Value	2	0.5	0.39	0.8	0.4

In order to gain a better grasp on the scleral thickness value, an experimental study was conducted. A total of 25 human eyes procured from the Old Dominion Eye Foundation (Richmond, VA) were measured for scleral thickness. The eyes were inflated to physiological conditions using saline and were then fixated by using Bouin's Fixative. Bouin's Fixative was chosen for its ability to preserve tissue, its compatibility with trichrome stains, and because it is routinely used to preserve whole eyes (Latendresse

2002). Bouin's Fixative is composed of parts buffered formaldehyde, acetic acid, and picric acid. The use of formaldehyde alone, or as formalin when it is combined with methyl alcohol, as a fixative is known to cause tissue shrinkage, mostly due to the fact that formaldehyde fixates tissue through dehydration (Dapson 1993, Dobrin 1996, Friedman 1992, Latendresse 2002, Noguchi 1997, Quester 1997, Werner 2000). A decrease in the volume of whole human and rabbit eyes that were fixated in formaldehyde have been documented, although no specific percentage of decrease was reported (Margo 1995). Bouin's Fixative also contains acetic acid which causes tissues to swell during preservation. The swelling effects of acetic acid counteract the shrinkage effects of formaldehyde, so tissue preserved using Bouin's Fixative should be very close to the physiologic dimensions (Latendresse 2002).

Once fixation was complete, the eyes were cut in half sagittally using a tissue blade. Each specimen was then encased in a paraffin mold, and histological slides were prepared using Hematoxylin and Eosin stain (H & E) for each specimen. The slides were then placed under a microscope and photographs were taken of the sclera at five regions of interest: the cornea, the superior equator, the posterior equator, near the optic nerve, and at the intersection with the limbus. Using UTHSCSA Image Tool for Windows Version 1.28 (Don Wilcox *et al.*, The University of Texas Health Sciences Center in San Antonio), the scleral thicknesses were measured across each of the five regions. From equation 2, it can be seen that scleral stress is inversely proportional to the scleral thickness. The largest possible scleral stress will occur where the sclera is the thinnest,

and the smallest value would be used to calculate the scleral wall stresses due to intraocular pressure.

In addition to the biaxial stresses in the sclera caused by the intraocular pressure, there are also stresses induced upon the sclera at the attachment points of the extraocular muscles (Figure 106). During posterior translation of the eye, as in the impact tests conducted in Chapter 2, the only muscles in tension are the superior oblique and the inferior oblique muscles (Figure 107). It can then be assumed that only these muscles would contribute to any additional scleral stresses, and the other four extraocular muscles are under compression.

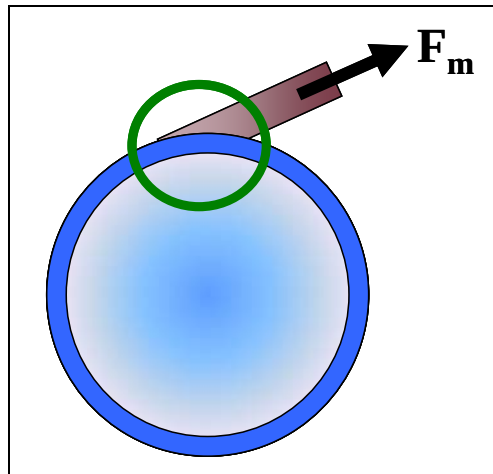


Figure 106. Cross section of the human eye highlighting the attachment point of an oblique extraocular muscle.

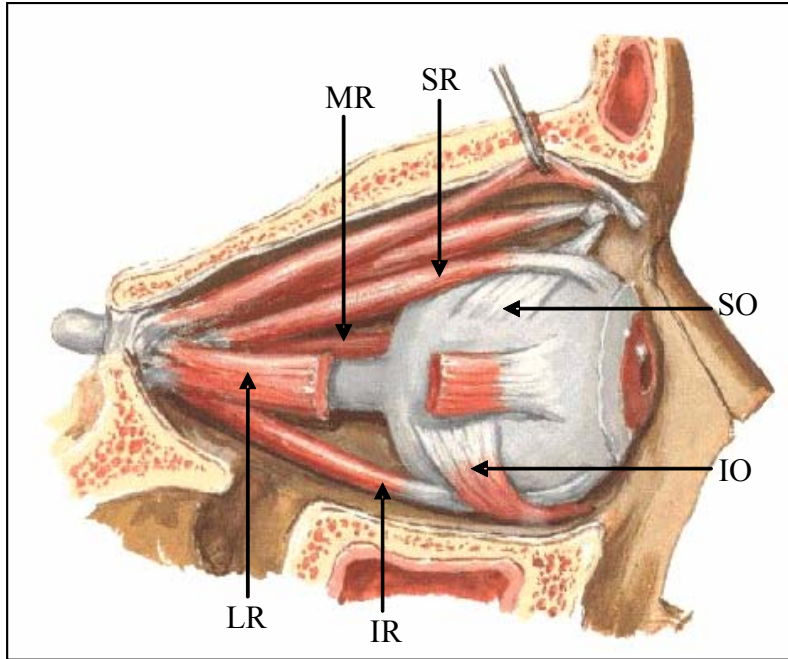


Figure 107. The extraocular muscles and their attachment points shown on the right eye: (SR) superior rectus, (IR) inferior rectus, (MR) medial rectus, (LR) lateral rectus, (SO) superior oblique, and (IO) inferior oblique.

The stresses imposed by the superior oblique and the inferior oblique extraocular muscles can be approximated by assuming that the forces are exerted perpendicular to the surface, using equation 3 (Shigley 2001):

$$\sigma_M = \frac{F_M}{A} \quad (3)$$

Where F_M is the force exerted by the muscle and A is the area of attachment of the muscle. If a small cross sectional area of the sclera is taken at the attachment point of an extraocular muscle, to the sclera it appears as if the force is being applied radially outward from the center of the eye (Figure 108). This is an exaggerated assumption, but it allows the calculated stresses to be combined in the following manner for a section of sclera at the posterior of the globe halfway in between the attachment points of each of the oblique muscles:

$$\sigma_T = \sigma_P + \sigma_{MS} + \sigma_{MI} \quad (4)$$

Where σ_T is the total stress experienced by the sclera, σ_P is the scleral stress due to internal pressure, σ_{MS} is the stress imposed by the superior oblique extraocular muscle, and σ_{MI} is the stress created by the inferior oblique extraocular muscle.

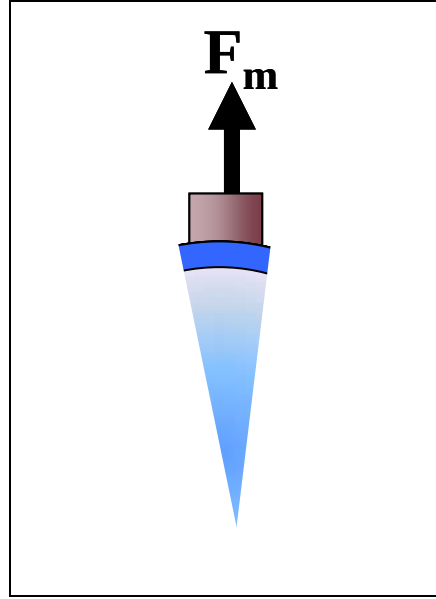


Figure 108. Small cross section of the sclera taken at the attachment point of an extraocular muscle.

Both the superior oblique and the inferior oblique muscles make their attachment to the eye near the equator, so this suggests that average thickness of the sclera at the equator should be used in the stress calculations. The muscles are actually attached to the eye with short lengths of tendon, but for these calculations it will be assumed that the thickness of the tendon at its point of attachment is the same as the width of the muscle body and any differences in physiological properties will be ignored.

The maximum force that any muscle can generate is proportional to its physiological cross sectional area. This relationship can be expressed as:

$$F_{\max} = PCA \times K \quad (5)$$

Where $F_{\max}$ is the maximum force that a muscle can generate in Newtons, PCA is the physiological cross sectional area of the muscle in square centimeters, and K is the muscle stiffness or force per unit area that the muscle can generate in Newtons per square centimeter (McGinnis 1999, Sellers 2005). K is a constant which ranges from 10 N/cm² to 100 N/cm² and is similar to a spring constant (Gray 1995, McGinnis 1999, Sellers 2005). The angle of pennation, or orientation of the muscle fibers, must be taken into account when calculating the physiological cross sectional area. Since the extraocular muscles have a fusiform or parallel muscle fiber arrangement, all of the muscle fibers should pass through any cross section taken perpendicular along the length of the muscle. Therefore, the width of each of the extraocular muscles can be used to calculate its physiological cross sectional area. The physiological cross sectional area can then be multiplied by the constant K to obtain the maximum tensile force that each of the muscles can generate. A K of 30 N/cm² will be used for each of the extraocular muscles since this value is reported as the average for human muscle by McGinnis and it falls well within the range given by Gray and Sellers.

3.3 Results

The results of the human sclera thickness measurements for the cornea, the superior equator, the posterior equator, near the optic nerve, and at the intersection with the limbus are reported in Table 13. The photographs of these locations of interest can be seen in Appendix B. The thickness values for the sclera and cornea were similar to the values reported in the literature (Table 12). The average thickness of the cornea was found to be

0.74696 ± 0.13762 mm, falling right in between the maximum and minimum thickness values reported in the literature (1 mm and 0.5 mm). The average sclera thicknesses at the superior and inferior locations of the equator were 0.62005 ± 0.16950 mm and 0.65711 ± 0.12561 mm respectively. These measure values were about 10% higher than those reported in the literature. The average sclera thickness at the posterior of the globe, near the insertion of the optic nerve, was 0.91737 ± 0.19845 mm, once again falling right in between the maximum and minimum thickness values reported in the literature (1.275 mm and 0.8 mm). The average measured sclera thickness at the attachment of the limbus was 0.70868 ± 0.09841 mm, which is also between the maximum and minimum reported values in the literature. As the sclera was the thinnest at the equator location this value would be used in all of the stress calculations. This also matches with the attachment locations of the superior oblique and inferior oblique extraocular muscles.

Table 14 reports the values of width and length values found in the literature for each of the extraocular muscles, along with the calculated physiological cross sectional area and estimated maximum tensile force that each muscle can generate. The maximum values for $F_{\max}$ and the minimum values for PCA for each muscle were then used to estimate the maximum scleral stress created by the superior oblique the inferior oblique extraocular muscles by using equation 3. If the same PCA was used for both the maximum force calculation and the stress calculation, the value of K used would also equal the calculated stress.

Table 13. Site thicknesses measured from histological sagittal cross sections procured from human eyes.

	Cornea	Sclera - Equator Site 1	Sclera - Equator Site 2	Sclera - Posterior Optic Nerve	Sclera - Limbus
Sample	Thickness (mm)	Thickness (mm)	Thickness (mm)	Thickness (mm)	Thickness (mm)
H001	0.94411	0.71035	0.85462	1.07310	0.73846
H002	0.90201	0.81442	0.73670	1.03095	0.67464
H003	0.83398	1.06096	0.87258	1.01673	0.89245
H004	0.97403	0.98353	0.86220	0.74267	0.86969
H005	0.95293	0.75115	0.58617	1.31945	0.78100
H006	0.61339	0.52173	0.74313	0.72607	0.59716
H007	0.61868	0.64740	0.73277	0.84100	0.64093
H008	0.89958	0.66763	0.53526	1.18578	0.75875
H009	0.76335	0.38430	0.60296	1.11526	0.73952
H010	0.82765	0.61186	0.68269	0.76031	0.84773
H011	0.62755	0.58634	0.57674	1.13101	0.59307
H012	0.85733	0.78623	0.72924	1.22640	0.71519
H013	0.77985	0.60503	0.64640	0.71727	0.67147
H014	0.66216	0.57377	0.38514	0.62887	0.64289
H015	0.58990	0.43085	0.60112	0.65911	0.62573
H016	0.66813	0.38621	0.60921	0.82249	0.58825
H017	0.66938	0.36010	0.52072	0.91599	0.63122
H018	0.56744	0.55104	0.52398	0.63700	0.55607
H019	0.73560	0.48879	0.60965	0.93912	0.84884
H020	0.95854	0.67442	0.82859	1.16210	0.81806
H021	0.55580	0.54329	0.61748	0.82808	0.71543
H022	0.76592	0.57028	0.49232	0.87962	0.76611
H023	0.67614	0.65432	0.62178	0.77637	0.74876
H024	0.62949	0.60506	0.66094	0.99653	0.57216
H025	0.60123	0.53229	0.79530	0.80303	0.68334
Average	0.74696	0.62005	0.65711	0.91737	0.70868
Standard Deviation	0.13762	0.16950	0.12561	0.19845	0.09841

Table 14. Reported geometric characteristics of the extraocular muscles, and calculated PCA and estimated F_{max} using $K = 30 \text{ N/cm}^2$. A dash (-) indicates information not reported or able to be calculated.

Muscle	Width	Length	PCA	PCA	F_{max}
Study	(mm)	(mm)	(mm²)	(cm²)	(N)
Superior Rectus (SR)					
<i>Bron</i>	9	42.00	63.59	0.6359	19.09
<i>Miller et al</i>	-	33.90	-	-	-
<i>Robinson</i>	-	41.96	-	-	-
<i>Tian et al</i>	5.1	-	20.43	0.2043	6.129
<i>Volkman</i>	3.8	41.80	11.34	0.1134	3.402
Inferior Rectus (IR)					
<i>Bron</i>	9	40.00	63.59	0.6359	19.09
<i>Miller et al</i>	-	35.00	-	-	-
<i>Robinson</i>	-	42.49	-	-	-
<i>Tian et al</i>	5.1	-	20.43	0.2043	6.129
<i>Volkman</i>	4.5	40.00	15.90	0.1590	4.771
Medial Rectus (MR)					
<i>Bron</i>	9	40.00	63.59	0.6359	19.09
<i>Miller et al</i>	-	31.60	-	-	-
<i>Robinson</i>	-	38.51	-	-	-
<i>Tian et al</i>	4	-	12.57	0.1257	3.771
<i>Volkman</i>	4.7	40.80	17.35	0.1735	5.205
Lateral Rectus (LR)					
<i>Bron</i>	9	48.00	63.59	0.6359	19.09
<i>Miller et al</i>	-	36.20	-	-	-
<i>Robinson</i>	-	49.11	-	-	-
<i>Tian et al</i>	3.9	-	11.95	0.1195	3.585
<i>Volkman</i>	4.6	40.60	16.62	0.1662	4.986
Superior Oblique (SO)					
<i>Bron</i>	-	-	-	-	-
<i>Miller et al</i>	-	32.00	-	-	-
<i>Robinson</i>	-	22.28	-	-	-
<i>Tian et al</i>	4.2	-	13.85	0.1385	4.155
<i>Volkman</i>	3.3	32.20	8.553	0.0855	2.566
Inferior Oblique (IO)					
<i>Bron</i>	-	-	-	-	-
<i>Miller et al</i>	-	29.10	-	-	-
<i>Robinson</i>	-	35.35	-	-	-
<i>Tian et al</i>	5.2	-	21.24	0.2124	6.372
<i>Volkman</i>	3.2	34.50	8.042	0.0804	2.413

The maximum stress created by the superior oblique muscle, σ_{MS} , was calculated to be 48.6 kPa while the maximum stress calculated for the inferior oblique extraocular muscle, σ_{MI} , was calculated to be 79.3 kPa. The stresses created in the scleral shell as a result of the intraocular pressure were calculated at each pressure step as reported in the CT tests (Figure 109). A value of 125 mm was used for the radius, as this was the average measured from the CT images, and an equatorial scleral thickness value of 0.6571 mm was used. The maximum scleral stress due to intraocular pressure, σ_p , was calculated to be 4,784 kPa at an intraocular pressure of approximately 50 kPa. The maximum total stress experience by the sclera is the sum of the aforementioned stress values, which is equal to 4,912 kPa. The combined stress effects from the extraocular muscles account for approximately 3% of the total stress at the maximum deflection of 30 mm.

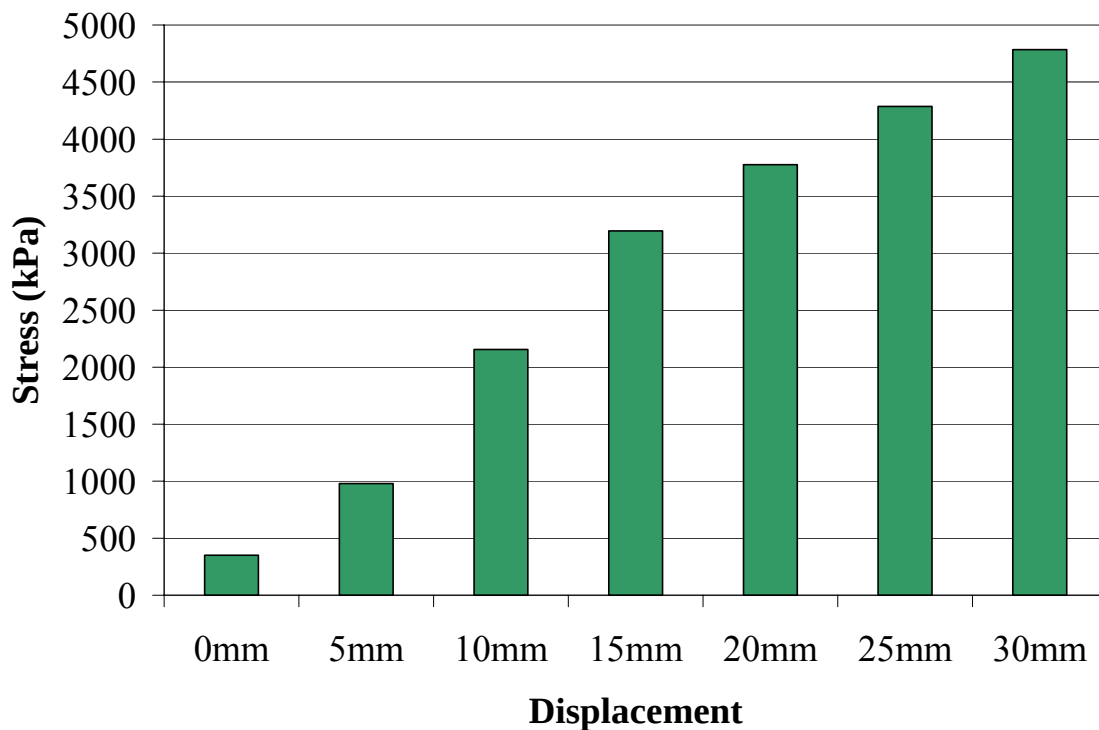


Figure 109. Calculated stresses induced in the scleral wall due to intraocular pressure for each step of the indentation for an eye with the extraocular muscles attached.

In comparison to the stresses created during globe rupture, the stresses created by the extraocular muscles are an even smaller percentage. The human eye has been reported to rupture quasi-statically at an intraocular pressure of 360 kPa and dynamically at a pressure of 910 kPa (Voorhies 2003). This results in scleral wall stress values of 34,241 kPa and 86,555 kPa, for the quasi-static and dynamic conditions respectively. When the stress effects from the extraocular muscles are included, these values increase to 34,369 kPa and 86,683 kPa. The stresses from the extraocular muscles account for only 0.37% and 0.15% of the total stress during quasi-static and dynamic globe rupture.

3.4 Discussion

All skeletal muscle, including the extraocular muscles, is similar in nature. Due to the physical composition of skeletal muscle, a muscle's ability to create force declines at both shortened and elongated lengths. This phenomenon is referred to as both a force – length relationship and a length – tension relationship, both meaning that the amount of force that a muscle can produce is directly related to its length (Hamill 1995, McGinnis 1999). To explain this, one must understand the anatomy of muscle (Figure 110).

Tendons attach skeletal muscle to bone. Generated muscle force is also transferred to the bone by the tendon. Each muscle contains muscle fibers that are organized in muscle bundles called fascicles. Each individual muscle fiber contains myofibril strands which run the length of the fiber.

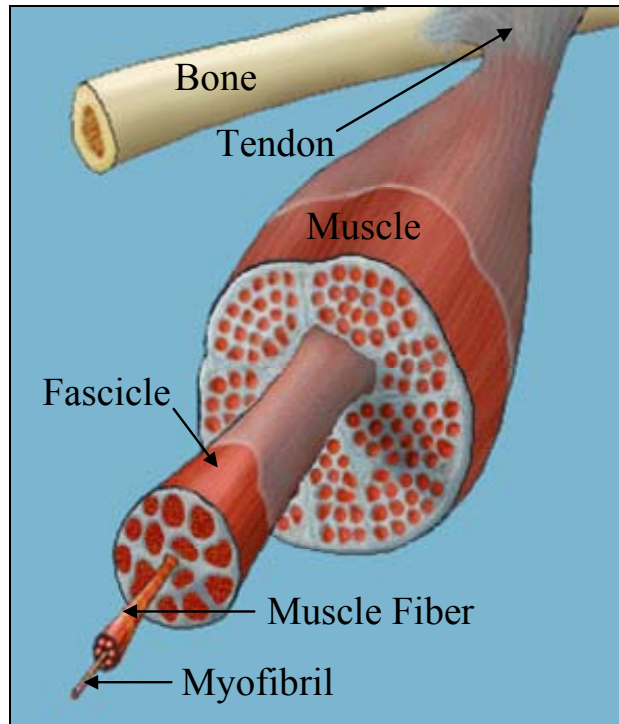


Figure 110. The anatomy of skeletal muscle.

Each myofibril contains many sarcomeres connected in series down the length of the myofibril. The sarcomeres are the actual contractile units in muscle. Muscle shortening, or contraction, occurs in the sarcomere as the myofilaments, actin and myosin, in the sarcomere slide towards each other (Figure 111). It is theorized that myosin cross bridges are formed with the actin which contract the length of the sarcomere. Each sarcomere is divided by a Z line. The change in length between the two Z lines of a sarcomere can be equated to contractile force produced, or active force. The greatest active force is created at resting length, ℓ_o , the muscle's natural length in the body (Figure 111a). Here, the overlap between the actin and myosin filaments is ideal. The sarcomere can shorten further but because the opposing actin filaments begin to overlap the myosin cross bridges cannot attach, and the generated force decreases (Figure 111b). No force is created once the two actin filaments become wedged against the opposing Z line, this

happens at approximately 60% of its resting length (McGinnis 1999). When the sarcomere is lengthened beyond its resting length, fewer myosin bridges can be created, and less force is developed (Figure 111c). Force can still be generated until myosin bridges can no longer be formed, this occurs at approximately 160% of the muscle's resting length.

In addition to the force generated by the muscle, there is also a passive force present. Passive force is created when the length of muscle is stretched beyond its resting length. This type of force can also be generated beyond 160% of the muscle's resting length, where active forces cease to be generated. Thus, the maximum force is reached when the muscle is stretched to its maximum length. This length is dependent on what is creating the displacement, as the muscle cannot stretch to that length on its own. These forces can be added together, and the resulting force – length relationship can be seen in Figure 112. In New Zealand white rabbits, the passive failure force for live skeletal muscle is 46 N, but this decreases to approximately 24 N in post-mortem muscle that has been frozen (Van Ee 2000). Van Ee also reported that the modulus for muscle tissue 72 hours post-mortem was 18.3 kPa. Using this information, and assuming that rabbit skeletal muscle is similar to human extraocular muscle, the passive force can be added to the estimated active force to estimate the actual force generated by the extraocular muscles.

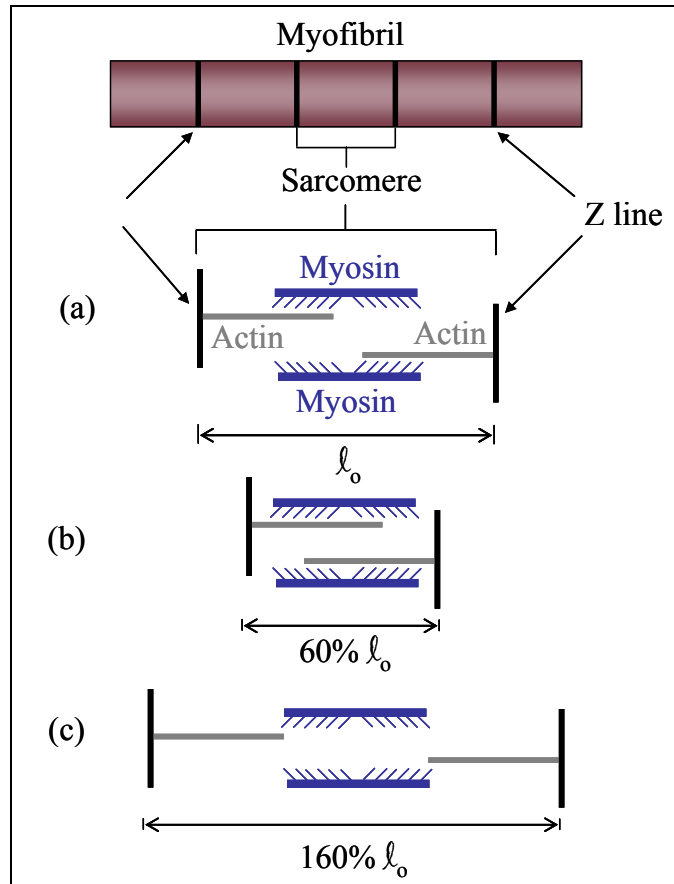


Figure 111. The sarcomere is the contractile unit of muscle: (a) the greatest force is created at resting length (b) illustrates the minimum length for producing force (c) illustrates the maximum length for producing force.

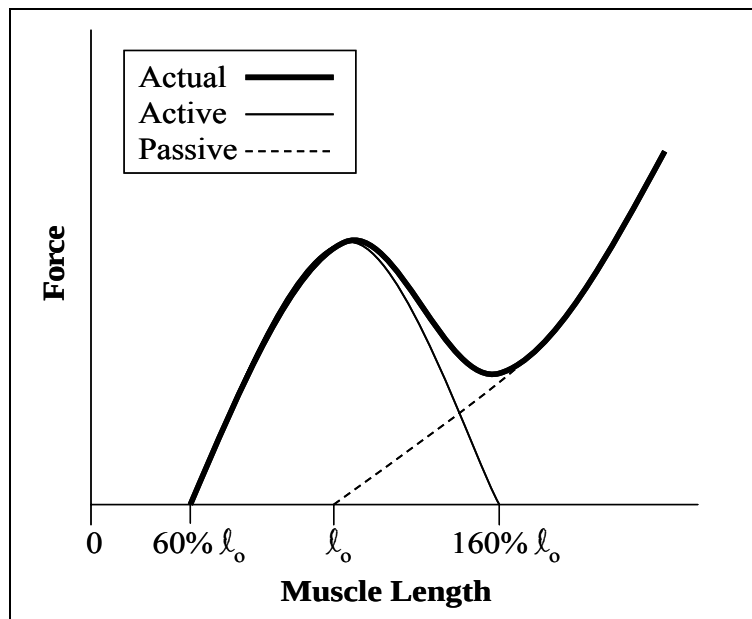


Figure 112. The force versus muscle length relationship, shown to muscle failure.

The active force – length relationship has been documented specifically for all of the extraocular muscles of the eye in relation to movements of the eye to accommodate vision (Clement 1987, Simonsz 1986, Miller 2002). However, the force values calculated or measured during these studies are of no use here, as the changes in length of the muscles during vision movements are very small relative to the types of displacements imposed in this study. Simonsz documented a maximum measured force of 0.39 N during his force – length investigation of the extraocular muscles conducted *in vivo*, while Miller found a maximum force of 0.1 N in his investigation of the rectus muscles *in vivo*. Clement reported a maximum calculated force of 0.15 N for the extraocular muscles during vision adjustments.

The type of muscle reaction experienced by the oblique extraocular muscles in this study is eccentric loading, or loading which creates muscle lengthening. When a muscle is lengthened due to an imposing outside force there is a dynamic response to consider. The tension created increases with the speed of lengthening. The higher the velocity of the loading the higher the force that can be produced, up until a maximum lengthening velocity where the curve will end abruptly and the muscle can no longer control the movement of the load (Hamill 1995) (Figure 113). This relationship has been documented for muscles in the human hand, elbow, and knee (De Ruiters 2001, Dudley 1990, Komi 1973). There was a reported average increase of 16% - 50% in muscle tension at the maximum lengthening velocity.

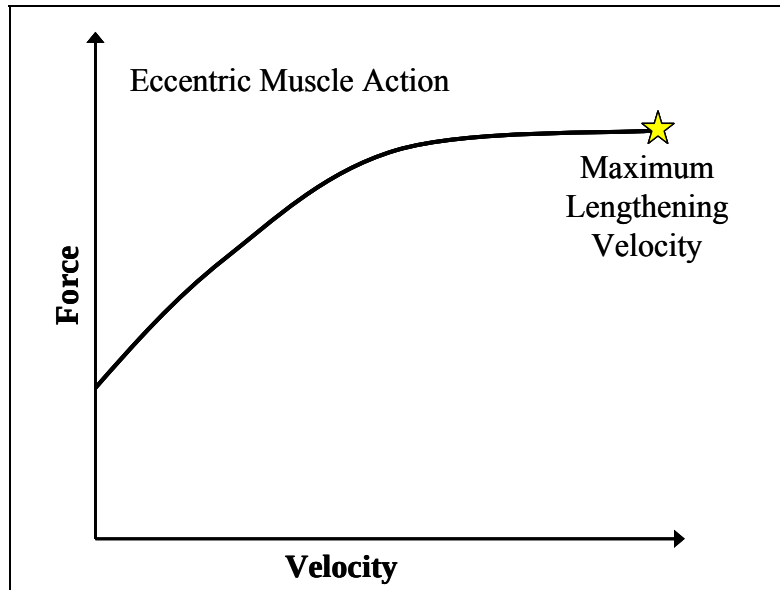


Figure 113. The force-velocity relationship for a muscle undergoing eccentric loading.

The muscle fibers in the extraocular muscles are among the fastest muscles in mammals and are comprised of mostly fast twitch muscle fibers (Bron 1997, Spencer 1988). Fast twitch muscle fibers are bigger, stronger, and quicker to respond than the slow twitch muscle fibers. They are able to burn energy faster since they don't depend on the vascular system for oxygen. Since these types of fibers have the ability to create more force per unit area than the slow twitch muscle fibers, it is probable that the maximum K value of 100 N/cm^2 could be used in the equation to calculate the maximum force that the extraocular muscles can produce.

The complete force – length relationship for the extraocular muscles cannot be calculated at this time, as the passive muscle response of these muscles is not reported in the literature. Tensile tests of the extraocular muscles in question, the superior and inferior obliques would fill in this variable, and the graph could be completed. Of course like all other tissues that have a viscoelastic response, this relationship is also time dependent,

and the rate of testing would dictate the result. However, several assumptions can be made to estimate the maximum stresses imposed upon the sclera by the oblique extraocular muscles during a dynamic displacement of an eye *in vivo*. If it is assumed that the passive failure force and modulus of live extraocular muscles is the same as that of live rabbit skeletal muscle, 46 N can be added to the maximum active force that the muscles can produce. Since the extraocular muscles are fast-twitch muscles, a K value of 100 N/cm² will be assumed. It will also be assumed that the muscles are displaced at a rate equal to the maximum length velocity and a 50% increase in muscle tension will be added. This yields maximum forces of 90 N and 101 N in the superior oblique and inferior oblique extraocular muscles respectively. These much higher force values yield higher stress contributions from the muscles, 1,050 kPa and 1,254 kPa in the superior oblique and inferior oblique extraocular muscles respectively. The combined stress of these muscles account for 6.3% and 2.6% of the total stress at rupture under quasi-static and dynamic rupture conditions respectively. This does not seem like a very large contribution in comparison to the scleral wall stress due to intraocular pressure, but it may make a difference. Dynamic *in vitro* matched pair tests should be conducted to evaluate this possibility.

3.5 Conclusion

As calculated in this chapter, the stresses created by the extraocular muscles can be neglected. The values relative to those experienced during globe rupture are insignificant. The maximum forces calculated in the discussion portion of this chapter are the estimated forces and stresses that could be produced in a live human. The stresses

contributed by the extraocular muscles may become significant with regard to globe rupture location and risk of rupture but further tests need to be conducted.

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APPENDIX A

CT Image

Reconstruction Directions

CT Image Reconstruction Directions

(ImageJ 1.33u, Wayne Rasband, National Institutes of Health)

All of your CT images have to be alone in a single folder and be numbered in order with the same amount of digits (i.e. 001, 011, 102 not 1, 11, 102). There can be a header before the numbers but they all have to have the same header (i.e. IM001..., CT001..., or 3WML001...).

Open ImageJ

File>Import>Image Sequence...

Select the first image in the sequence and hit 'Open'

Enter the total number of images

Enter the starting image number

Enter the increment to count by

Once your Image Stack is open:

Image>Stacks>Reslice[/]...

Enter the input Z spacing (original slice thickness)

Enter the output Z spacing

Chose the direction to reslice in

To save a single image:

Scroll through the stack to the image that you want to save

Save As>Jpeg (or which ever file type)

To save an Image Stack/Sequence:

Save As>Image Sequence

Chose File Type (jpeg is good)

Chose to use the frame numbers

As long as they have their own folder, you will be able to open them up as a stack again, and also individually.

APPENDIX B

Histological Sclera Thickness Images

Eye: H001

Sample: 1

Age: 68



Figure B1. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

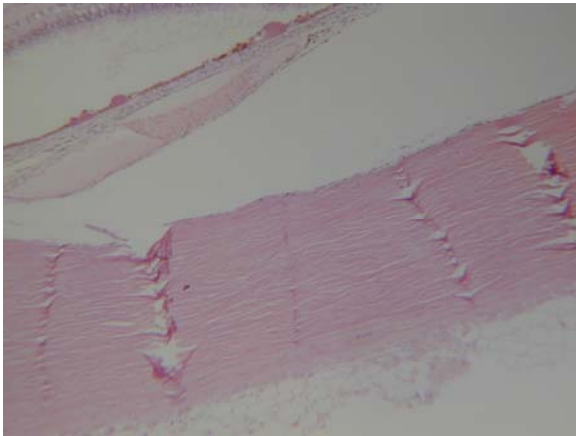


Figure B2. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

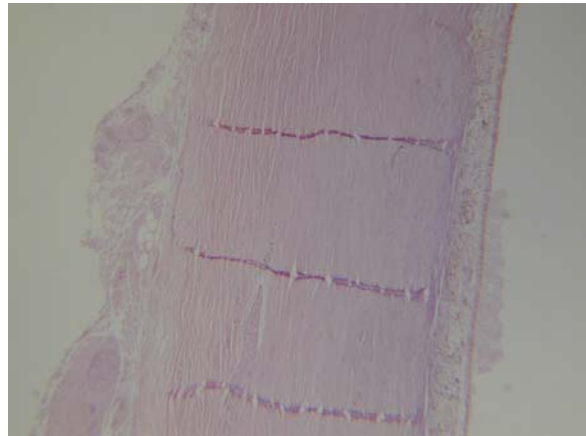


Figure B3. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

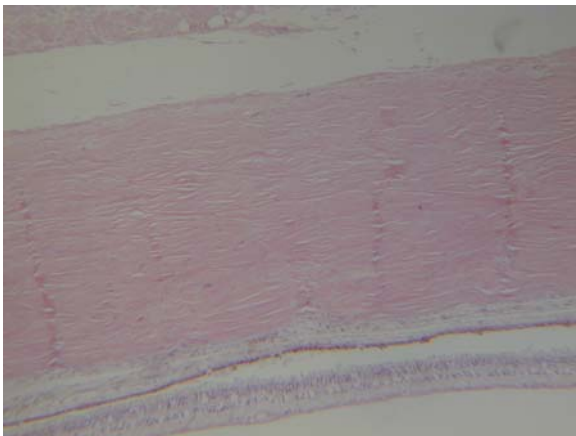


Figure B4. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

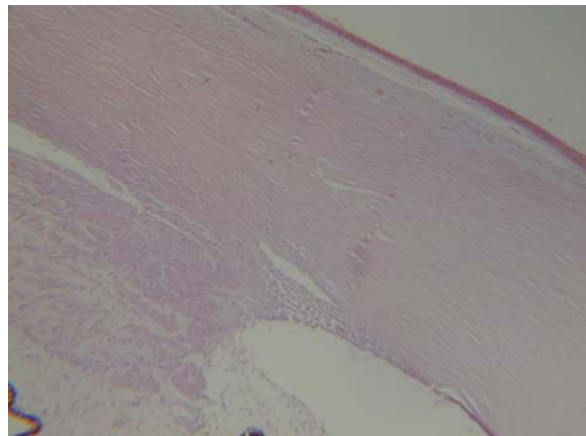


Figure B5. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H001

Sample: 2

Age: 68

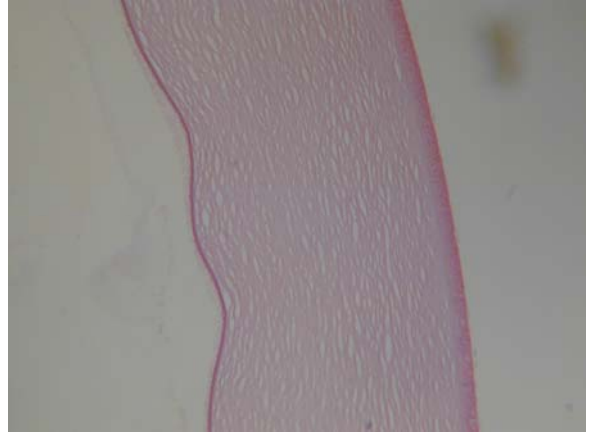


Figure B6. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

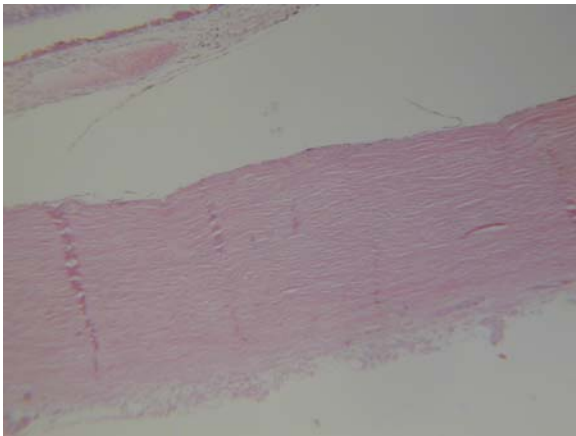


Figure B7. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

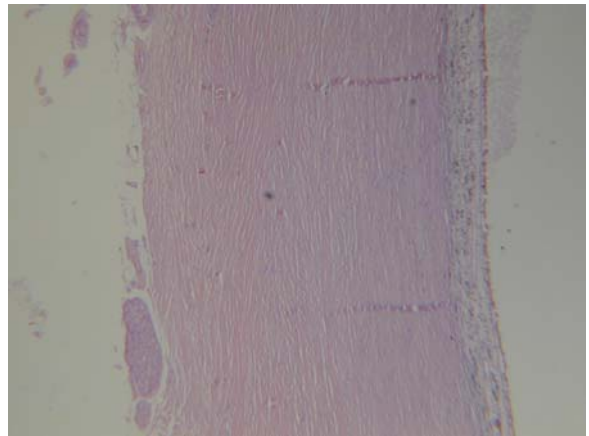


Figure B8. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

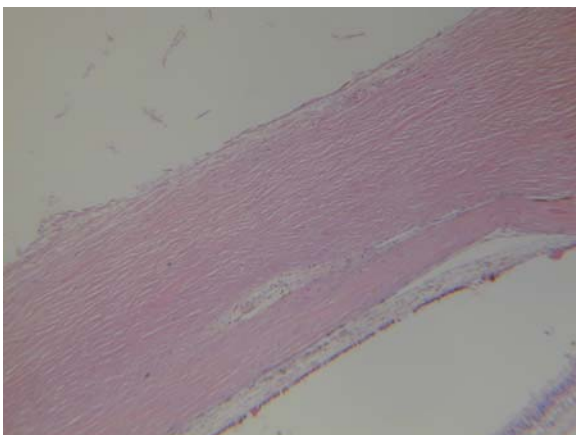


Figure B9. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

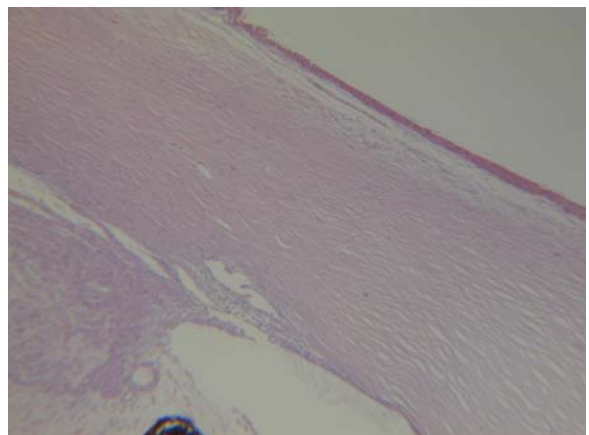


Figure B10. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H002

Sample: 1

Age: 68

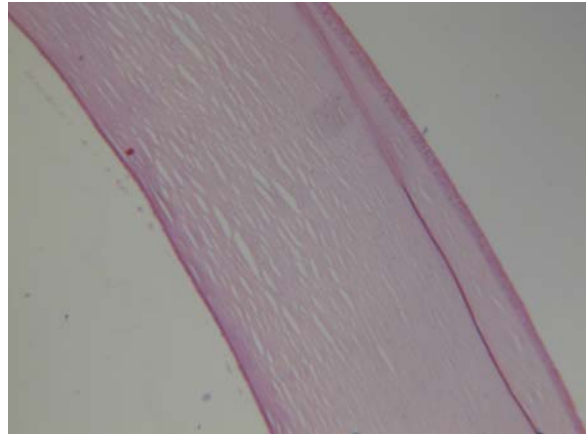


Figure B11. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

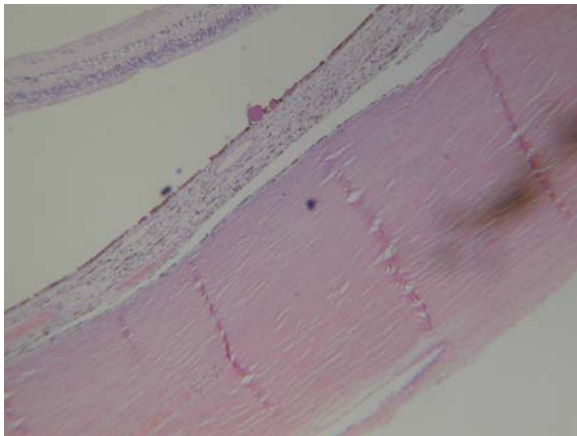


Figure B12. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

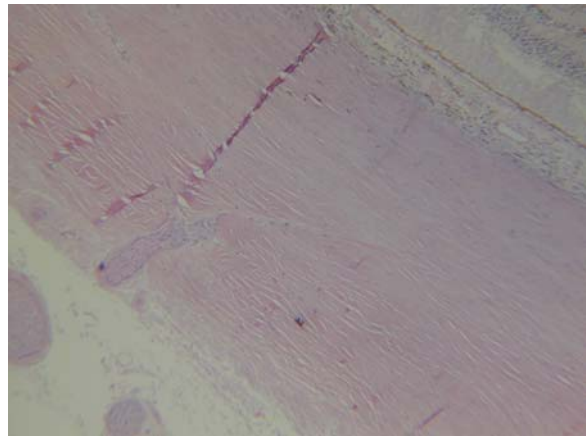


Figure B13. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

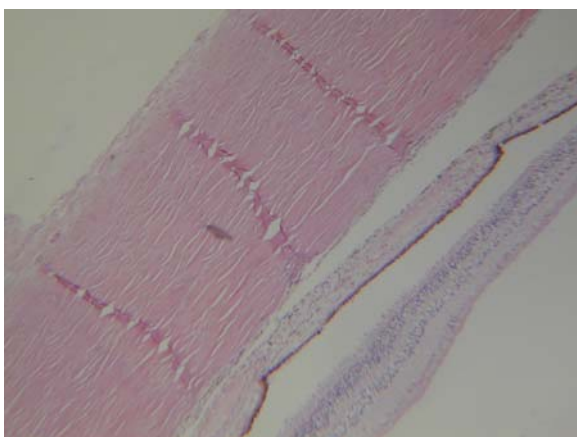


Figure B14. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

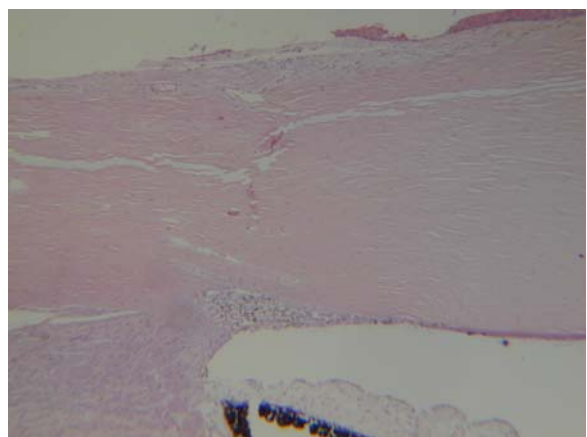


Figure B15. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H002

Sample: 2

Age: 68

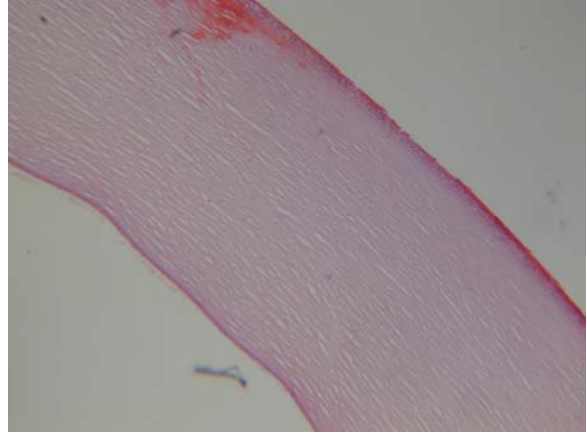


Figure B16. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

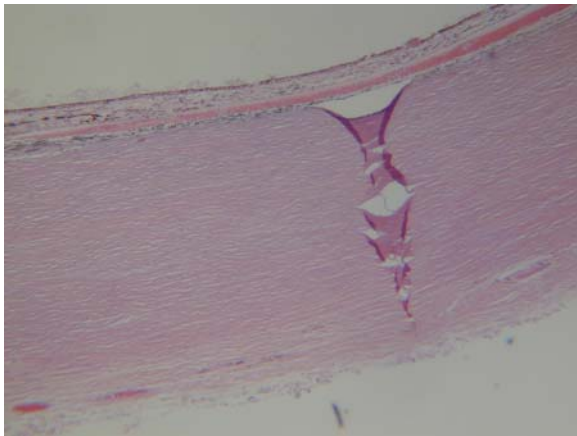


Figure B17. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

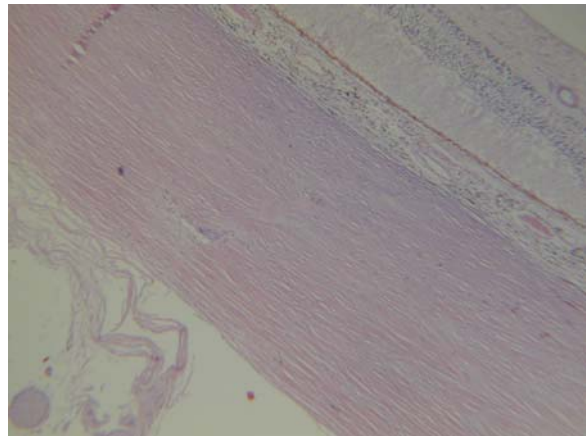


Figure B18. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

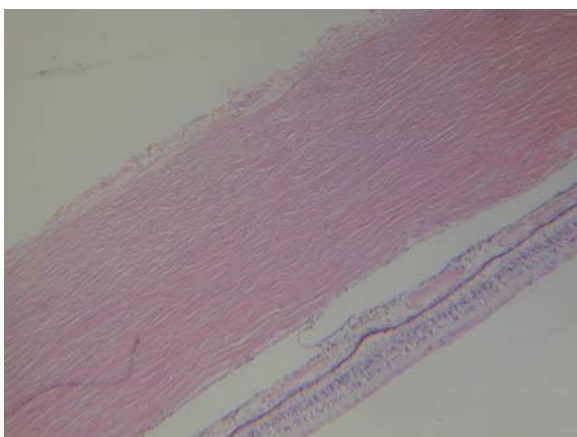


Figure B19. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

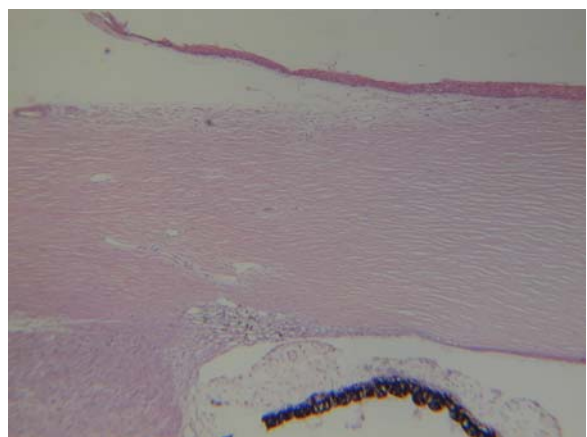


Figure B20. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H002

Sample: 3

Age: 68

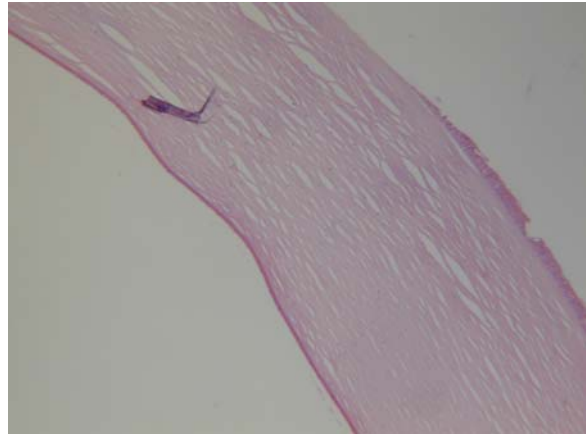


Figure B21. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

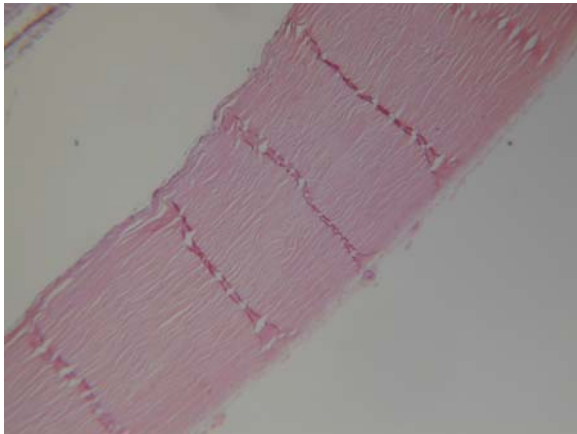


Figure B22. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

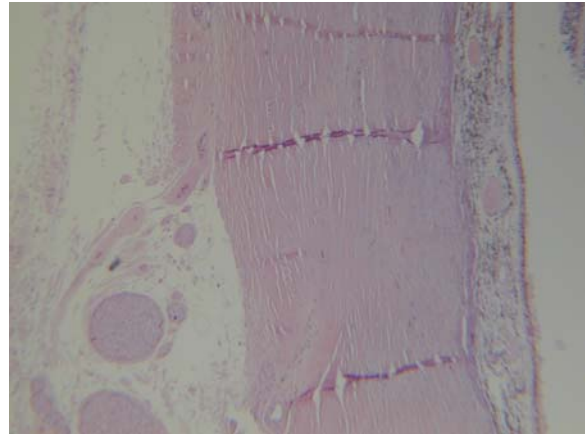


Figure B23. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

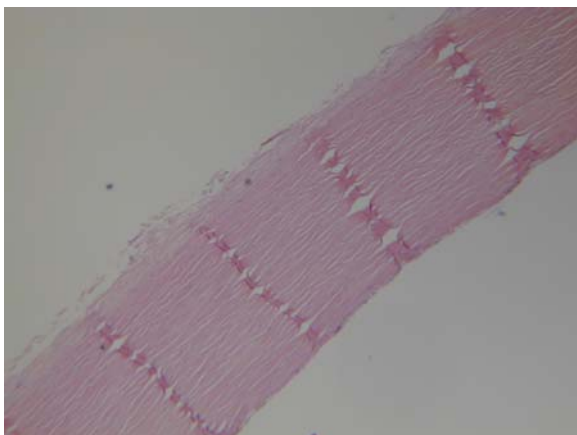


Figure B24. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

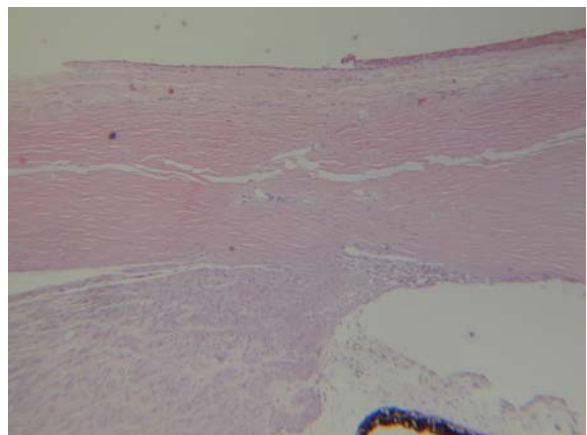


Figure B25. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H002

Sample: 4

Age: 68

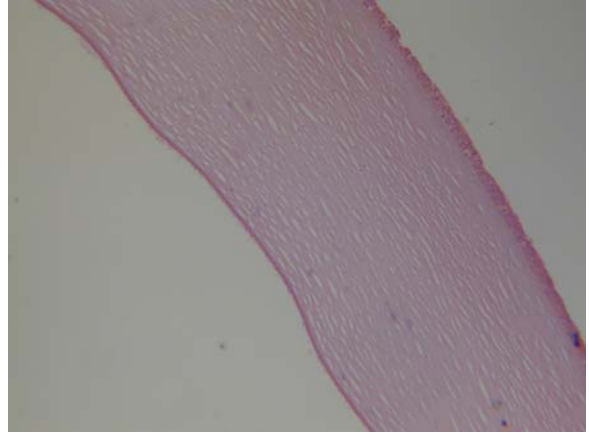


Figure B26. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

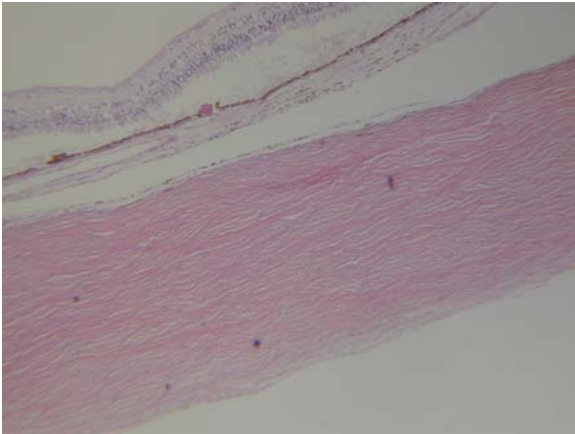


Figure B27. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

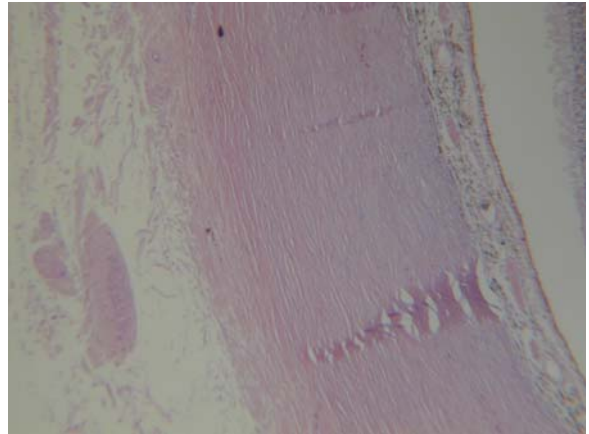


Figure B28. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

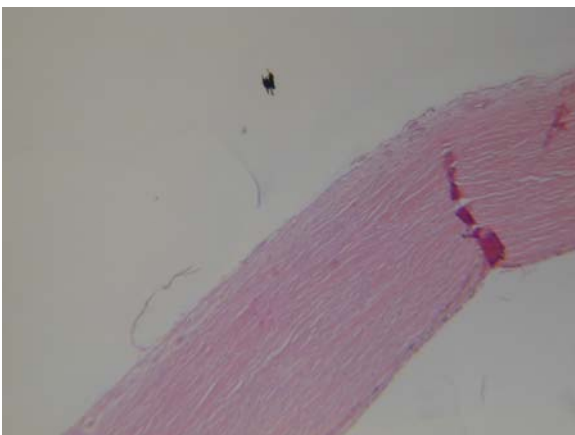


Figure B29. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

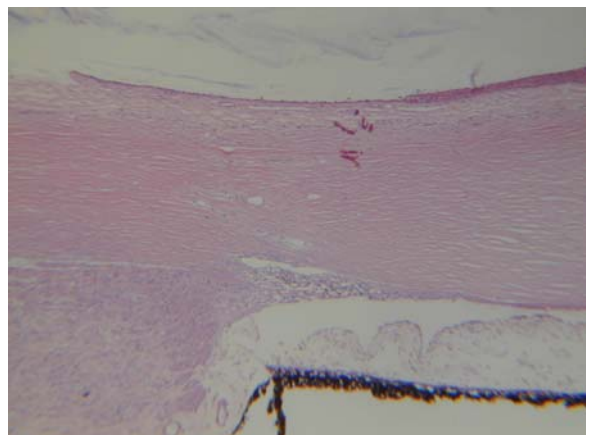


Figure B30. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H003

Sample: 1

Age: 51

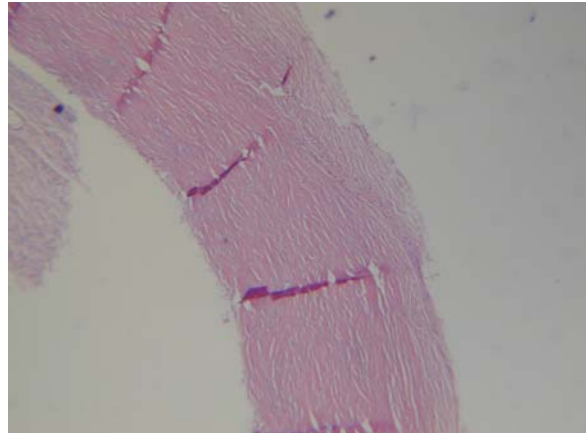


Figure B31. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

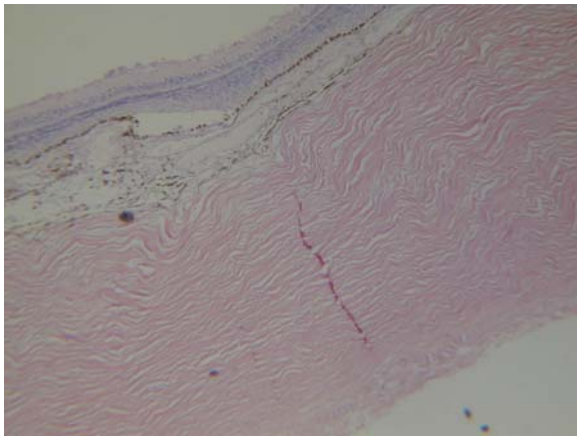


Figure B32. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

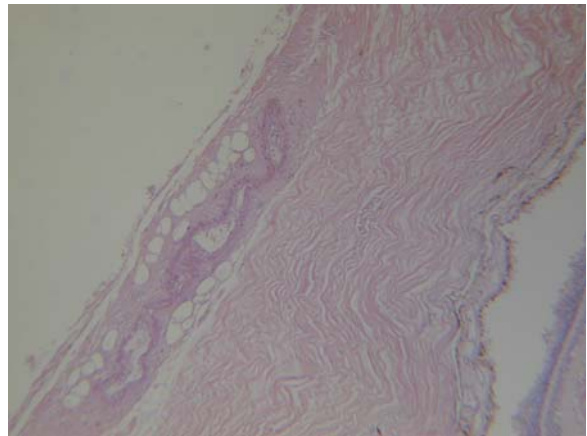


Figure B33. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

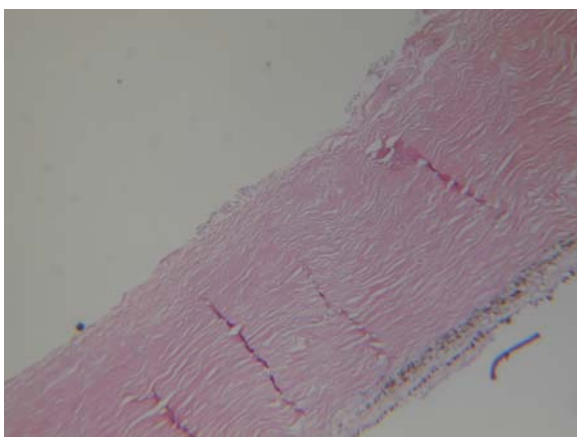


Figure B34. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

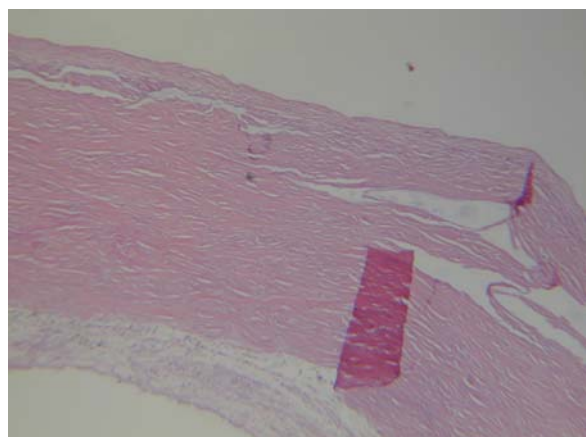


Figure B35. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H003

Sample: 2

Age: 51

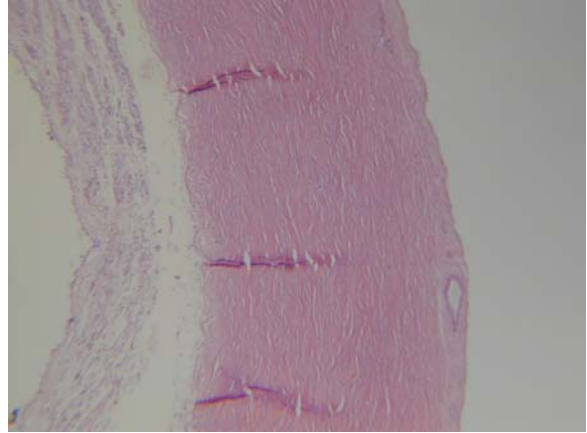


Figure B36. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

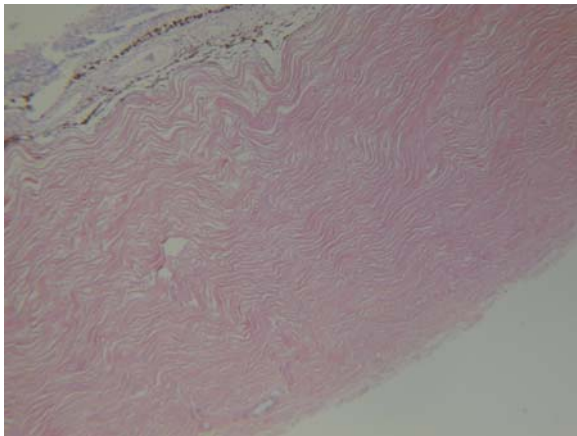


Figure B37. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

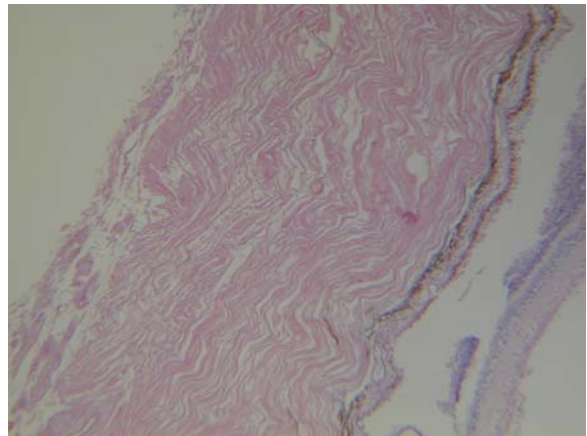


Figure B38. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

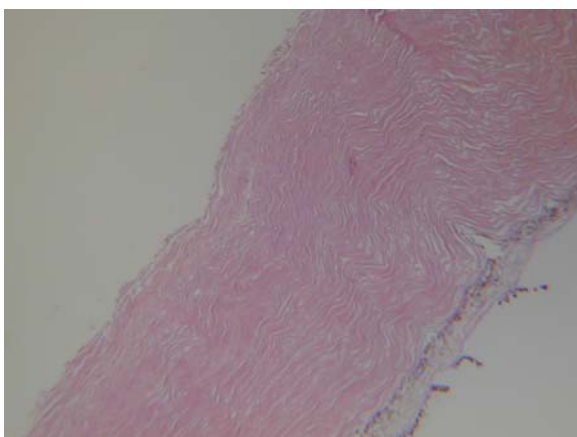


Figure B39. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

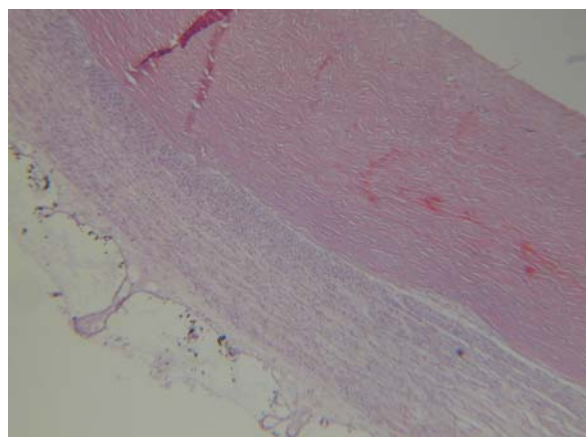


Figure B40. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H004

Sample: 1

Age: 51

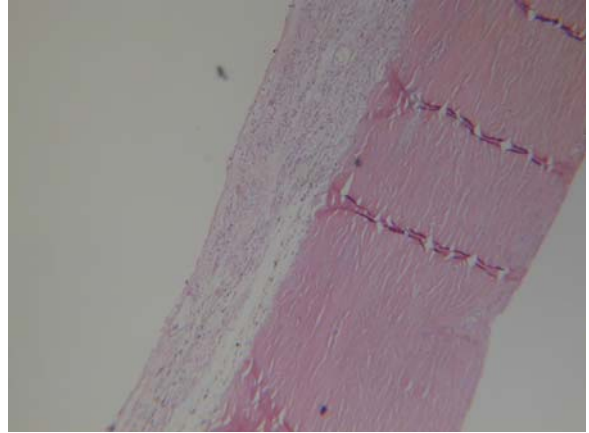


Figure B41. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

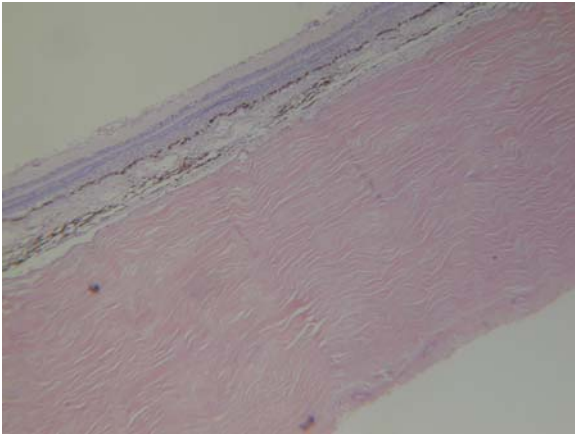


Figure B42. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

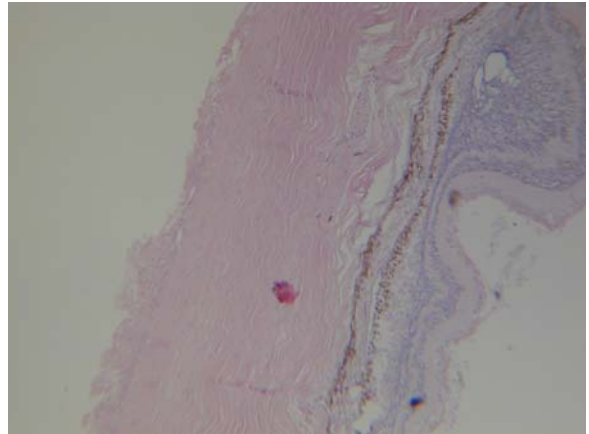


Figure B43. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

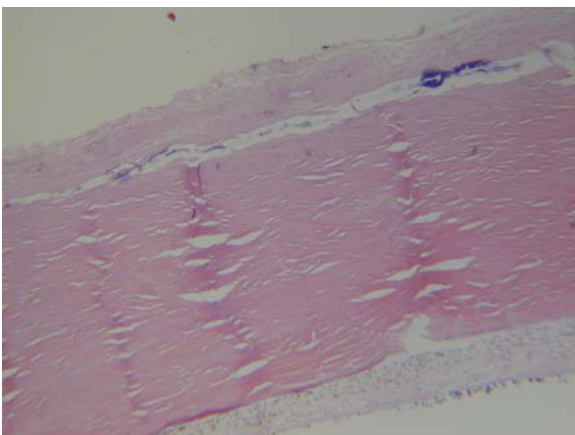


Figure B44. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

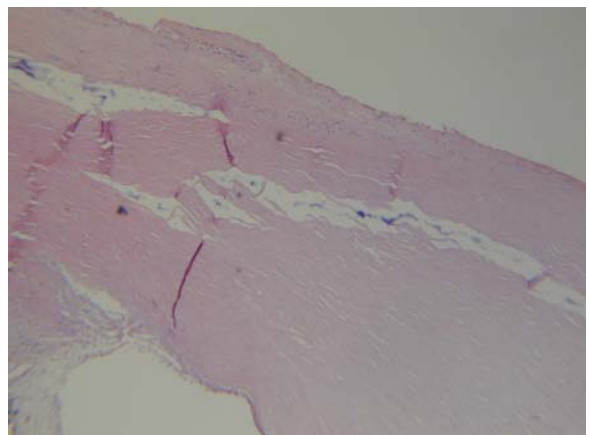


Figure B45. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H004

Sample: 2

Age: 51

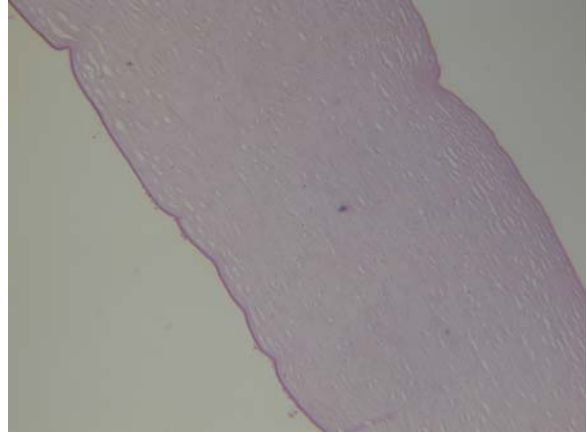


Figure B46. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

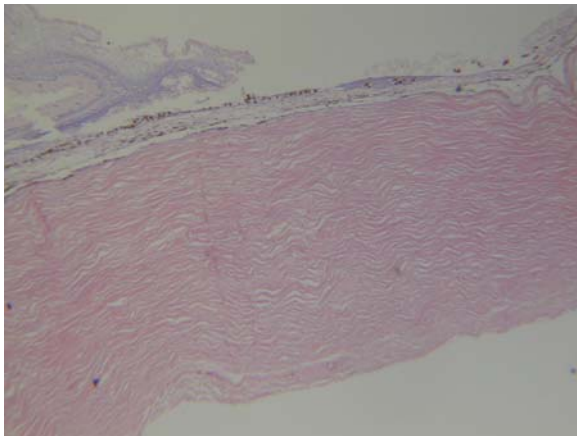


Figure B47. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

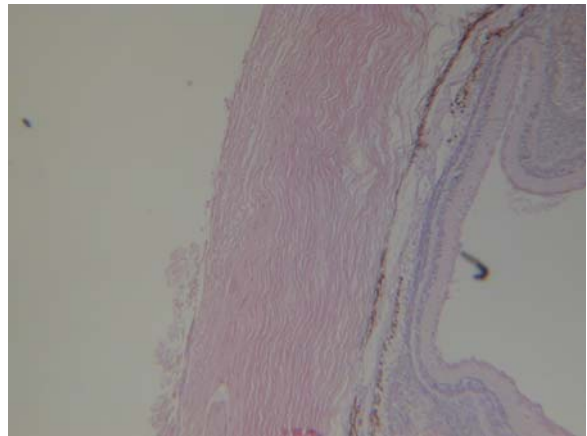


Figure B48. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

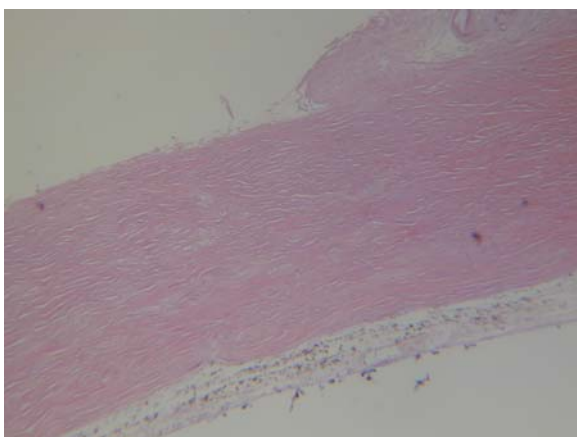


Figure B49. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

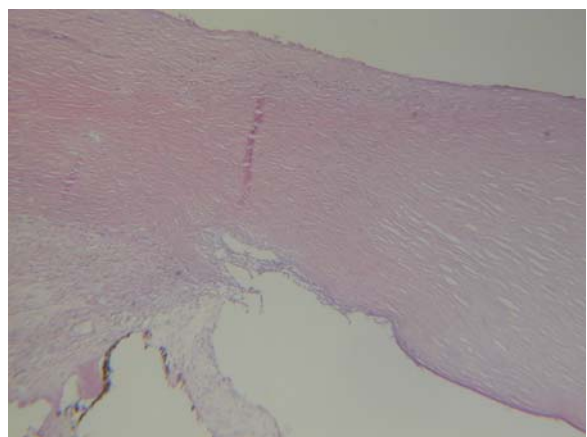


Figure B50. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H005

Sample: 1

Age: 70

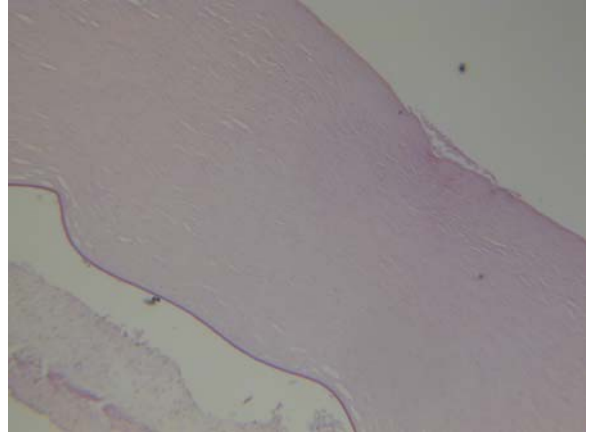


Figure B51. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

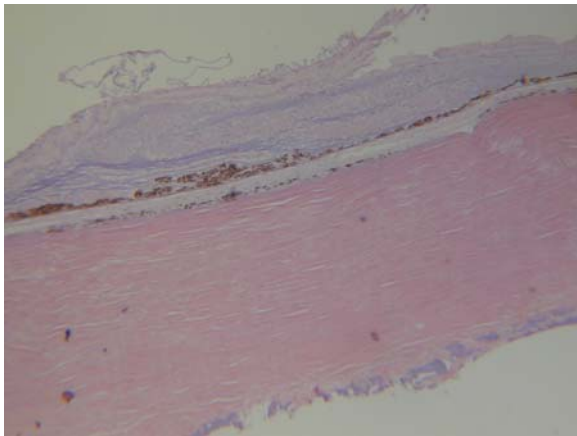


Figure B52. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

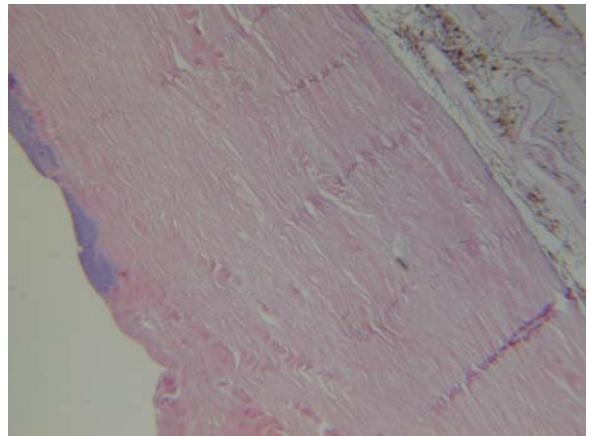


Figure B53. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

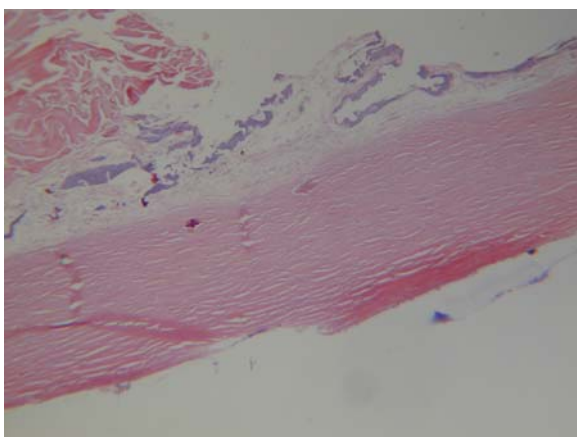


Figure B54. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

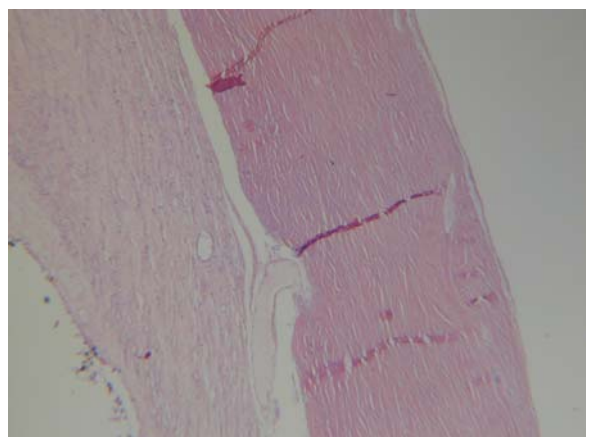


Figure B55. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H005

Sample: 2

Age: 70

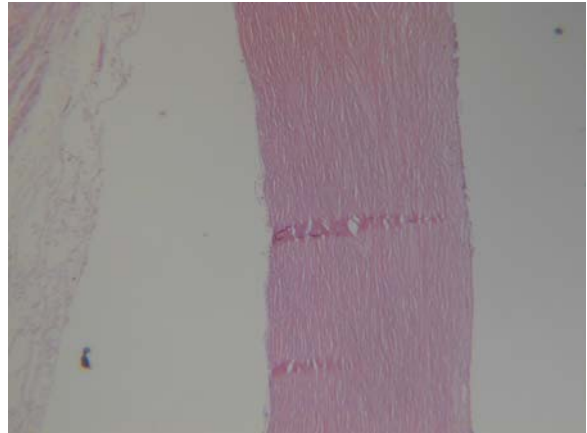


Figure B56. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

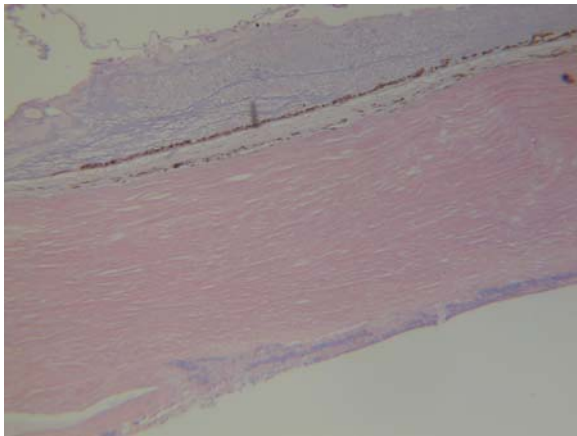


Figure B57. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

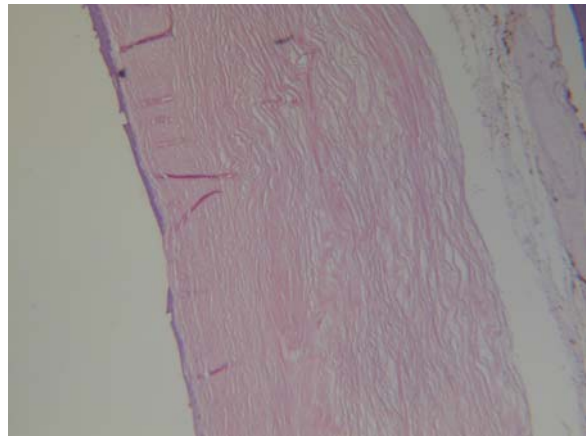


Figure B58. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

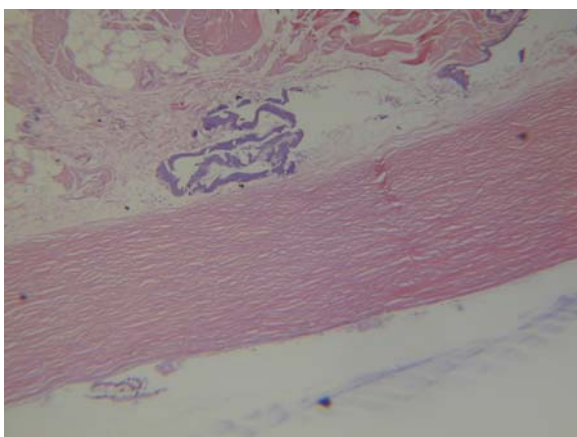


Figure B59. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

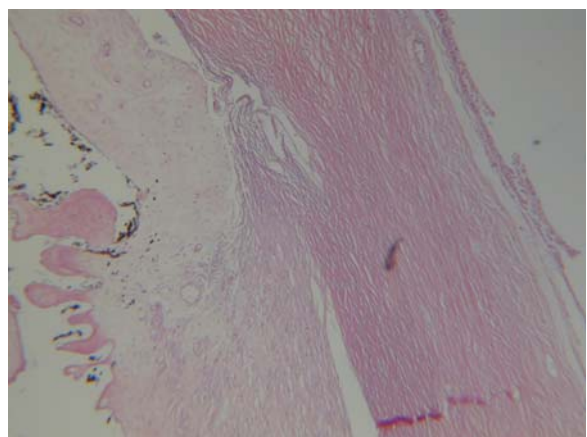


Figure B60. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H006

Sample: 1

Age: 70

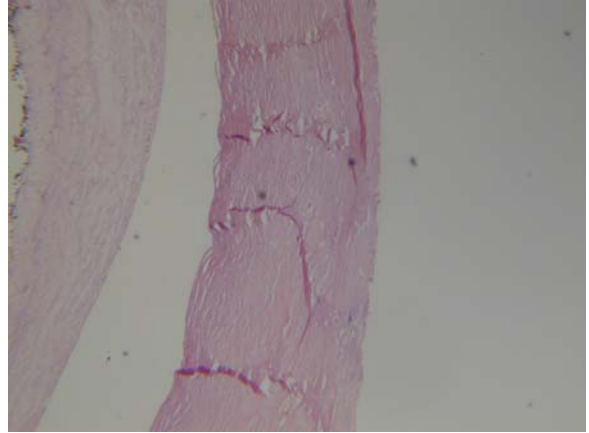


Figure B61. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

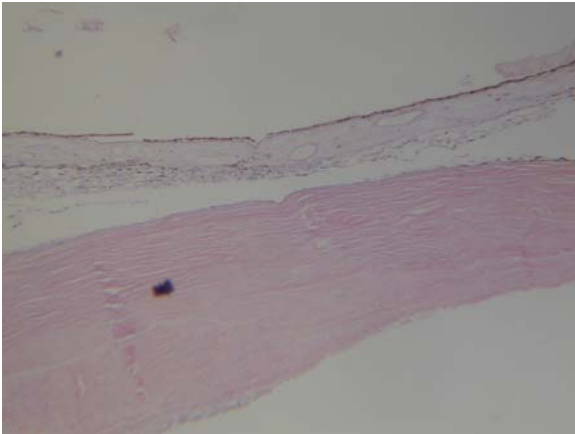


Figure B62. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

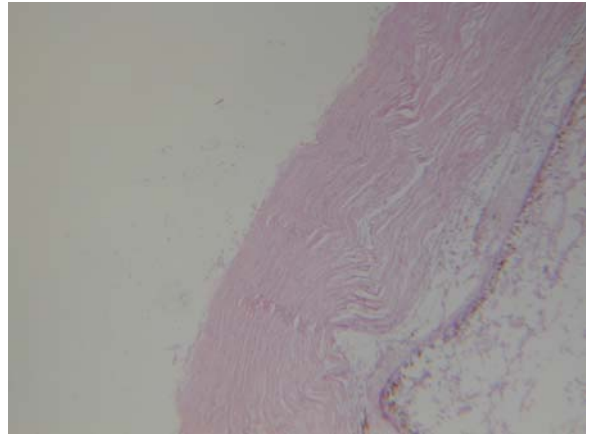


Figure B63. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

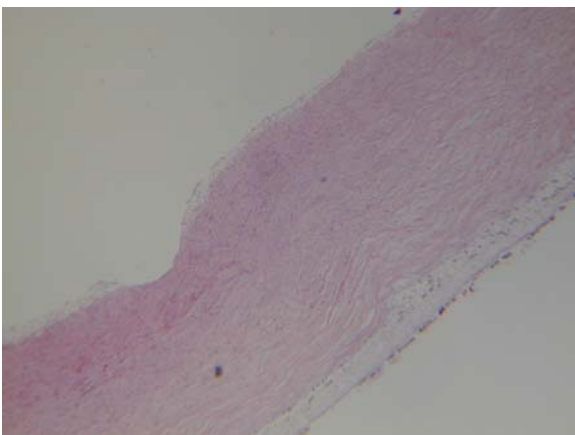


Figure B64. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

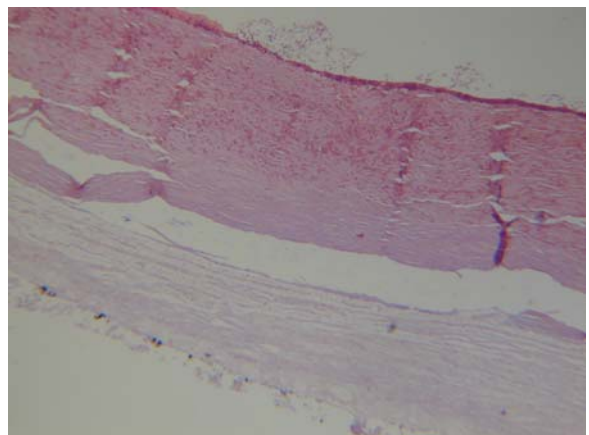


Figure B65. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H006

Sample: 2

Age: 70

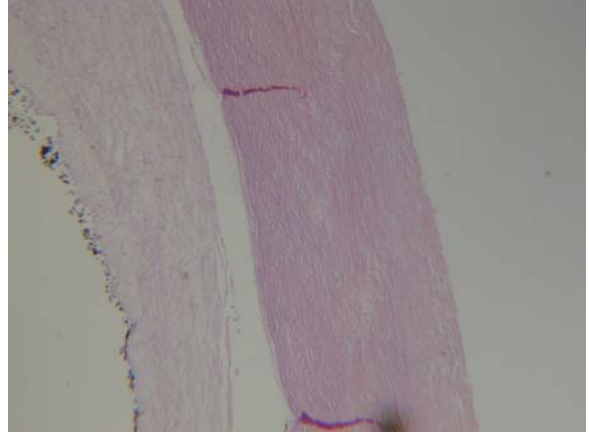


Figure B66. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

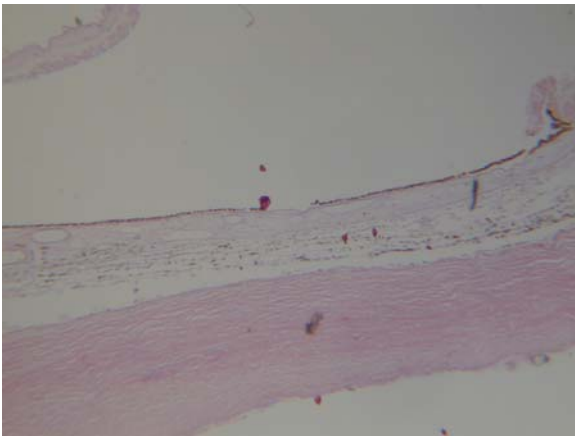


Figure B67. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

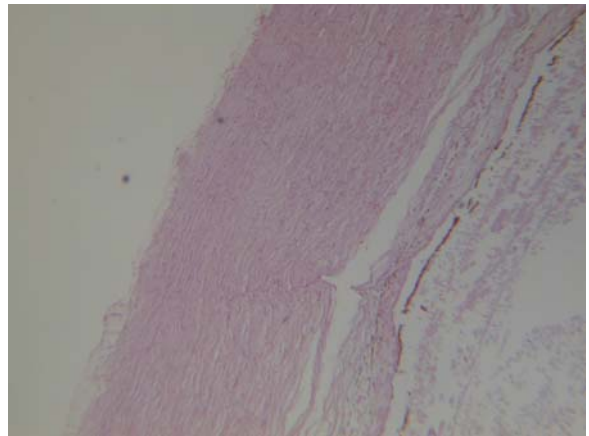


Figure B68. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

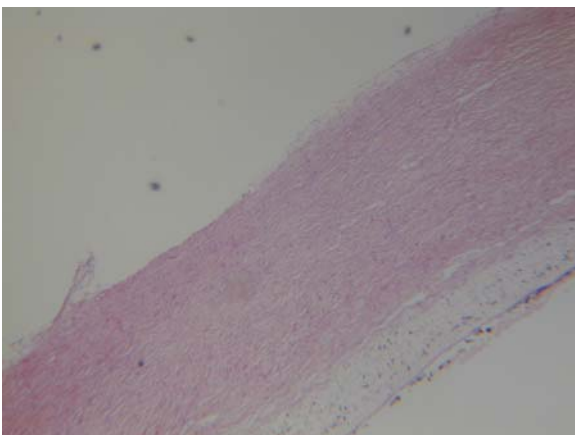


Figure B69. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

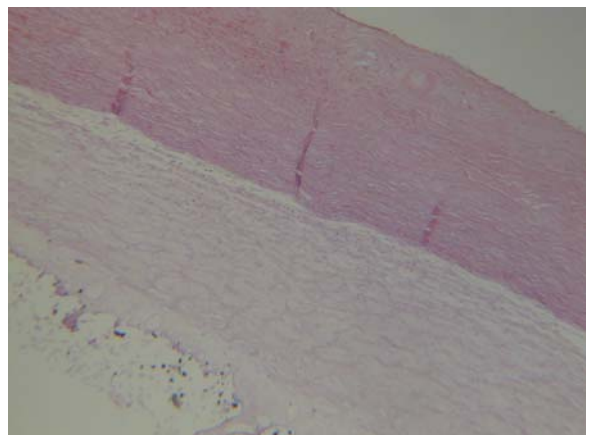


Figure B70. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H007

Sample: 1

Age: 71

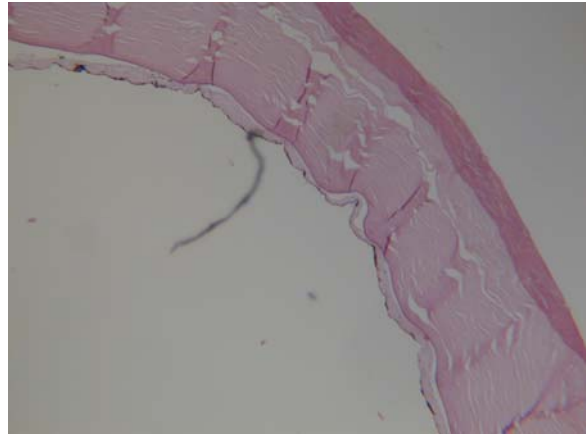


Figure B71. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

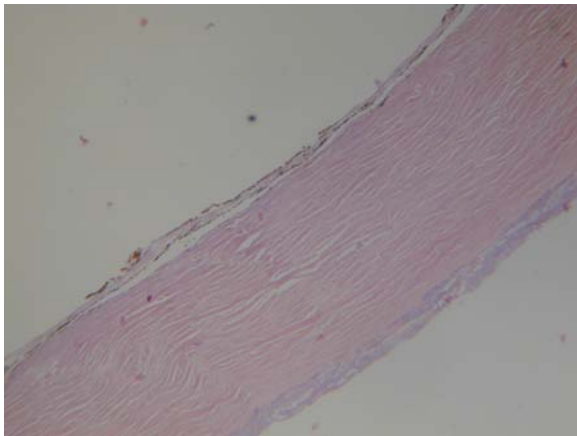


Figure B72. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

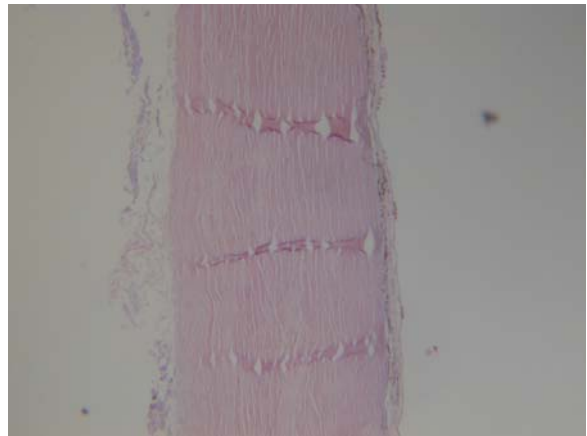


Figure B73. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

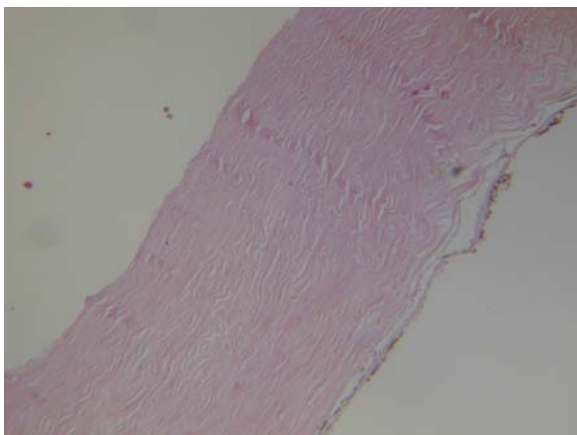


Figure B74. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

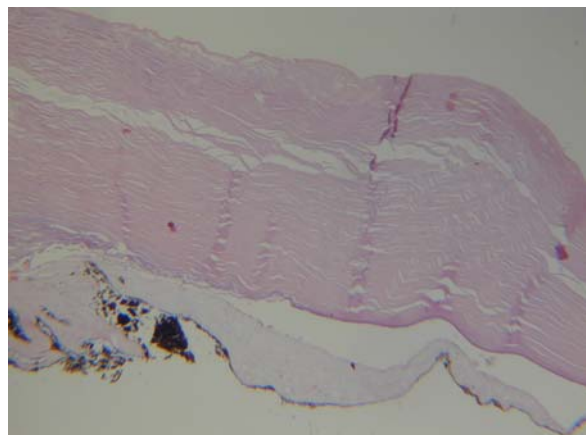


Figure B75. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H007

Sample: 2

Age: 71

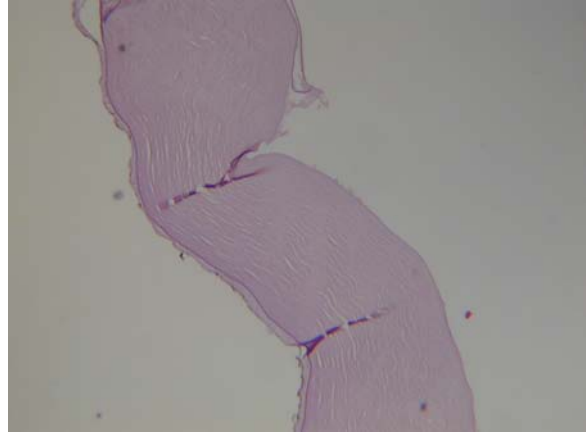


Figure B76. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

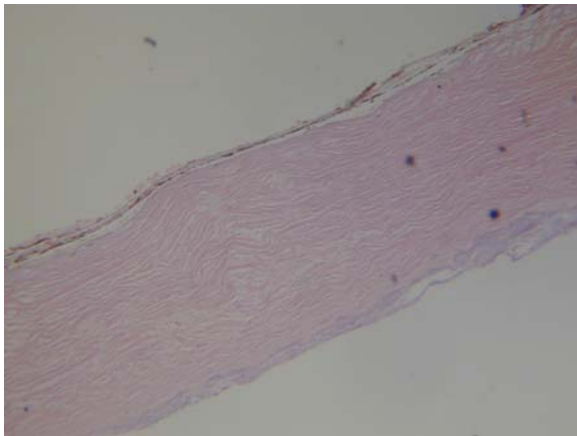


Figure B77. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

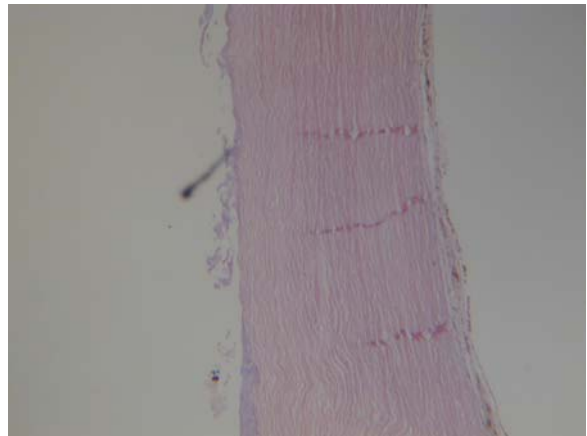


Figure B78. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

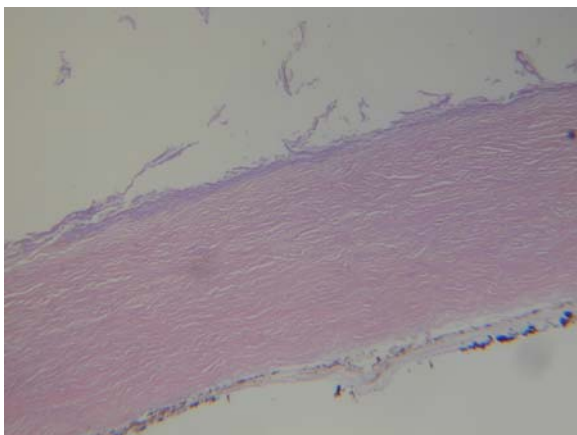


Figure B79. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

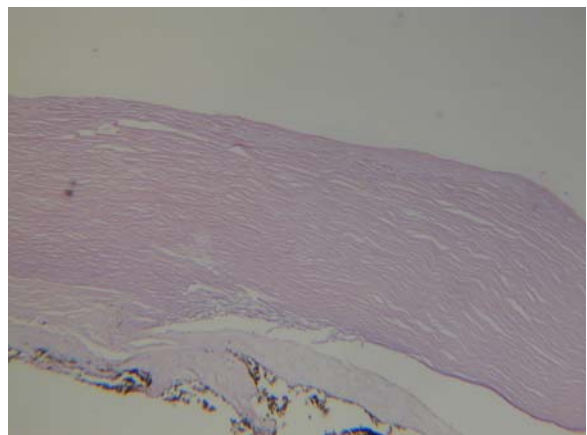


Figure B80. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H007

Sample: 3

Age: 71

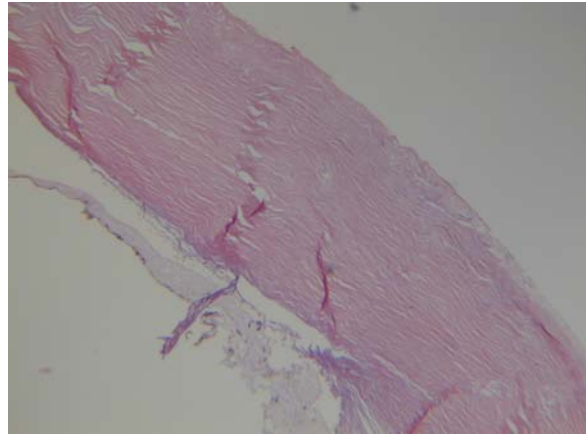


Figure B81. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

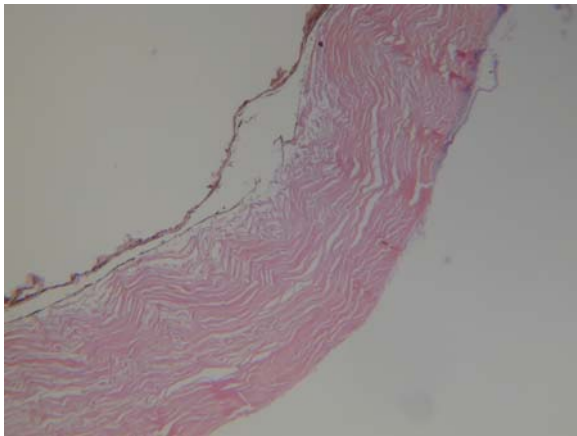


Figure B82. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

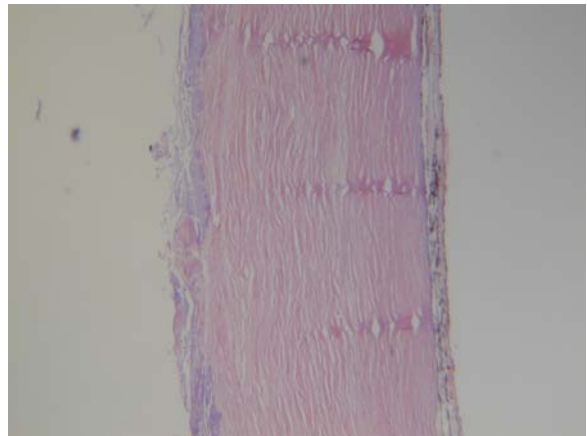


Figure B83. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

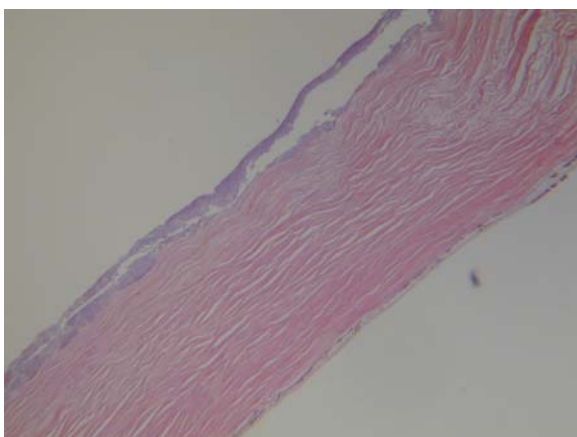


Figure B84. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

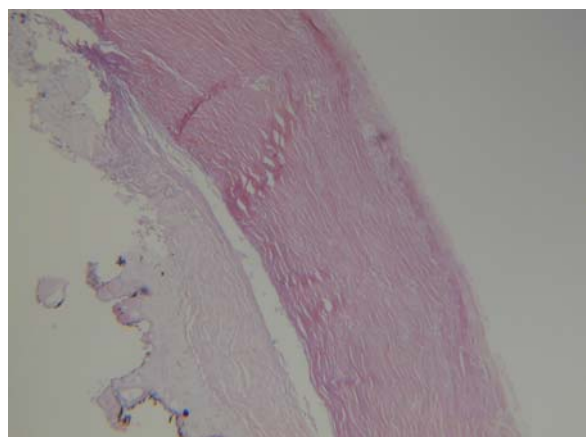


Figure B85. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H007

Sample: 4

Age: 71

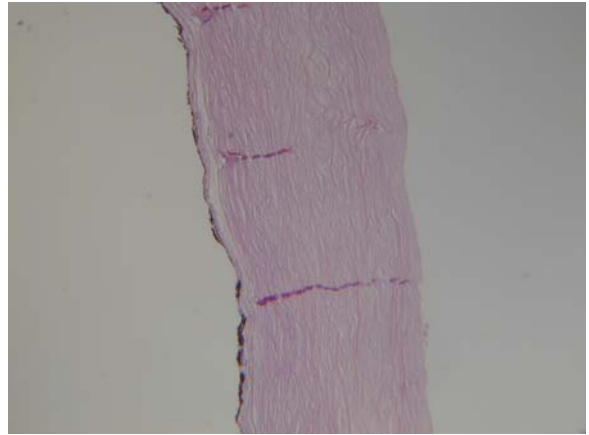


Figure B86. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

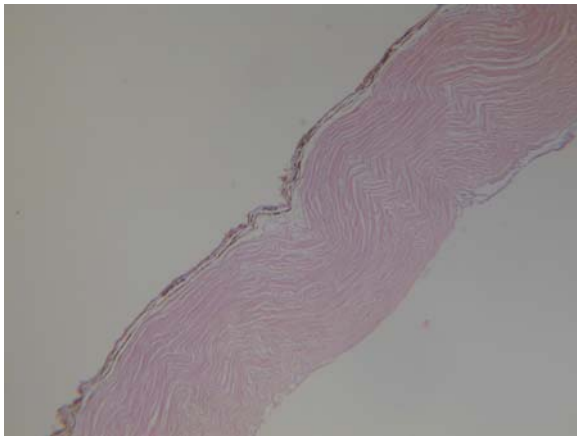


Figure B87. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

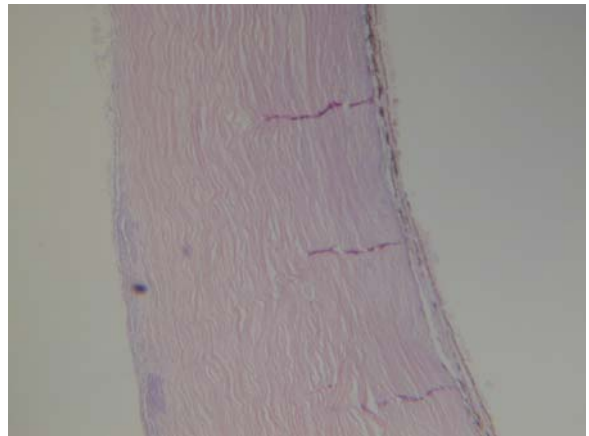


Figure B88. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

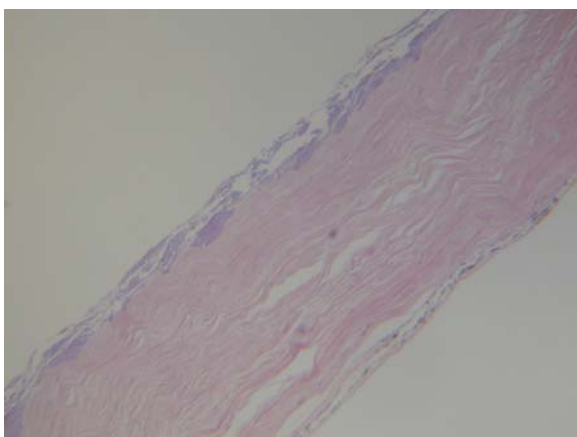


Figure B89. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

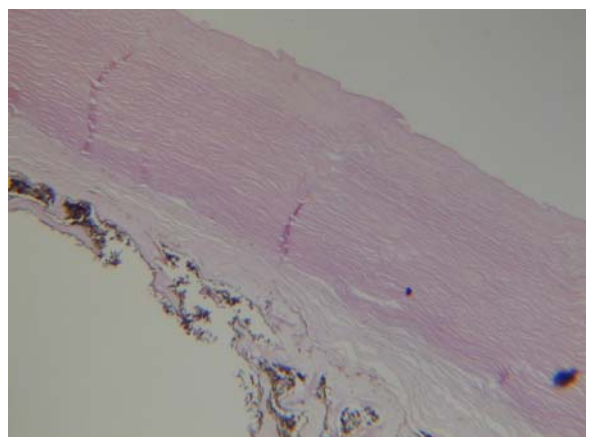


Figure B90. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H008

Sample: 1

Age: 55

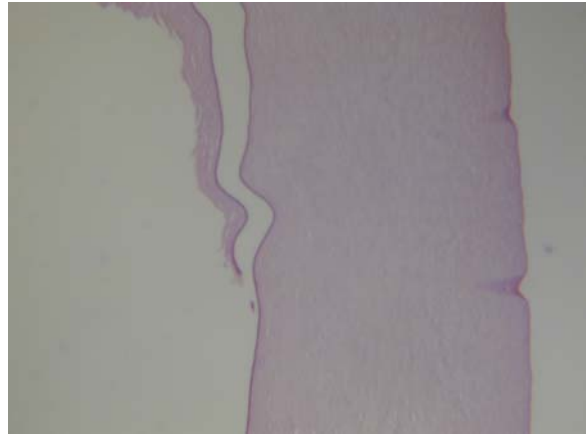


Figure B91. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

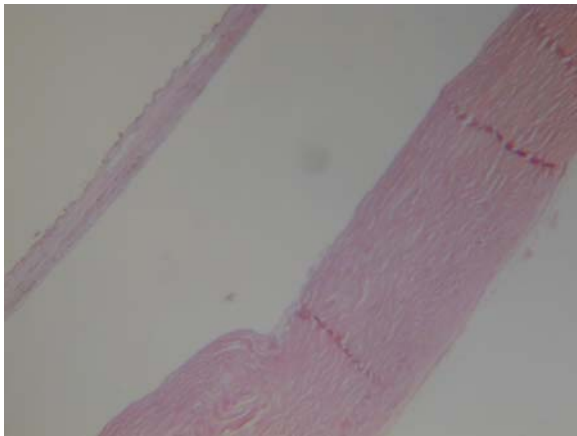


Figure B92. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

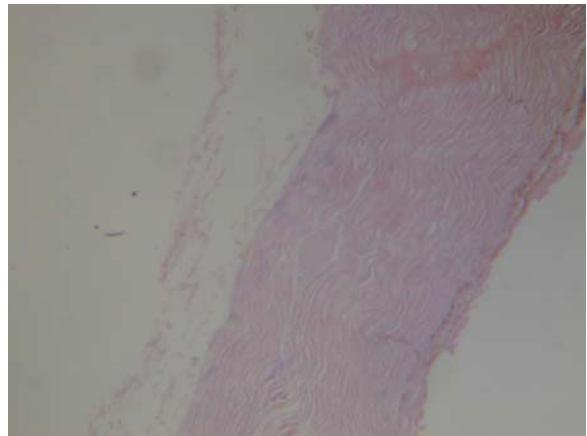


Figure B93. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

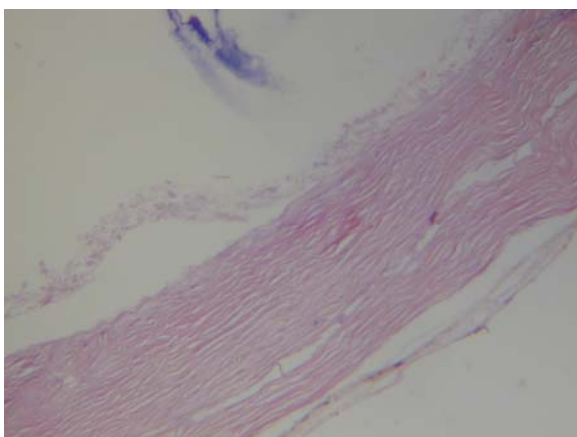


Figure B94. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

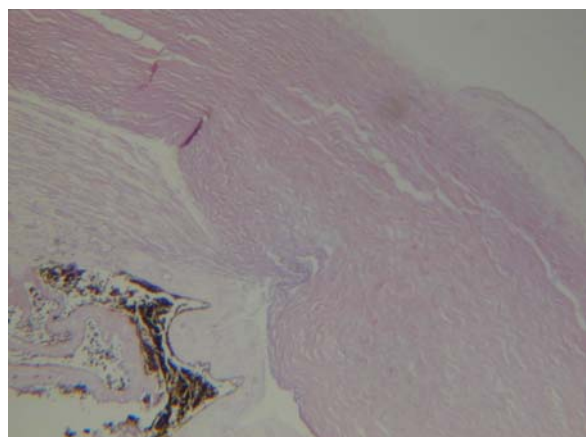


Figure B95. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H008

Sample: 2

Age: 55



Figure B96. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

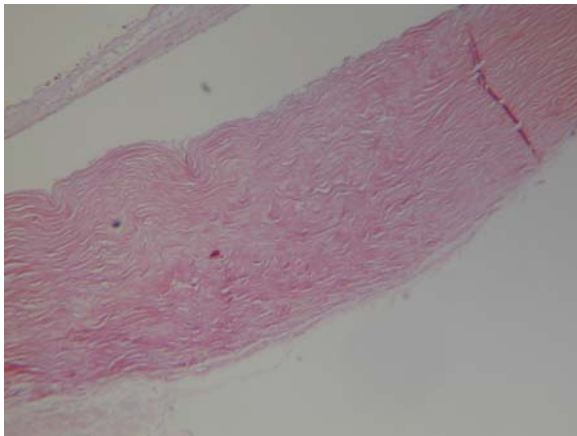


Figure B97. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

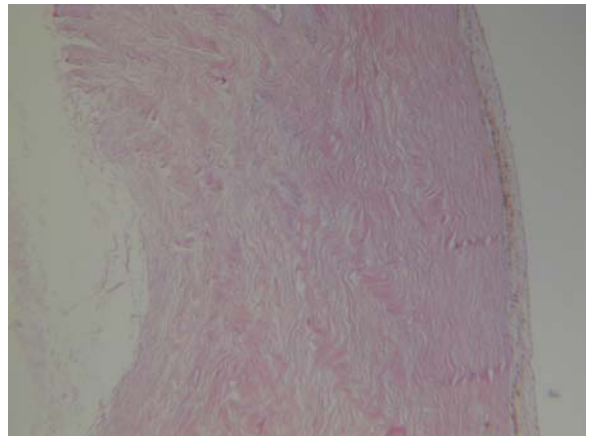


Figure B98. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

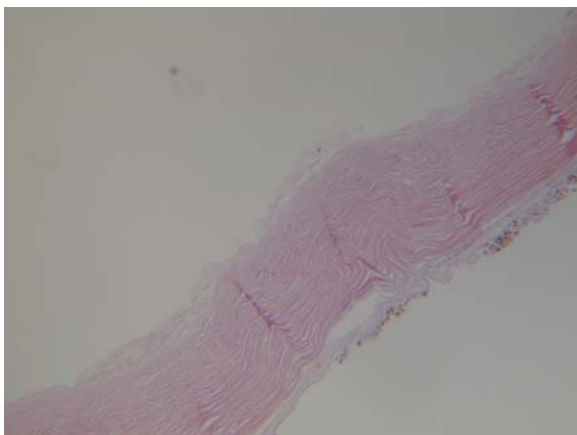


Figure B99. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

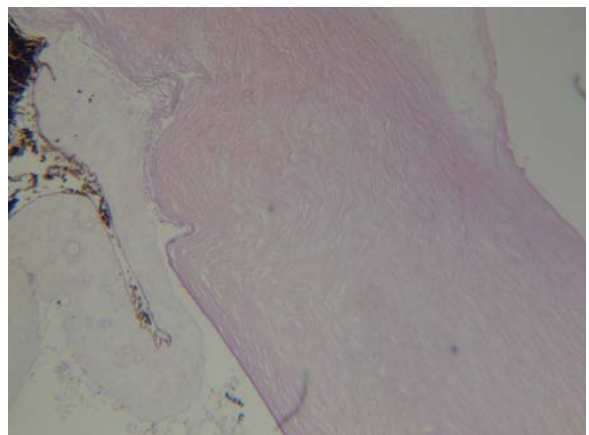


Figure B100. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H009

Sample: 1

Age: 73



Figure B101. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

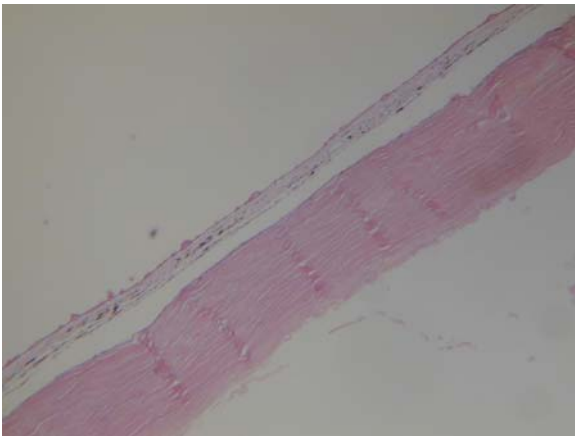


Figure B102. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

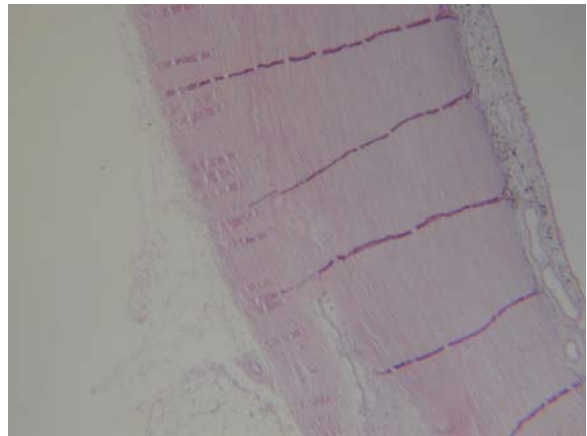


Figure B103. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

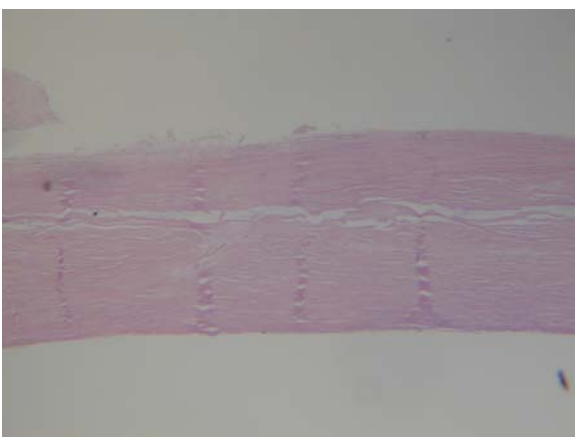


Figure B104. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

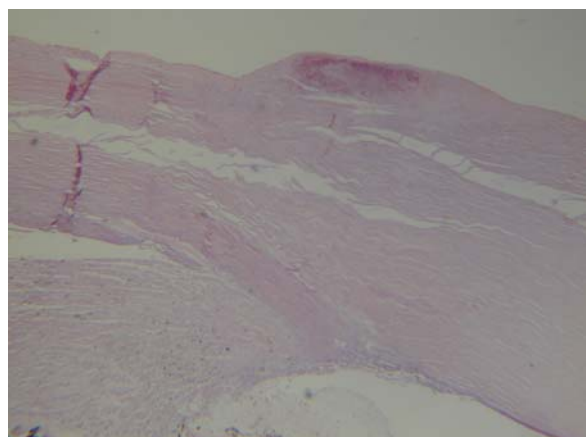


Figure B105. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H009

Sample: 2

Age: 73

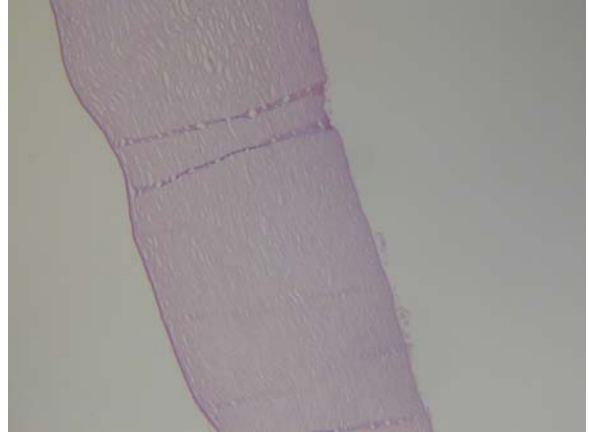


Figure B106. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

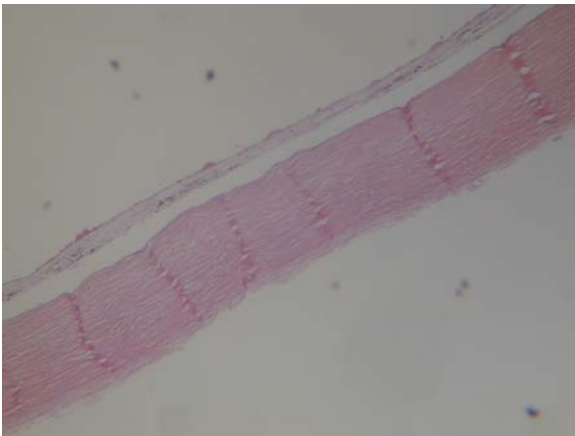


Figure B107. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

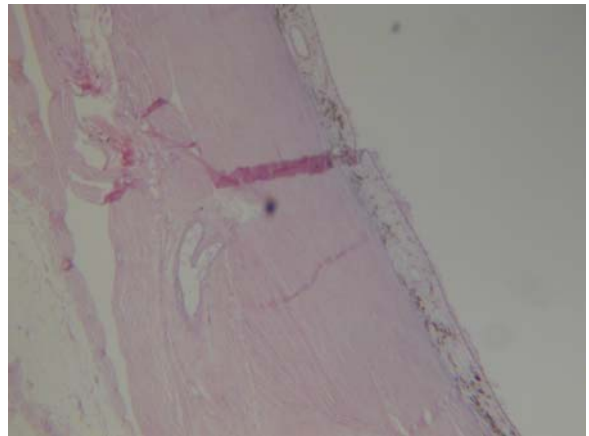


Figure B108. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

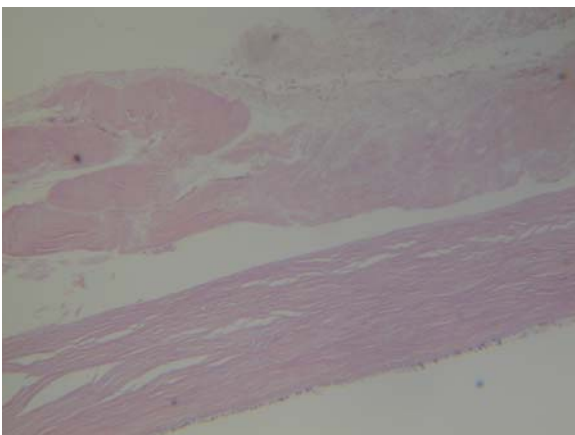


Figure B109. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

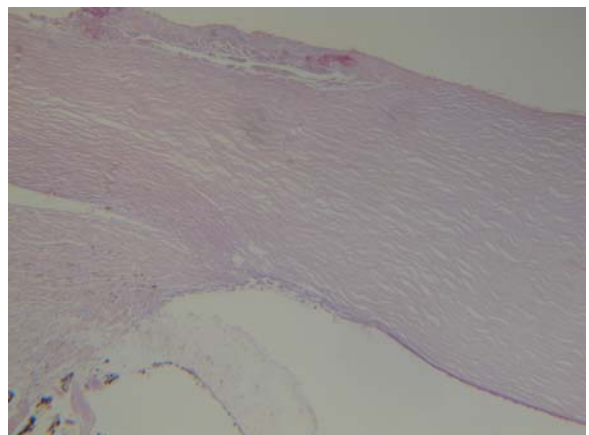


Figure B110. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H010

Sample: 1

Age: 57

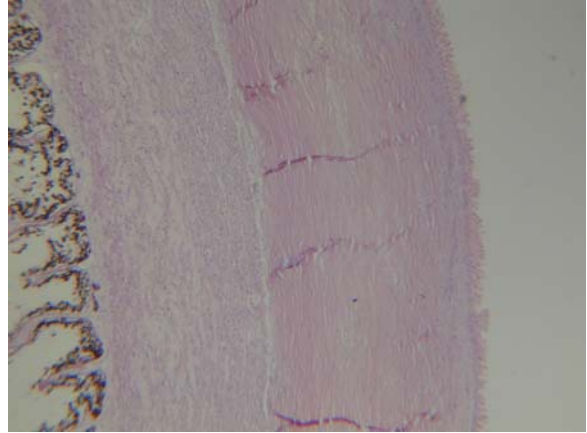


Figure B111. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

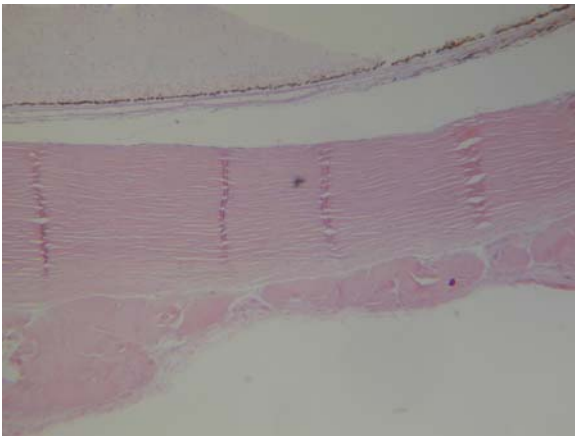


Figure B112. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

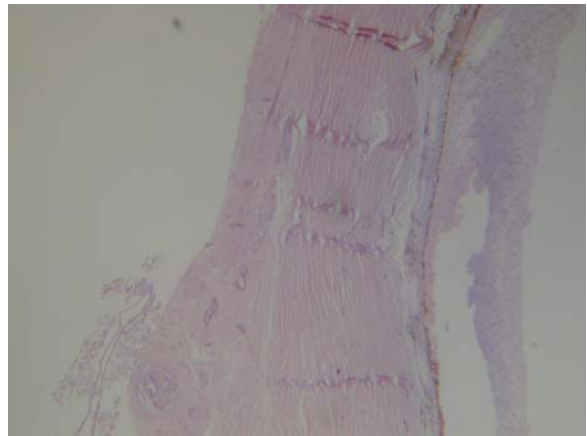


Figure B113. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

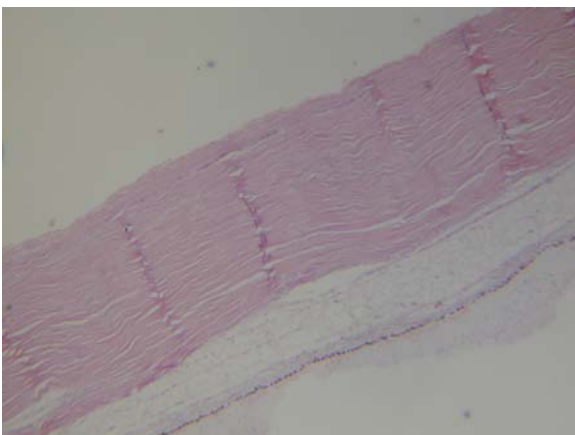


Figure B114. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

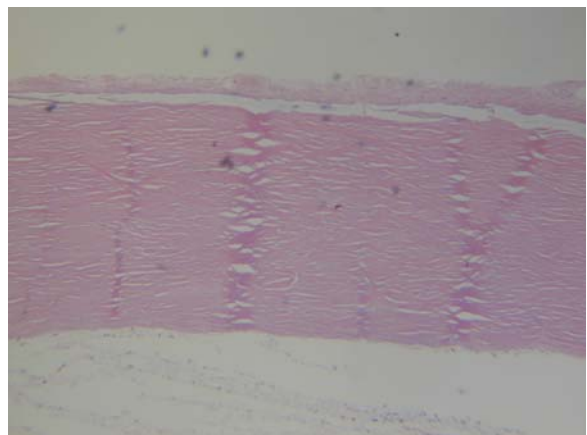


Figure B115. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H010

Sample: 2

Age: 57

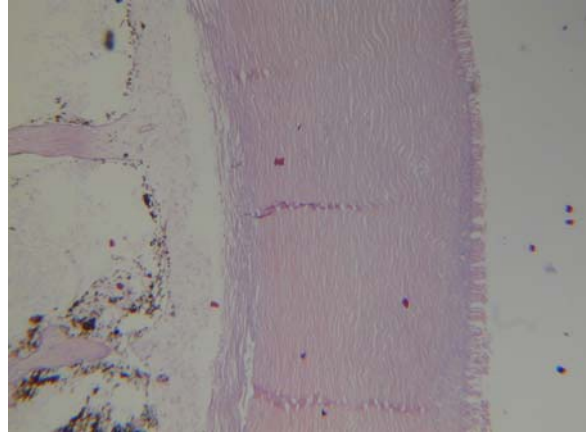


Figure B116. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

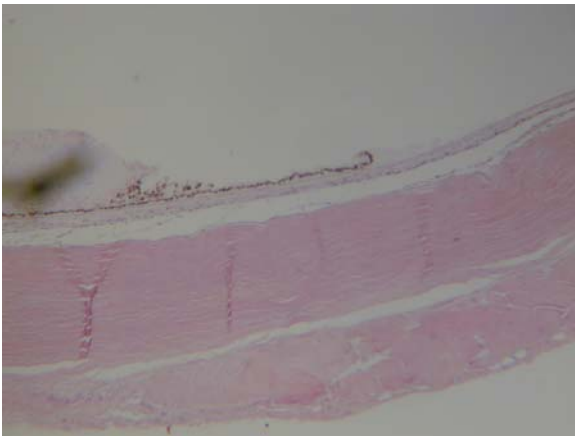


Figure B117. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

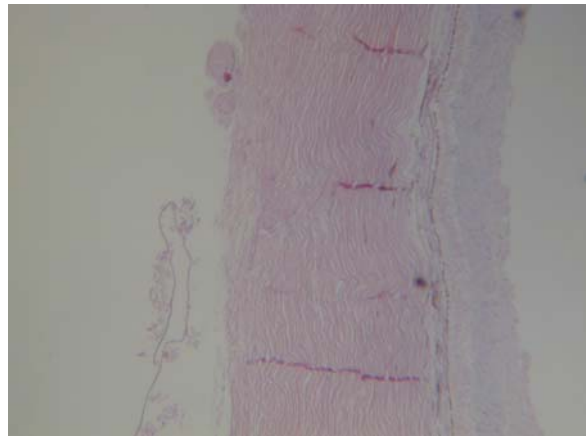


Figure B118. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

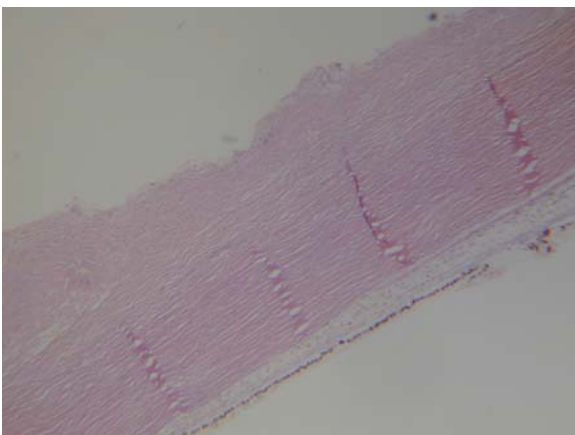


Figure B119. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

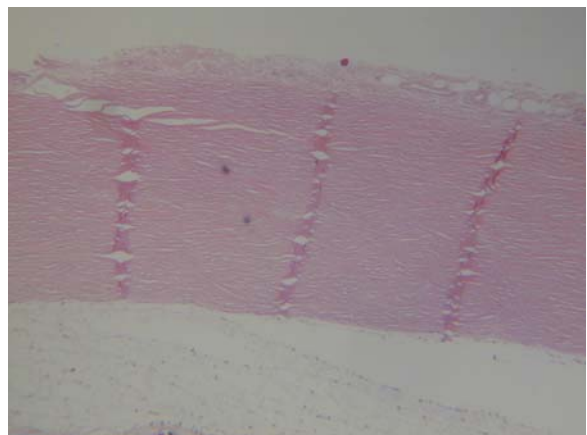


Figure B120. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H011

Sample: 1

Age: 69



Figure B121. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

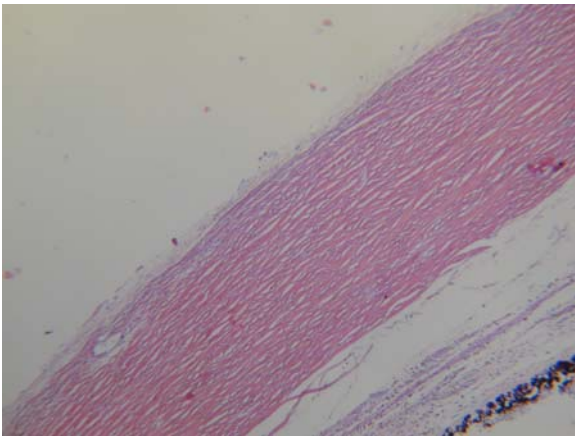


Figure B122. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

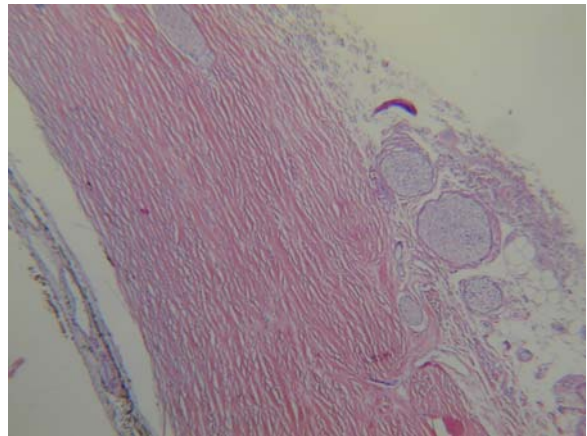


Figure B123. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

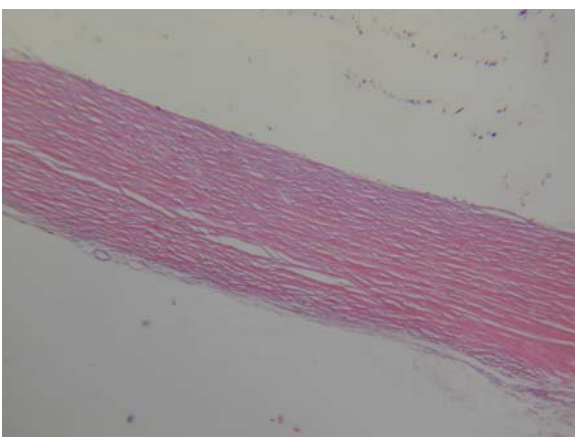


Figure B124. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

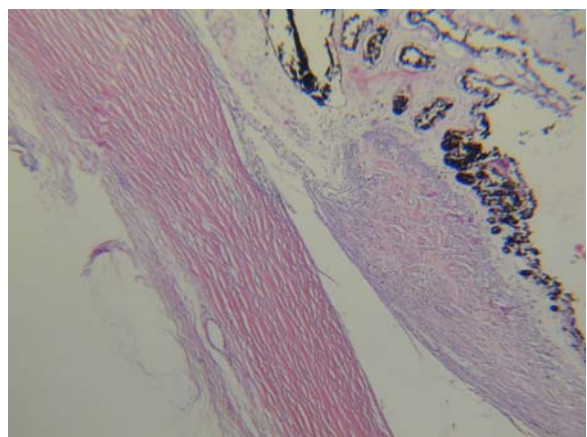


Figure B125. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H011

Sample: 2

Age: 69

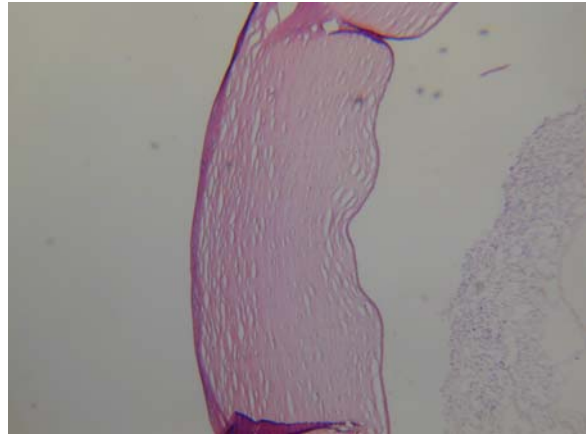


Figure B126. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

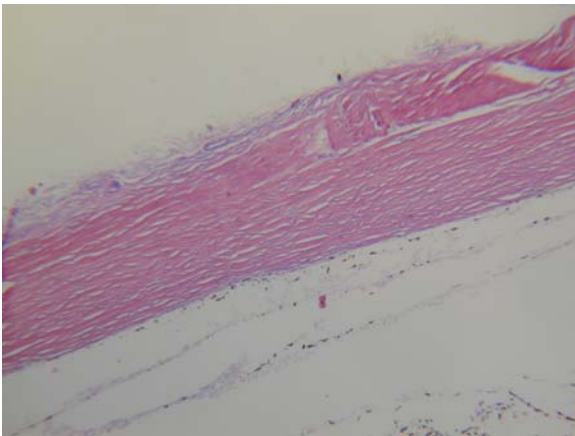


Figure B127. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

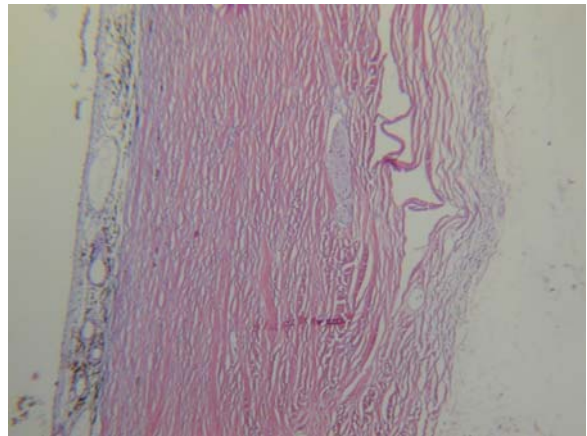


Figure B128. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.



Figure B129. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

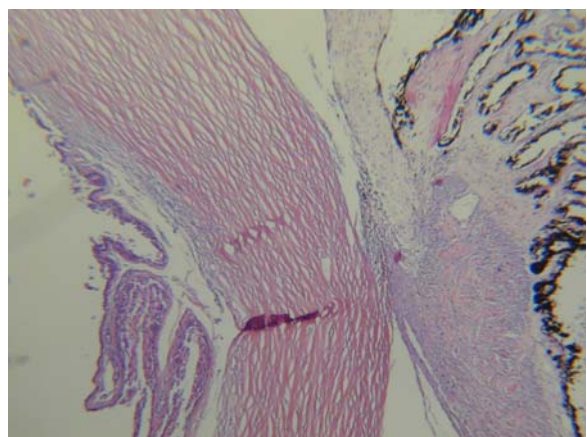


Figure B130. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H012

Sample: 1

Age: 69

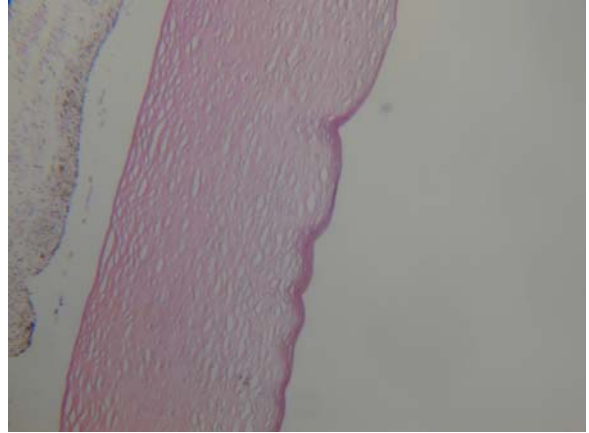


Figure B131. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

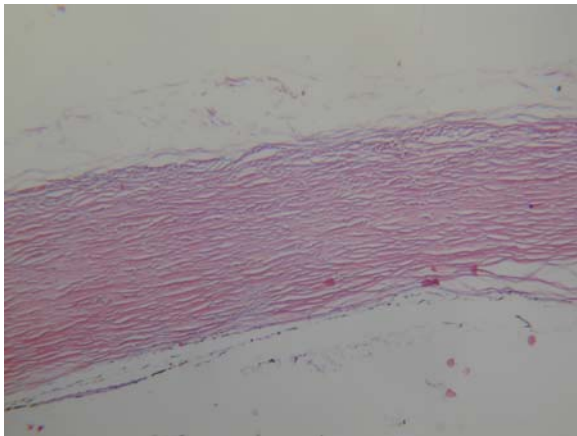


Figure B132. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

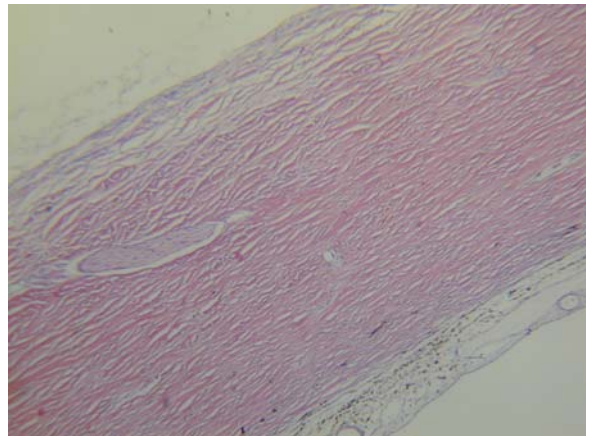


Figure B133. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

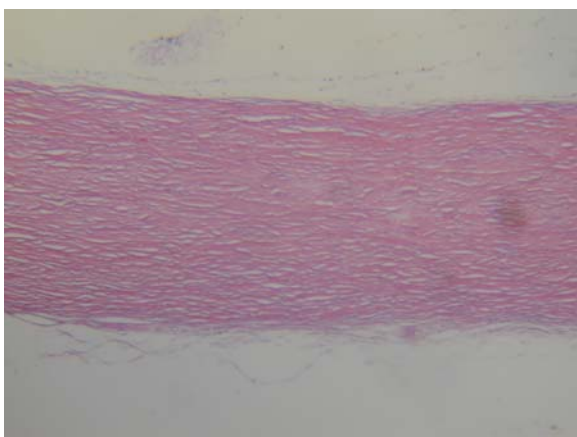


Figure B134. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

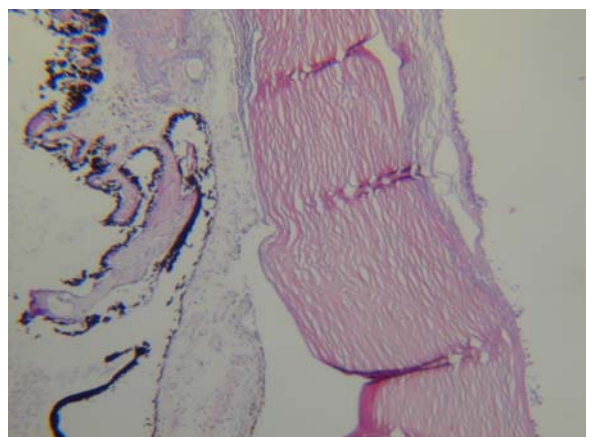


Figure B135. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H012

Sample: 2

Age: 69

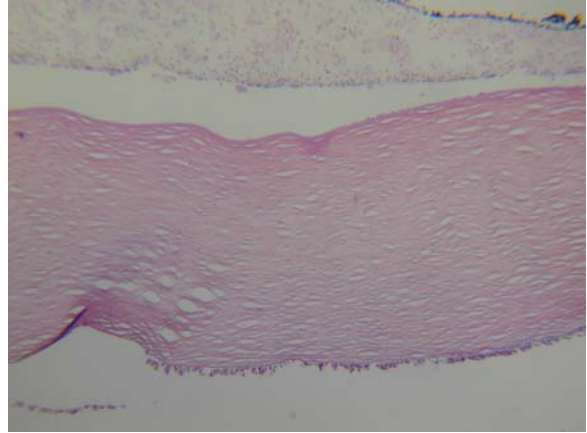


Figure B136. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

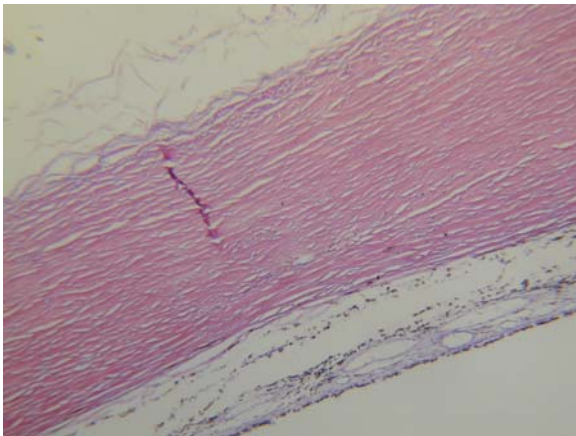


Figure B137. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

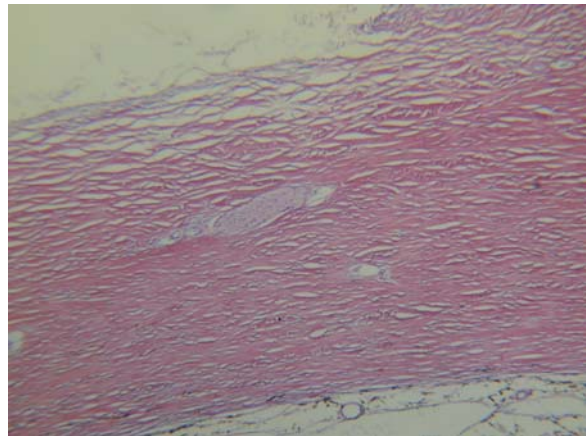


Figure B138. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

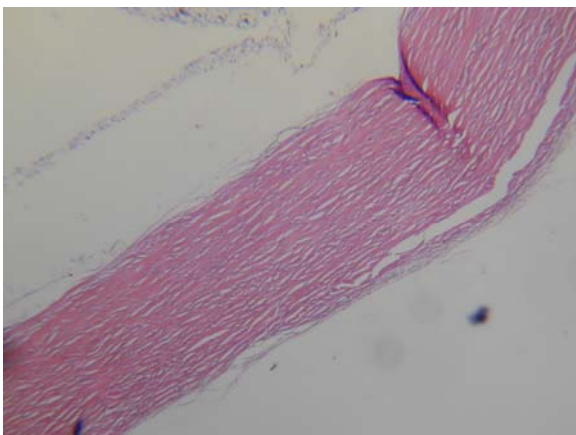


Figure B139. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

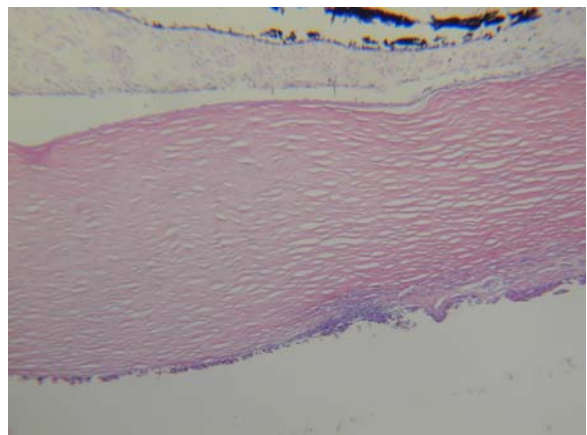


Figure B140. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H013

Sample: 1

Age: 67

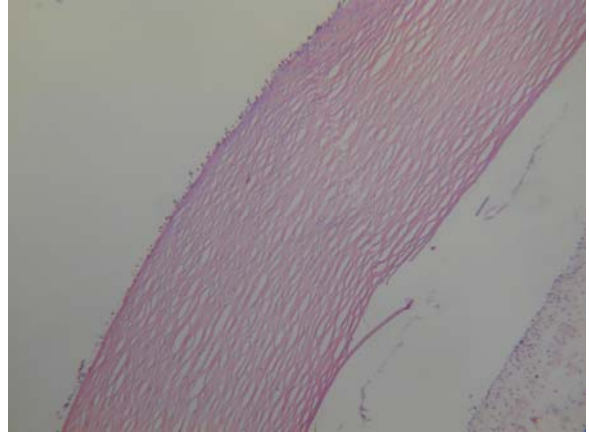


Figure B141. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

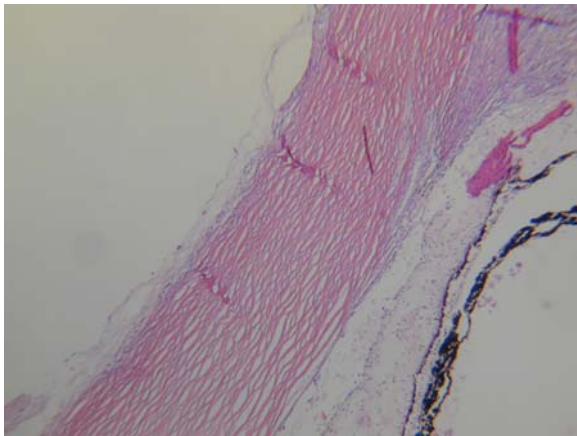


Figure B142. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

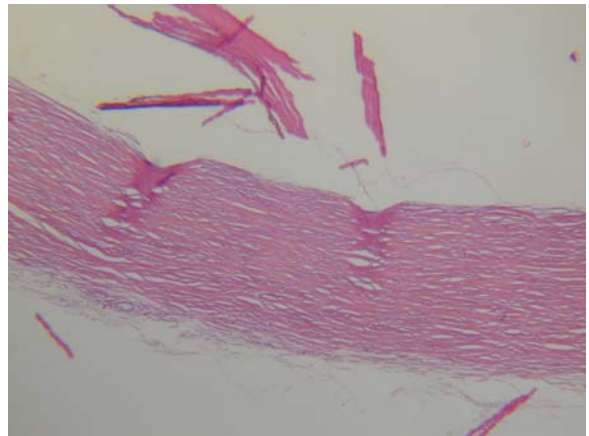


Figure B143. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

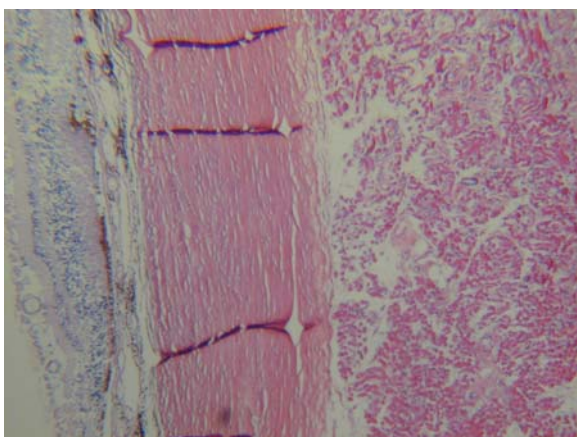


Figure B144. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

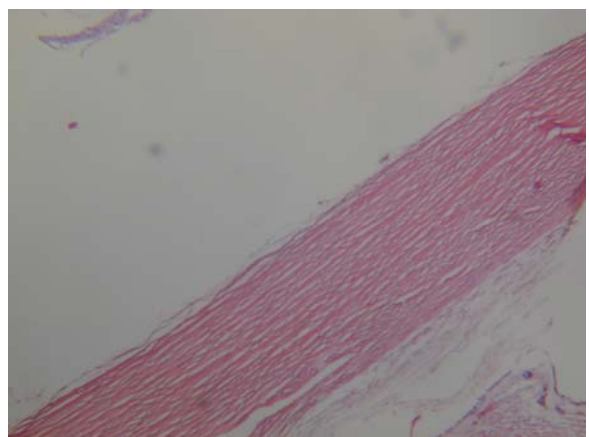


Figure B145. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H013

Sample: 2

Age: 67



Figure B146. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

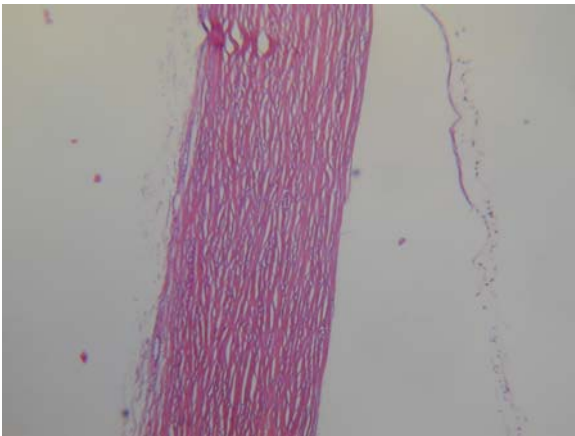


Figure B147. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

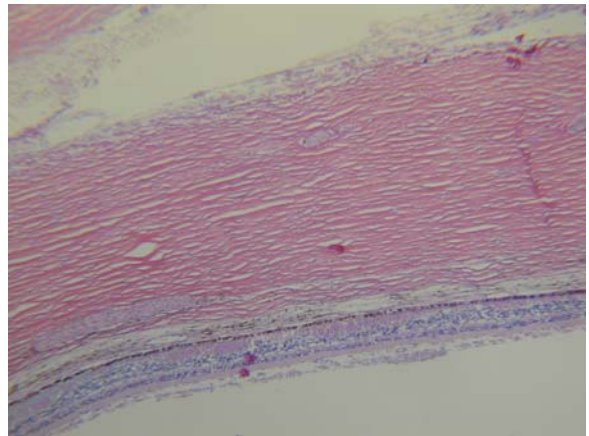


Figure B148. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

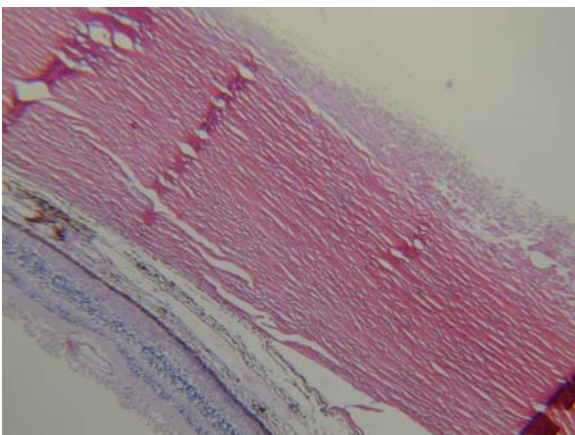


Figure B149. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

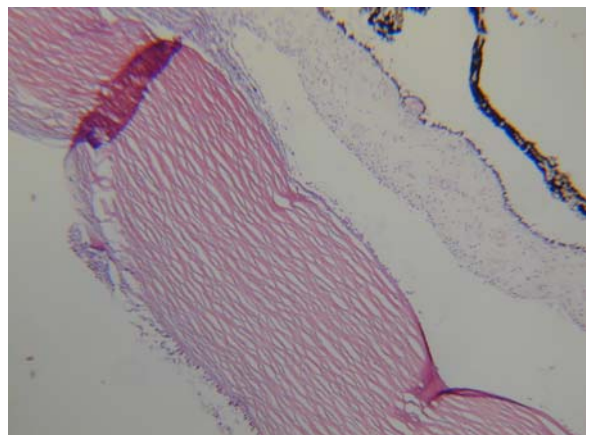


Figure B150. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H014

Sample: 1

Age: 67

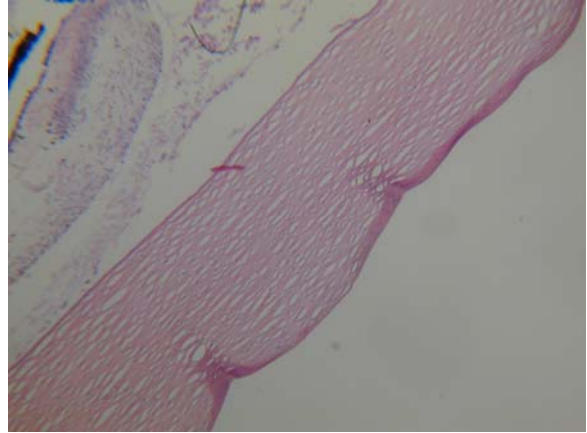


Figure B151. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

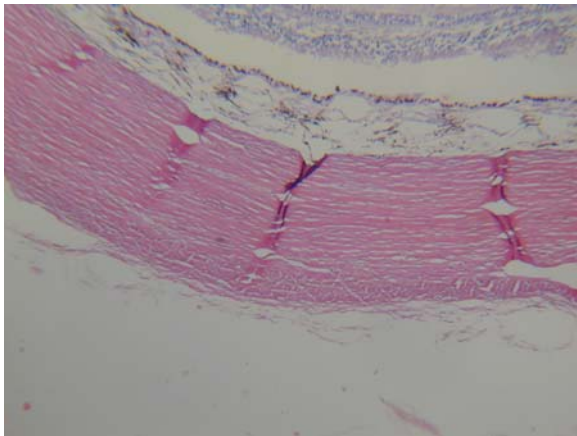


Figure B152. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

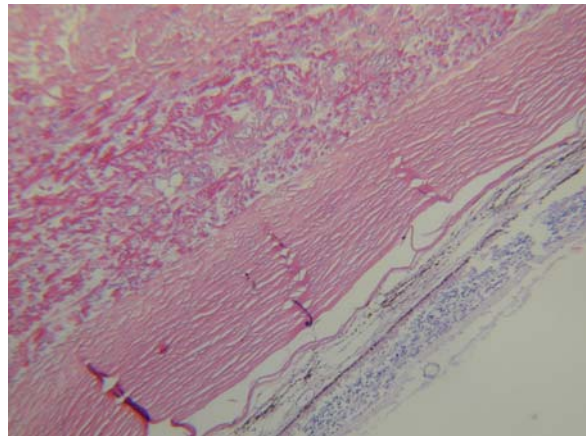


Figure B153. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

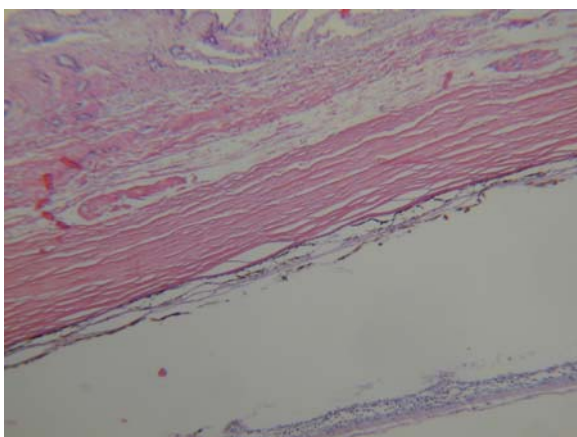


Figure B154. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

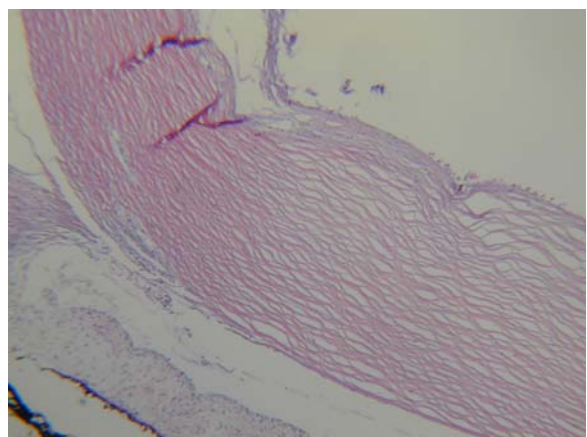


Figure B155. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H014

Sample: 2

Age: 67

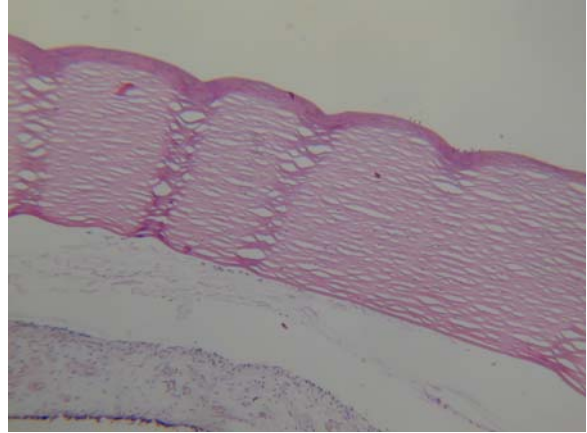


Figure B156. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

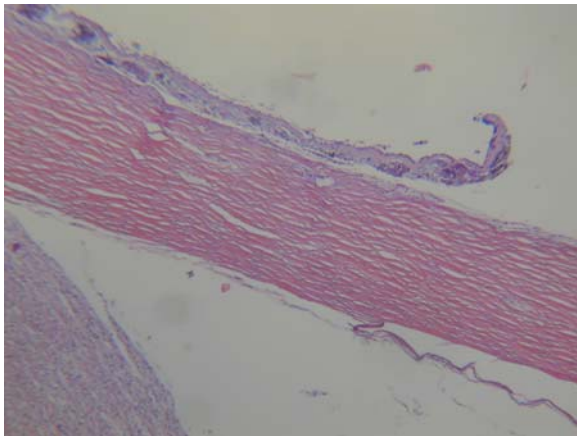


Figure B157. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

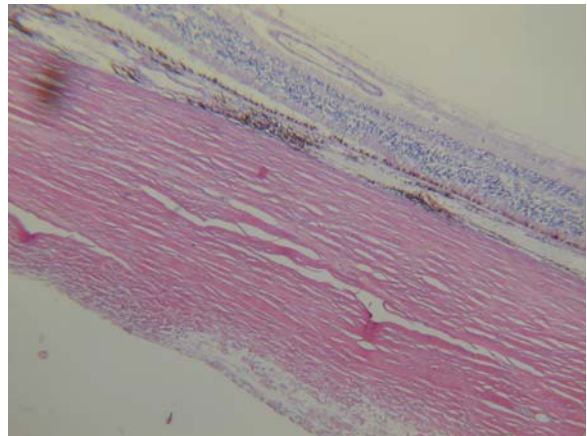


Figure B158. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

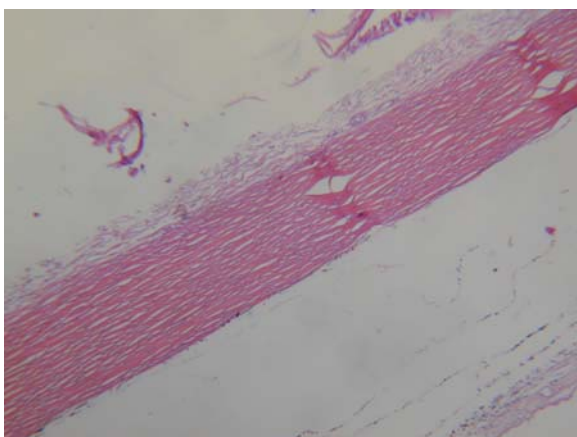


Figure B159. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

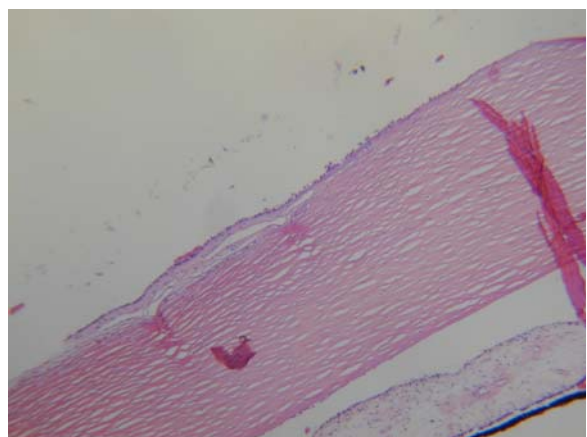


Figure B160. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H015

Sample: 1

Age: 57

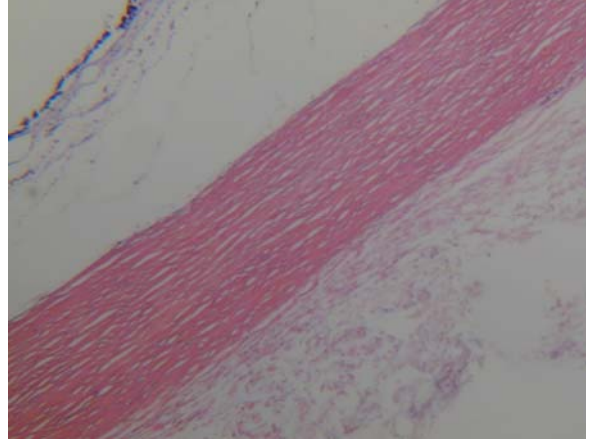


Figure B161. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

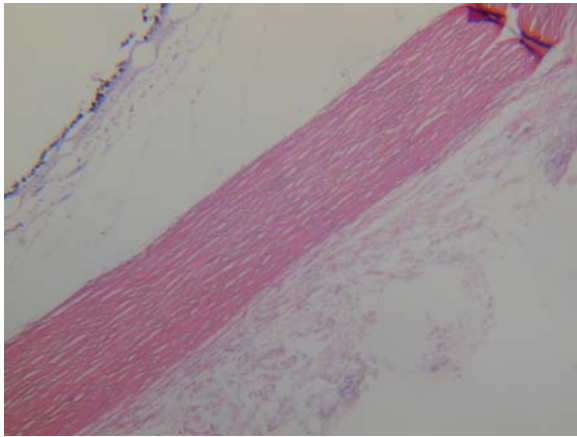


Figure B162. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

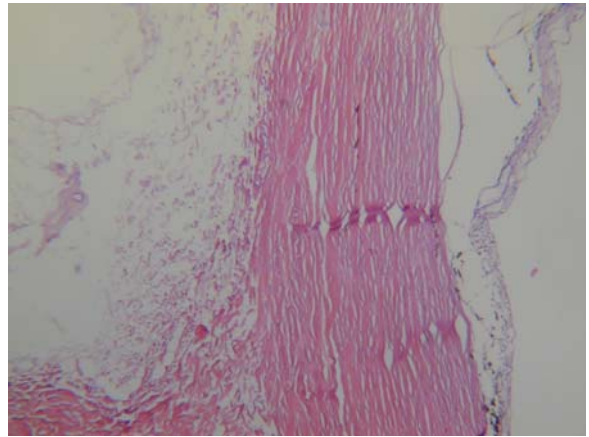


Figure B163. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

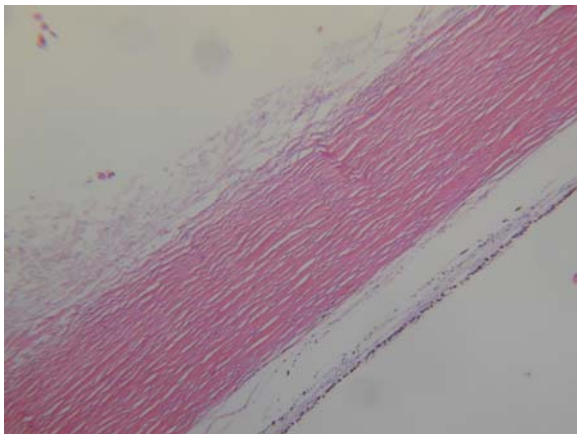


Figure B164. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

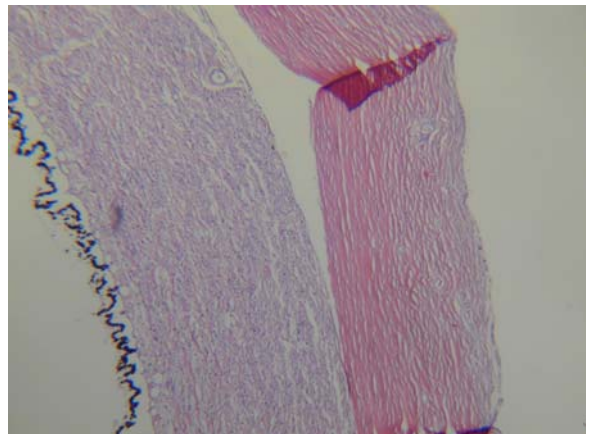


Figure B165. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H015

Sample: 2

Age: 57

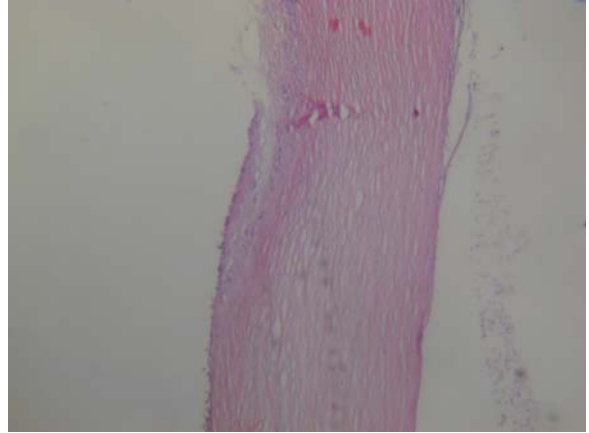


Figure B166. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

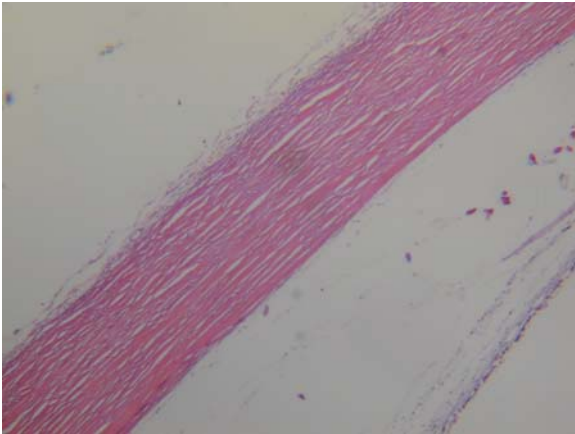


Figure B167. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

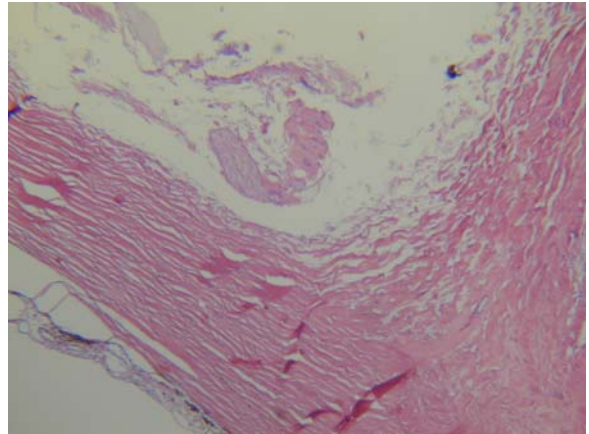


Figure B168. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.



Figure B169. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

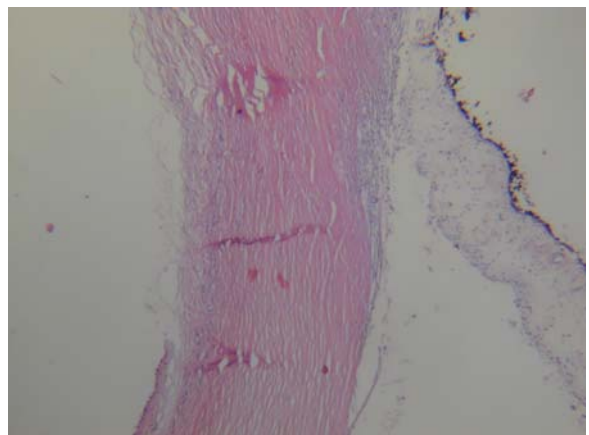


Figure B170. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H016

Sample: 1

Age: 57



Figure B171. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

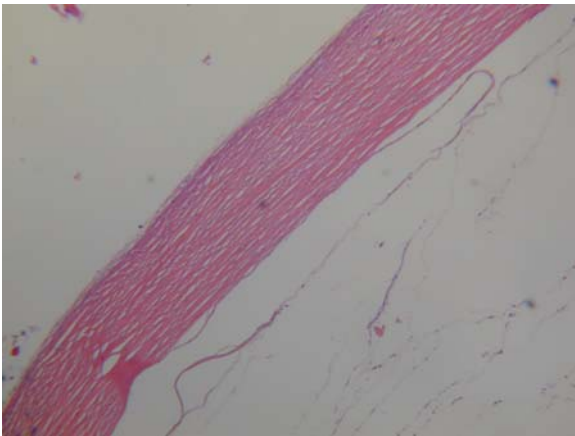


Figure B172. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

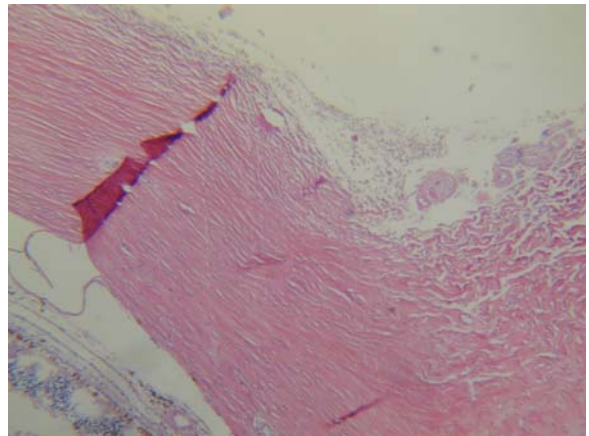


Figure B173. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

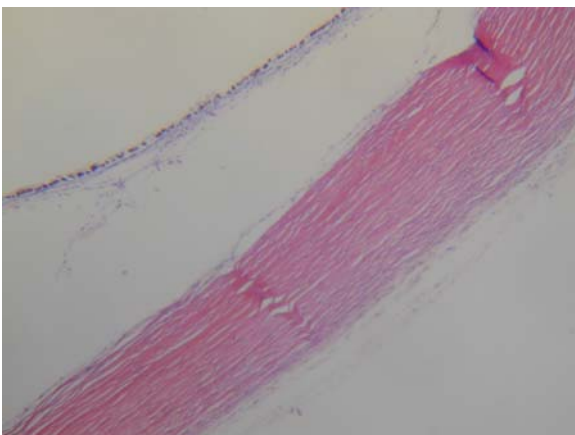


Figure B174. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

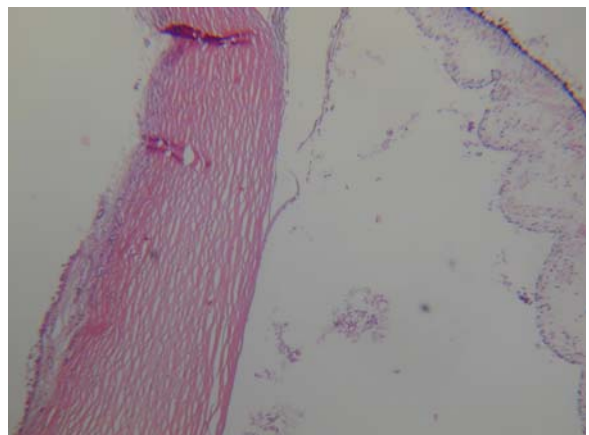


Figure B175. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H016

Sample: 2

Age: 57

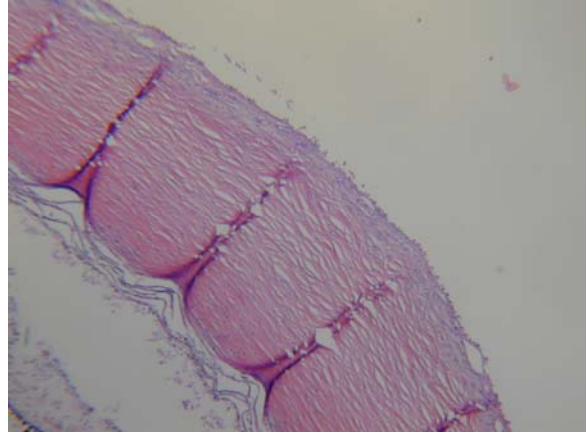


Figure B176. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.



Figure B177. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

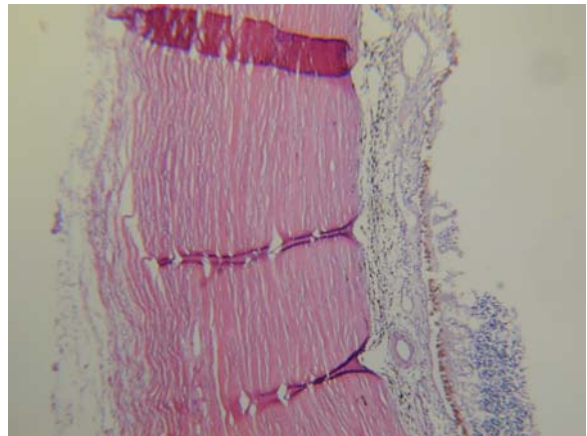


Figure B178. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

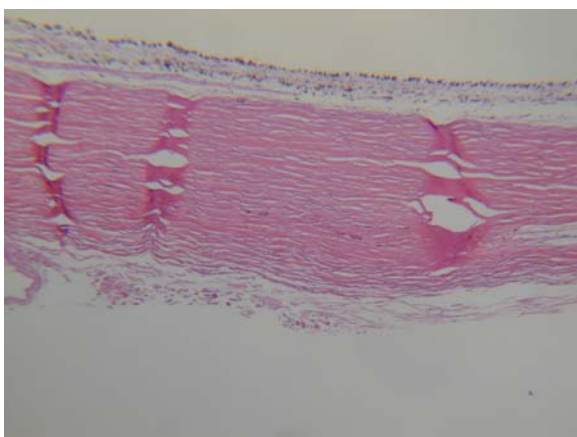


Figure B179. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

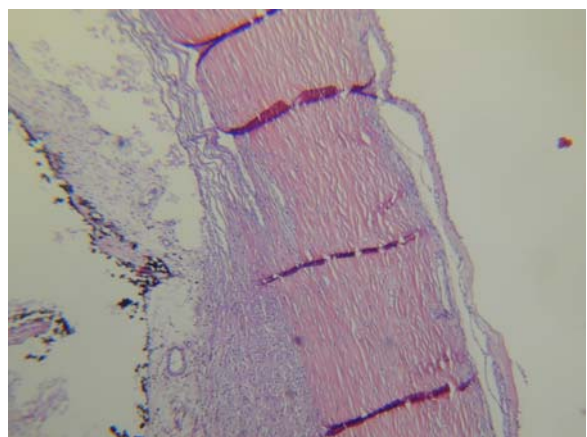


Figure B180. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H017

Sample: 1

Age: 70

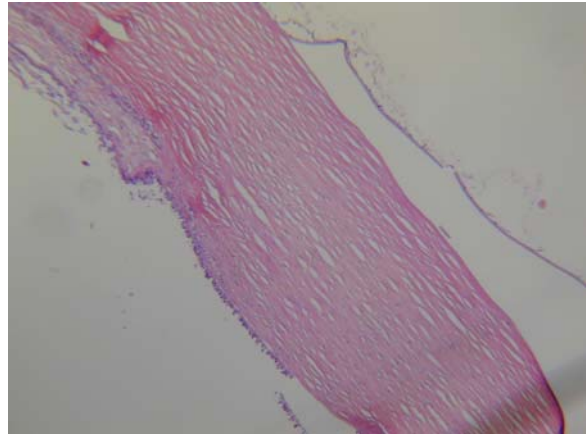


Figure B181. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

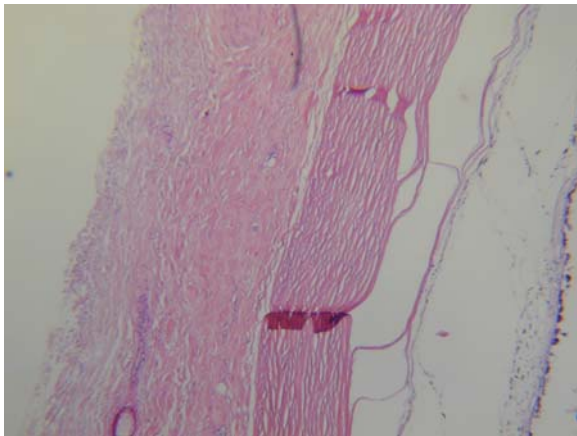


Figure B182. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

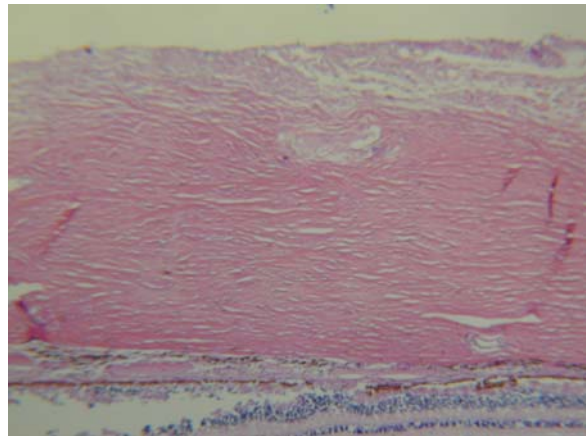


Figure B183. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

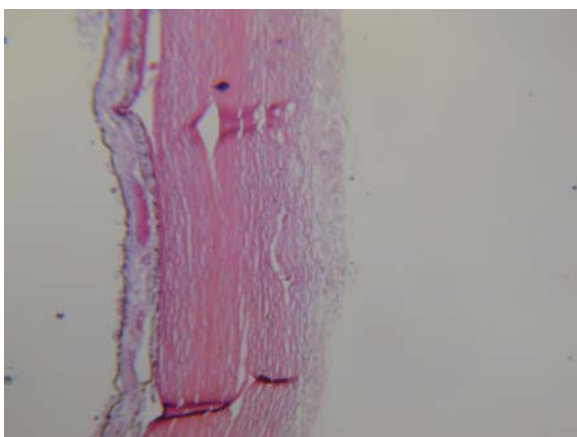


Figure B184. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

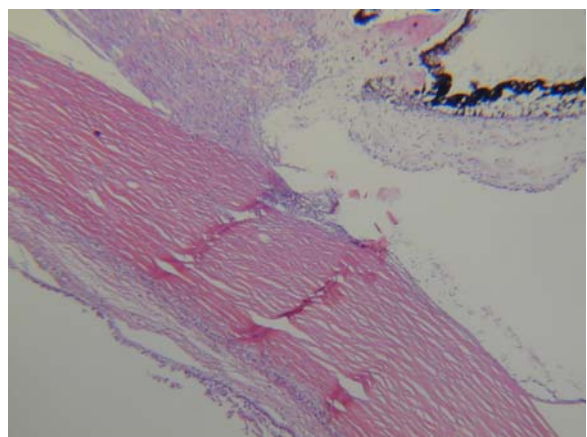


Figure B185. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H017

Sample: 2

Age: 70

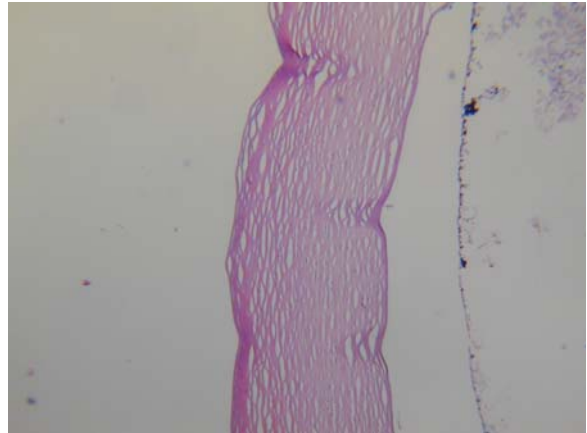


Figure B186. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

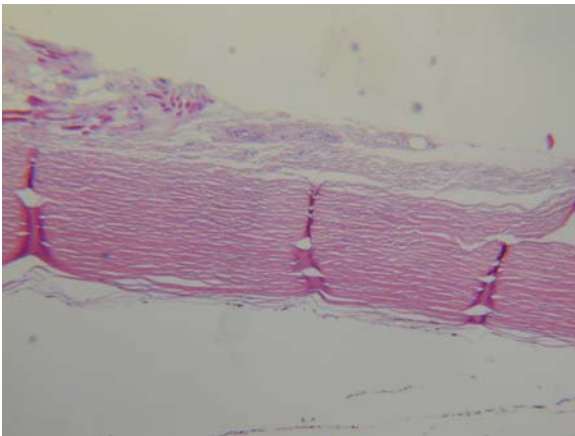


Figure B187. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

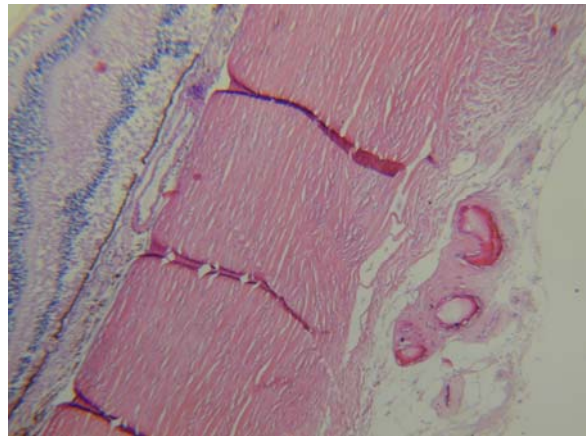


Figure B188. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

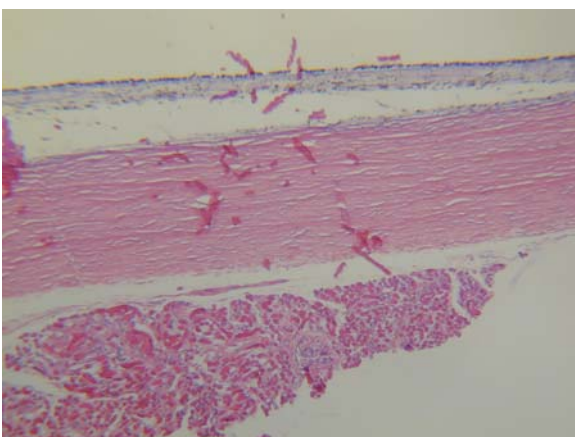


Figure B189. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

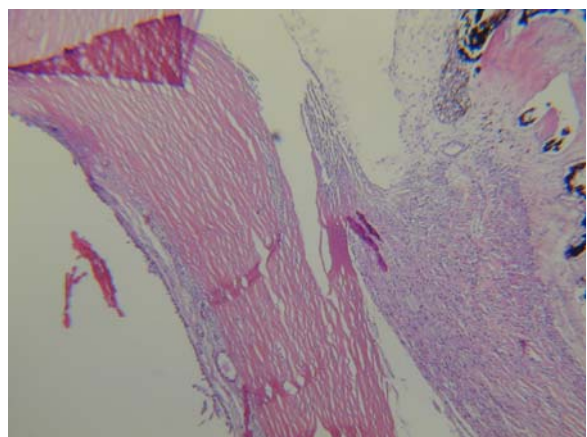


Figure B190. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H018

Sample: 1

Age: 70

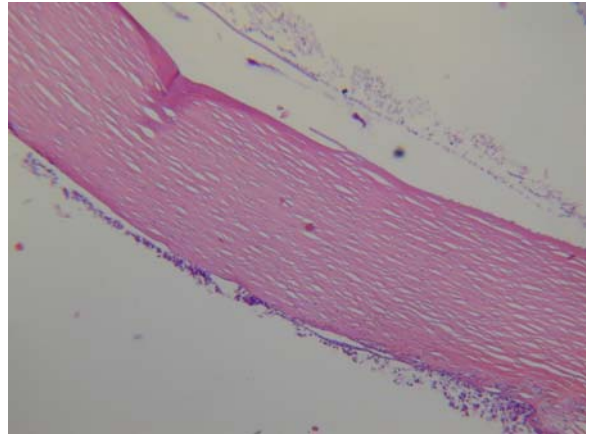


Figure B191. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

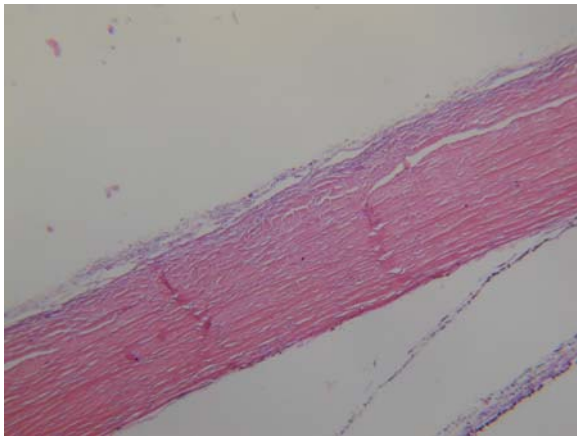


Figure B192. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

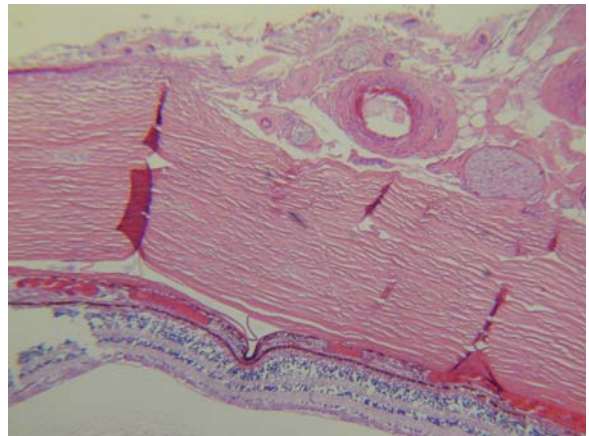


Figure B193. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

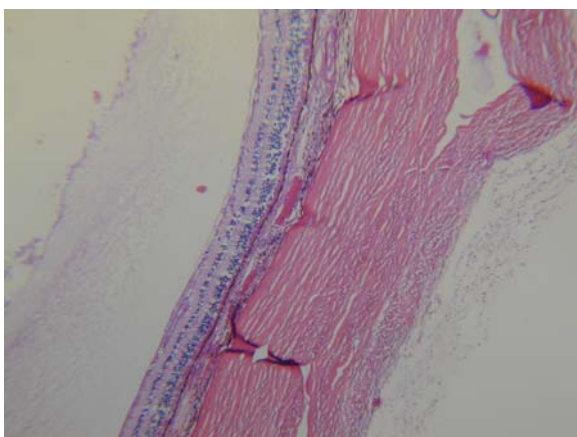


Figure B194. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

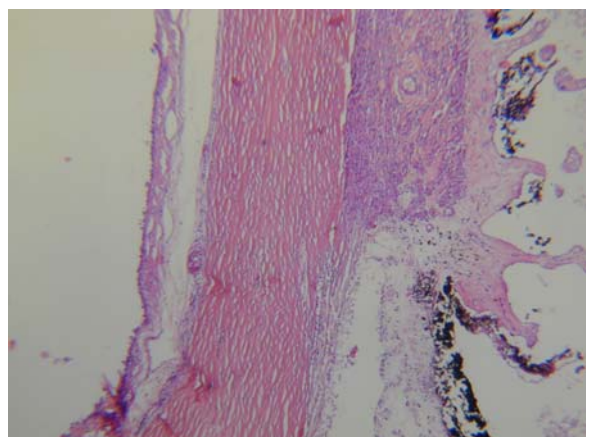


Figure B195. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H018

Sample: 2

Age: 70



Figure B196. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

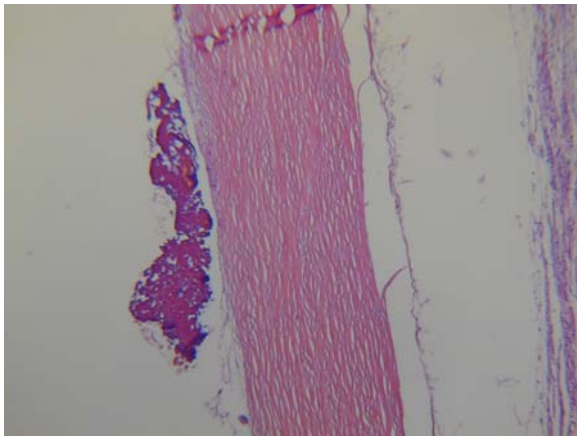


Figure B197. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

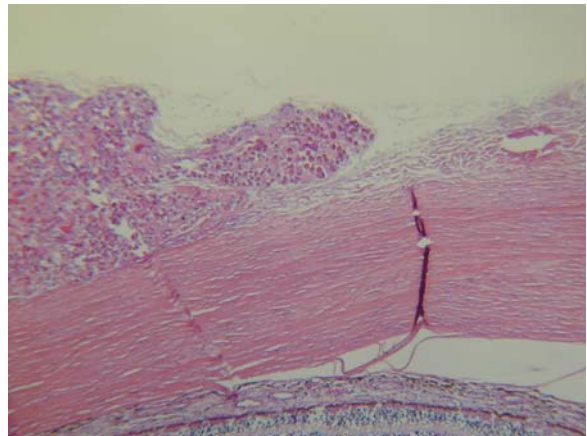


Figure B198. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

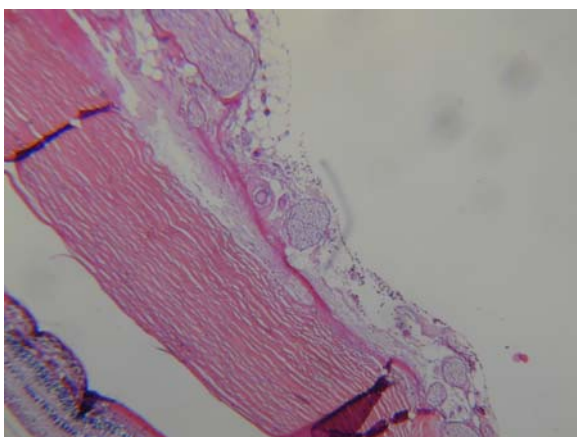


Figure B199. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

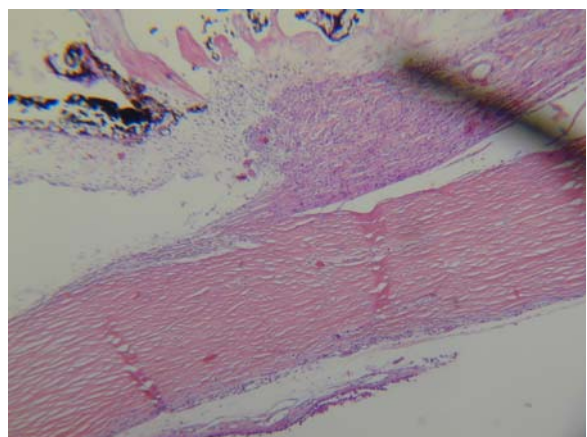


Figure B200. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H019

Sample: 1

Age: 71

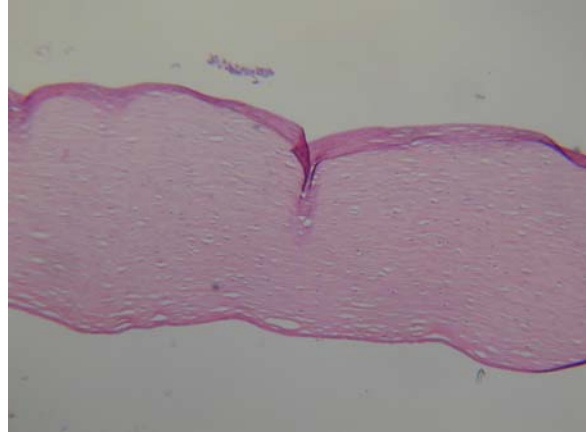


Figure B201. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

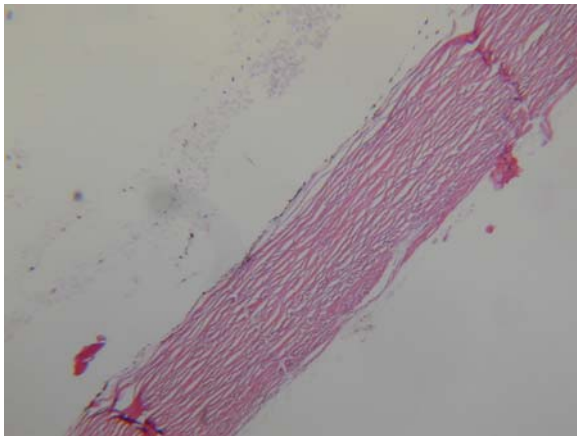


Figure B202. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

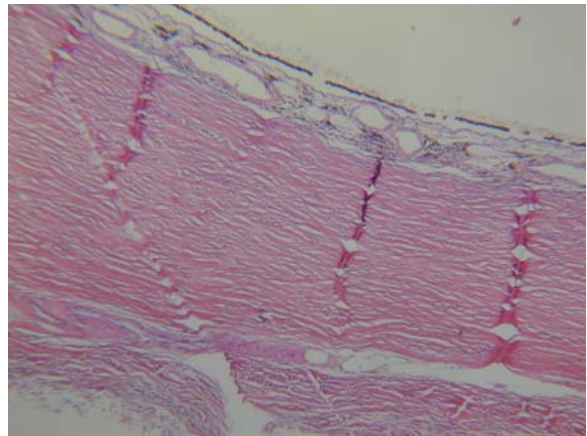


Figure B203. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

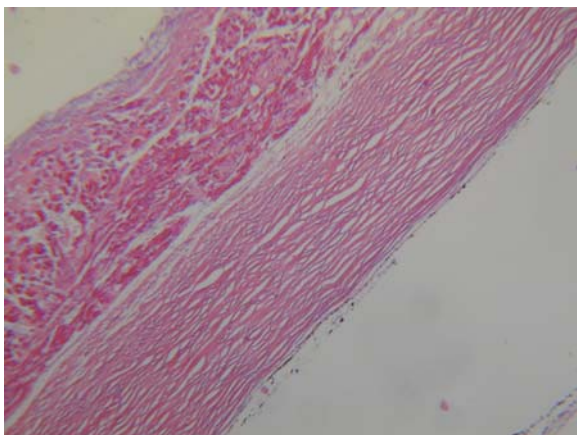


Figure B204. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

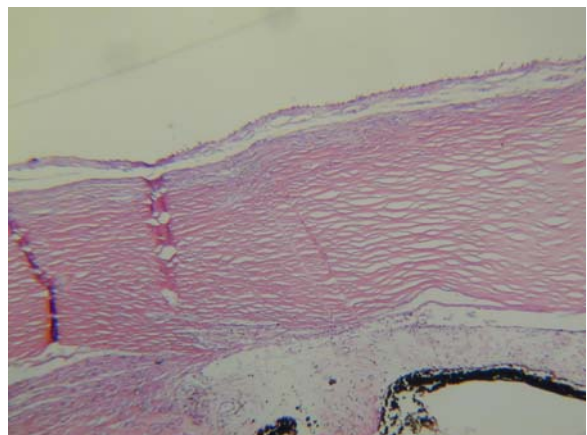


Figure B205. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H019

Sample: 2

Age: 71



Figure B206. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

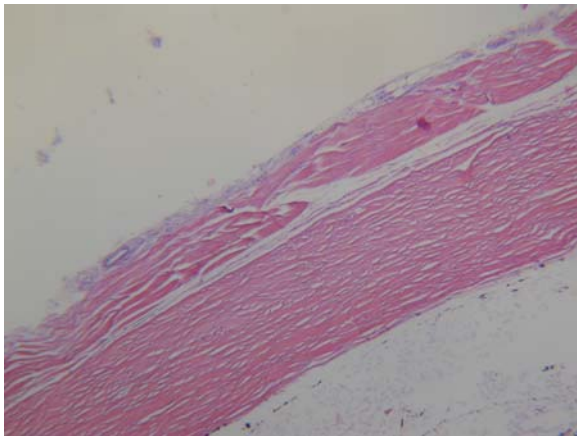


Figure B207. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

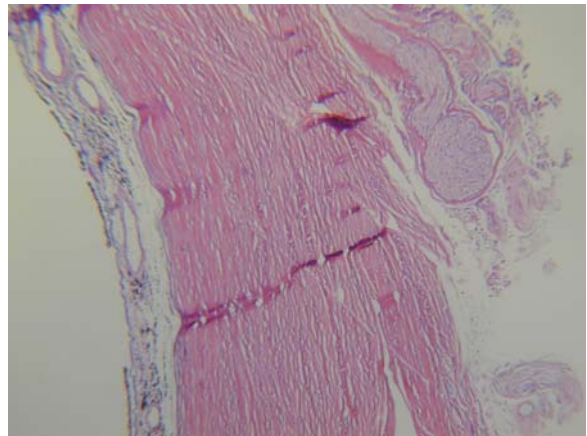


Figure B208. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.



Figure B209. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

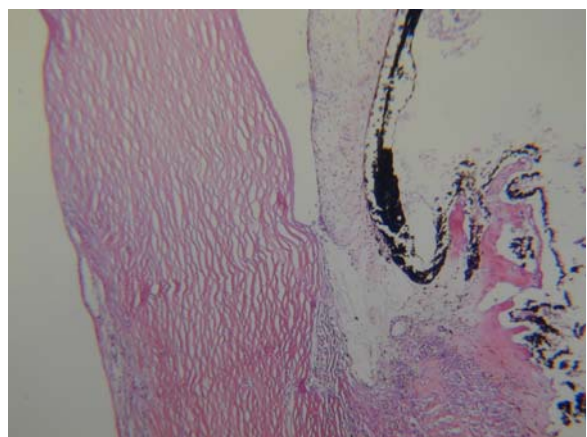


Figure B210. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H020

Sample: 1

Age: 71

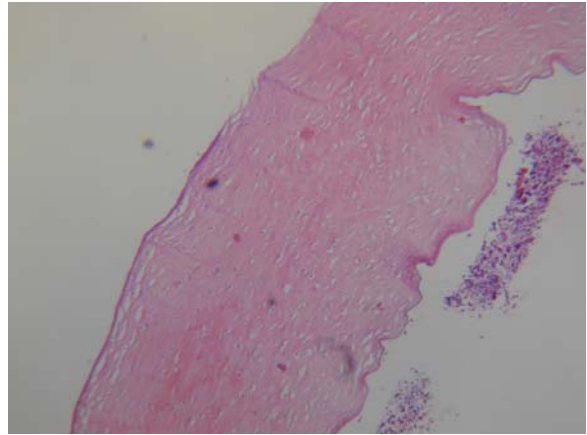


Figure B211. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

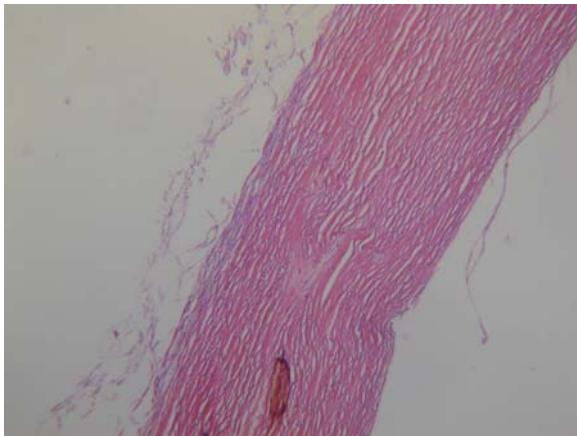


Figure B212. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

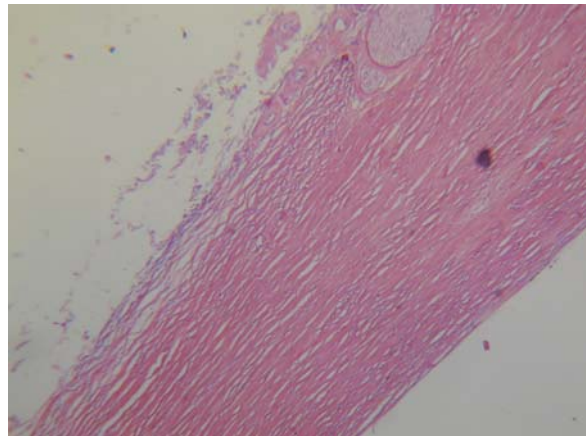


Figure B213. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

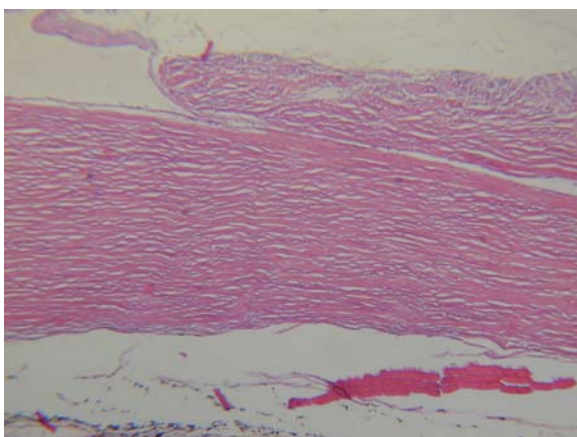


Figure B214. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

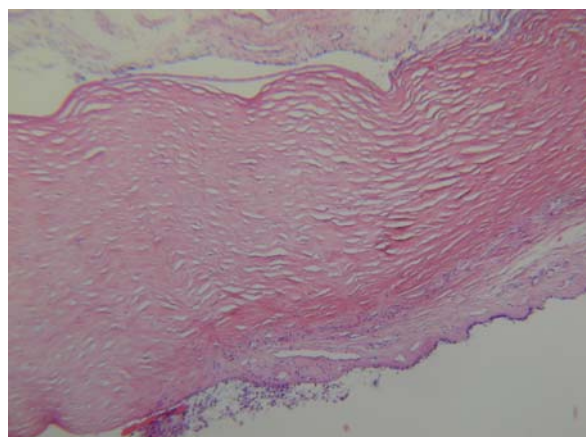


Figure B215. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H020

Sample: 2

Age: 71

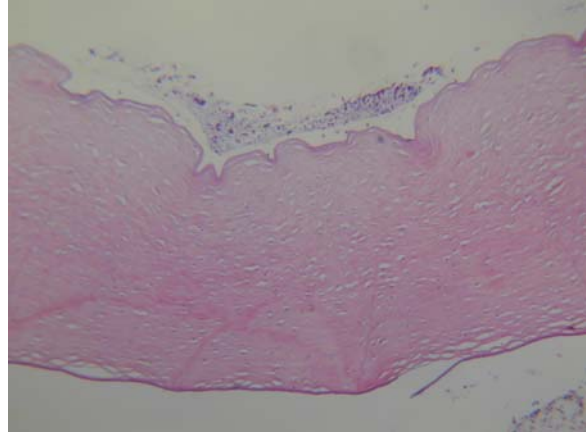


Figure B216. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

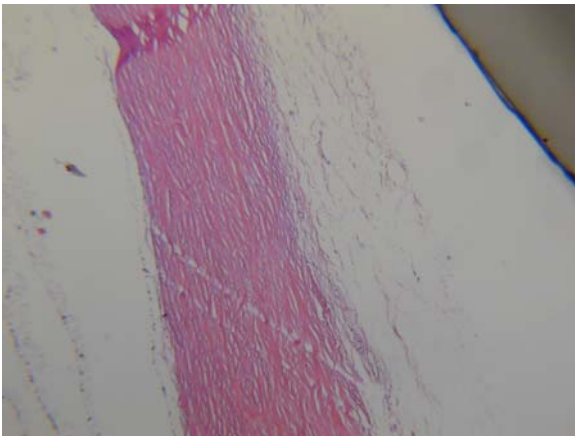


Figure B217. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

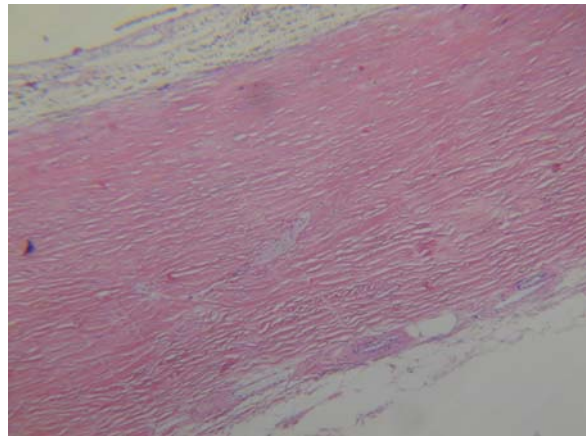


Figure B218. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

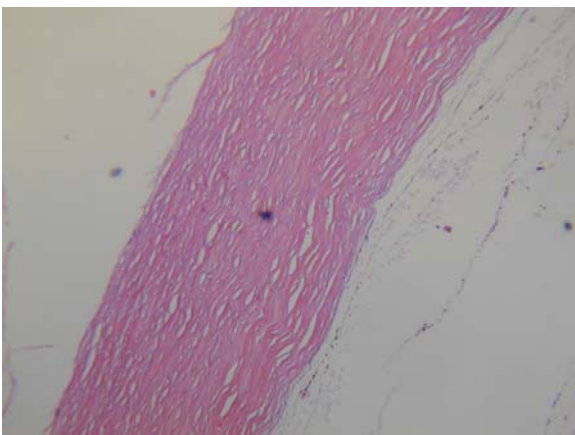


Figure B219. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

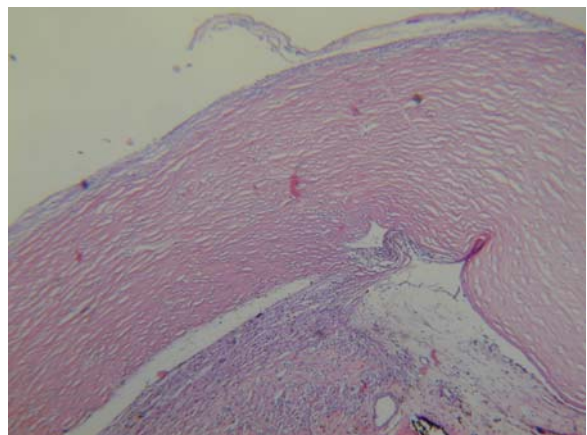


Figure B220. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H021

Sample: 1

Age: 68

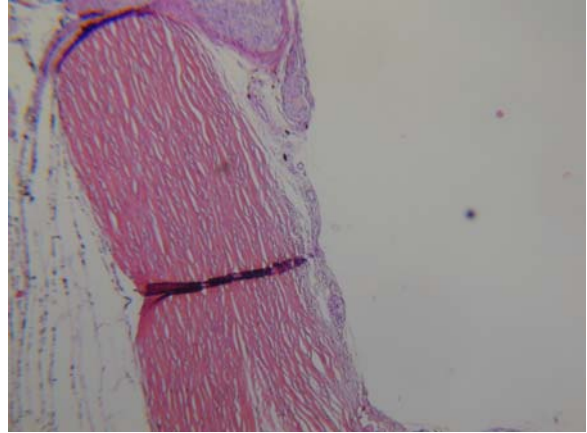


Figure B221. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

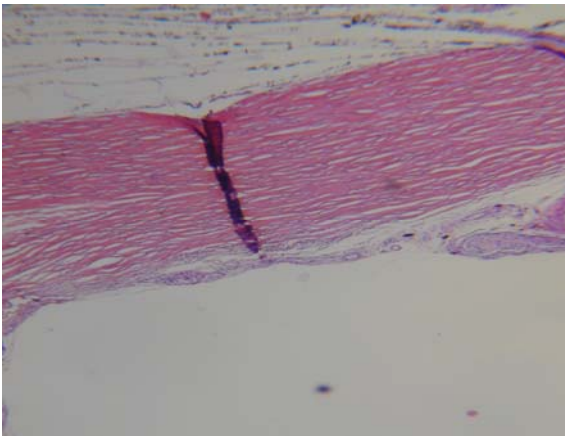


Figure B222. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

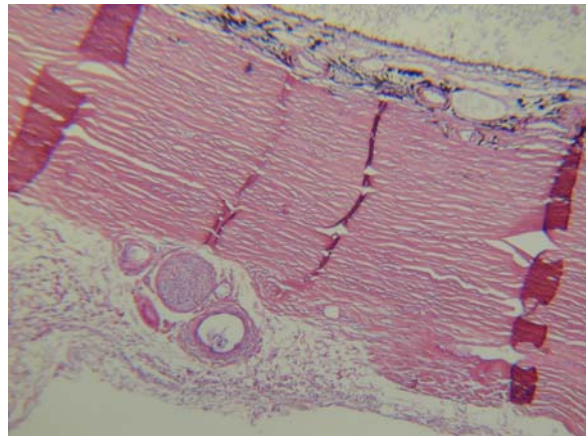


Figure B223. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

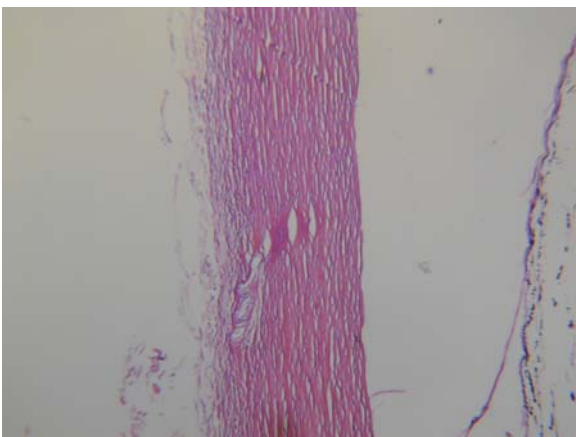


Figure B224. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

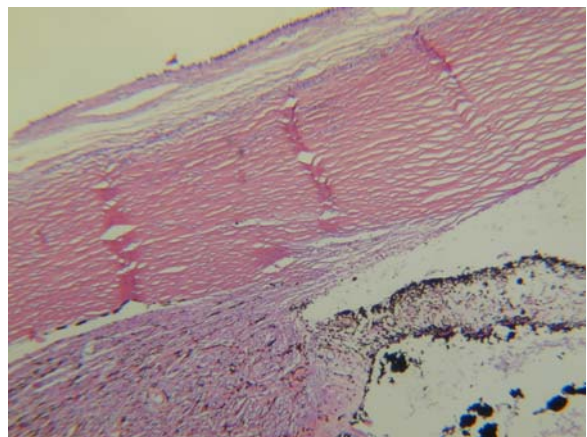


Figure B225. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H021

Sample: 2

Age: 68

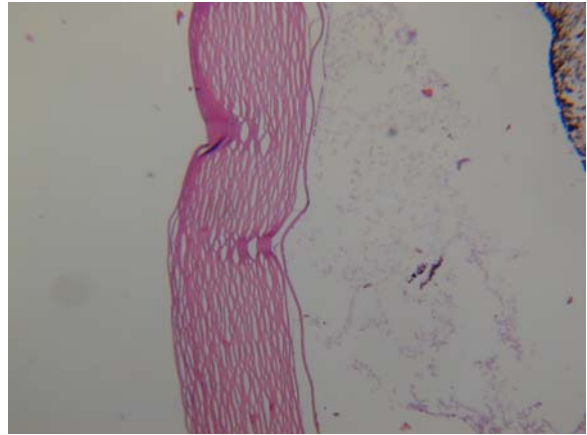


Figure B226. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

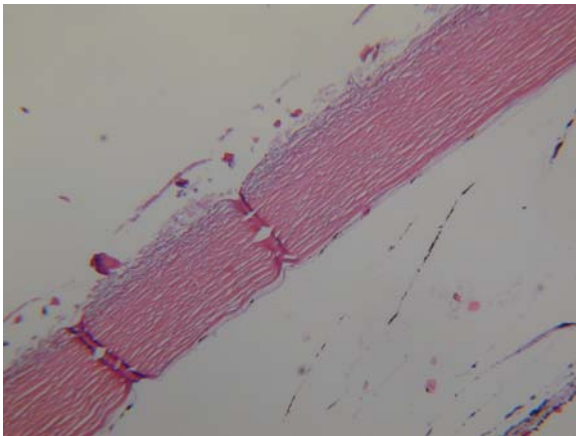


Figure B227. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

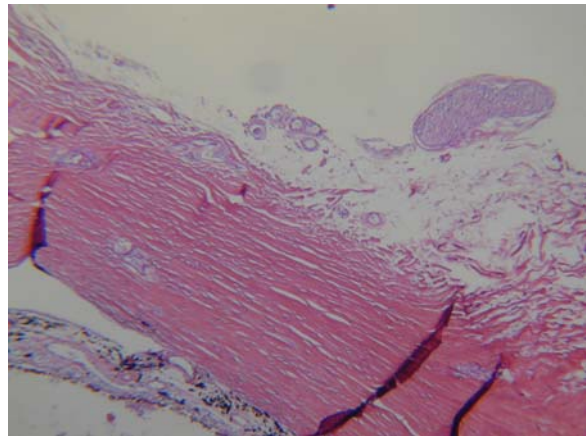


Figure B228. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

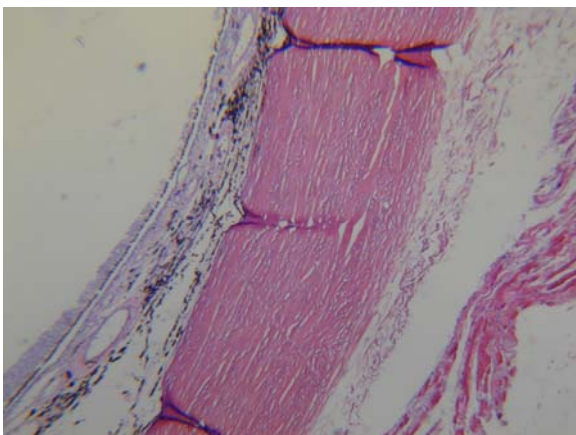


Figure B229. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

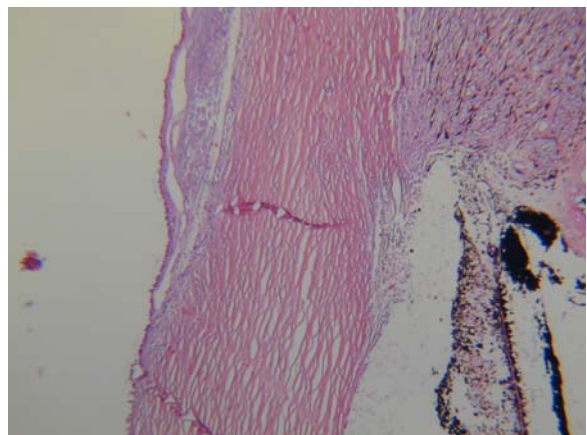


Figure B230. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H022

Sample: 1

Age: 58



Figure B231. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

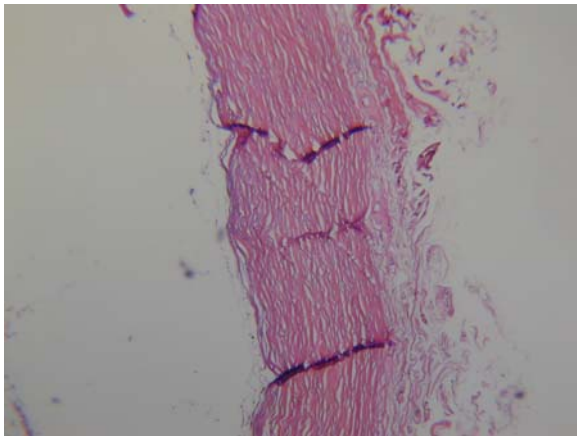


Figure B232. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

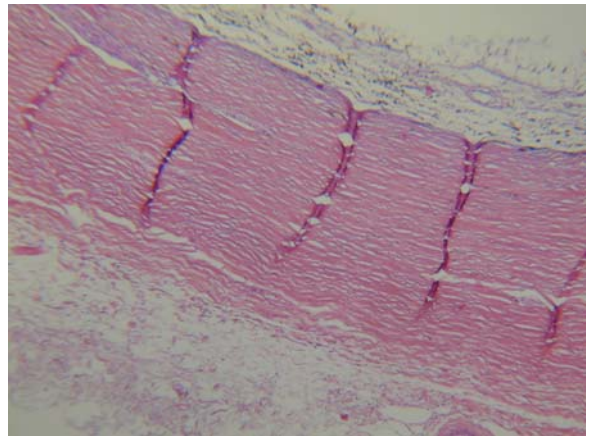


Figure B233. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

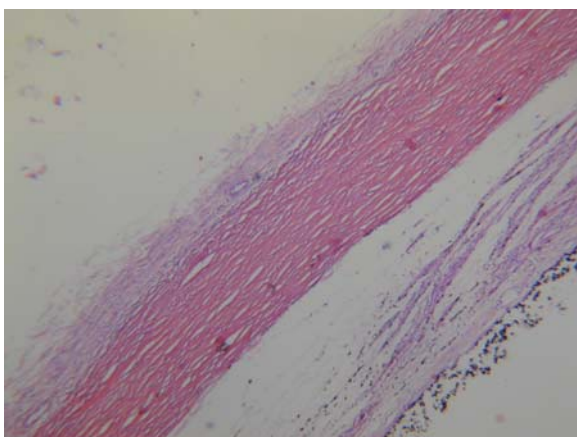


Figure B234. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

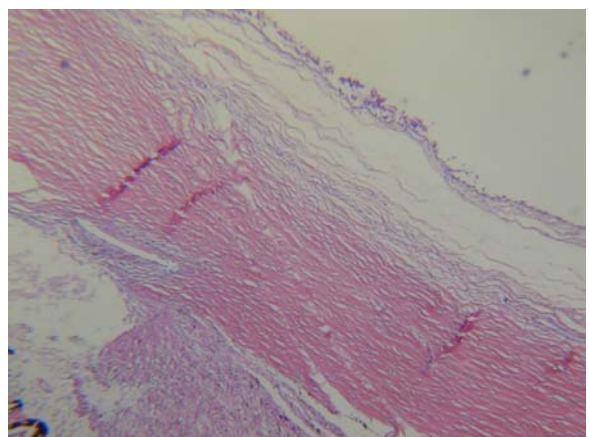


Figure B235. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H022

Sample: 2

Age: 58



Figure B236. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

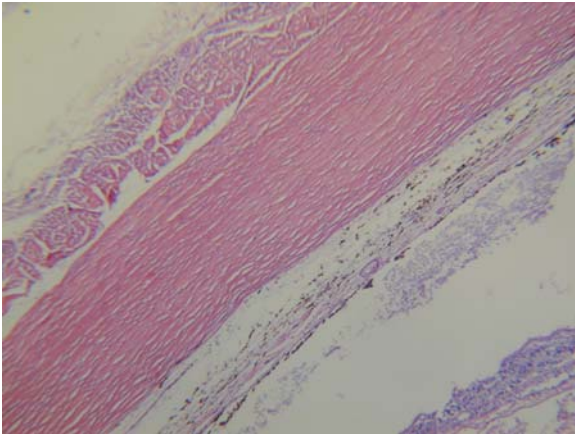


Figure B237. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

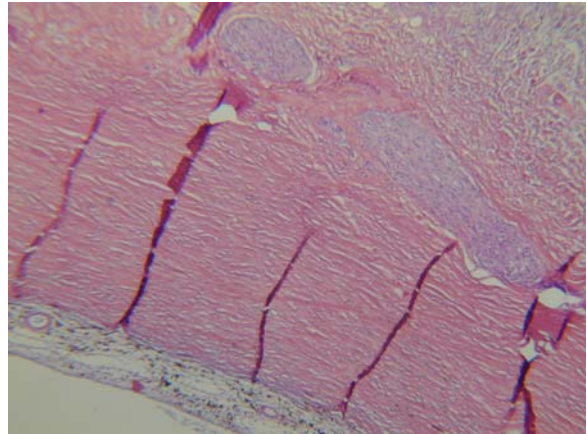


Figure B238. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

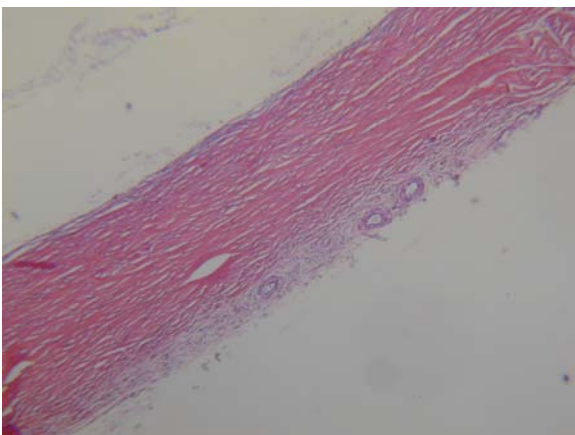


Figure B239. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

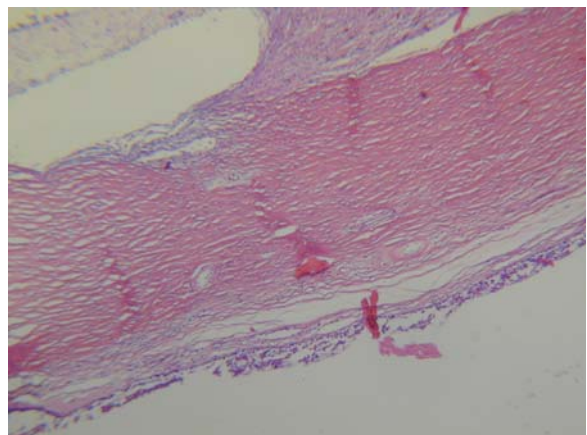


Figure B240. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H023

Sample: 1

Age: --

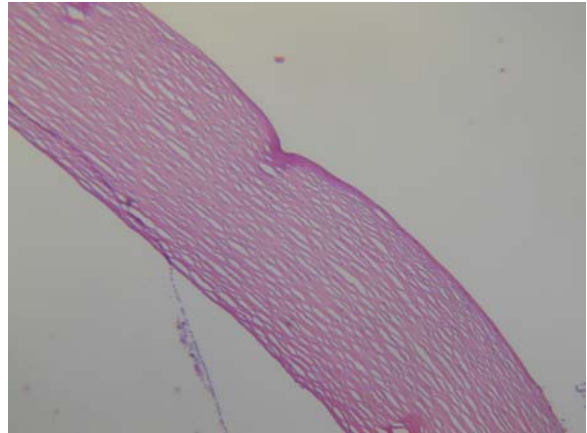


Figure B241. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

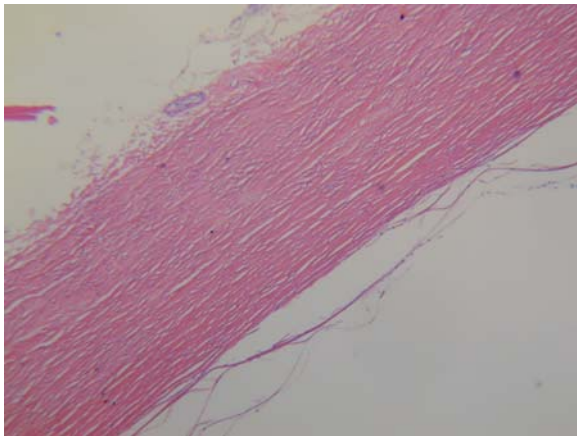


Figure B242. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

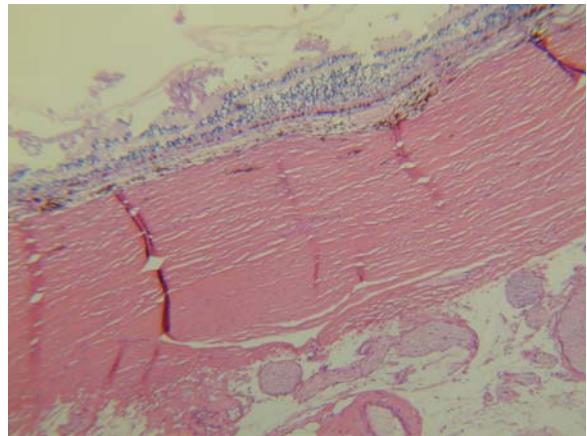


Figure B243. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

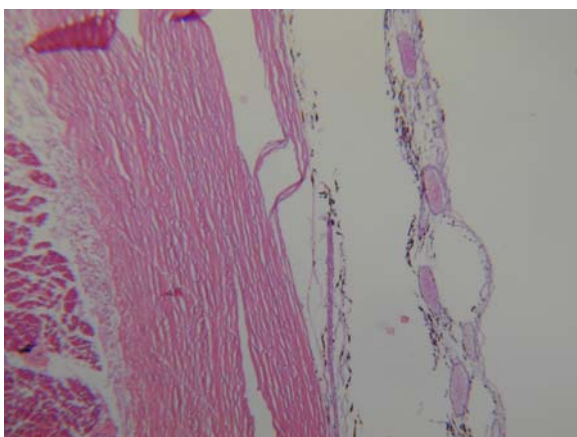


Figure B244. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

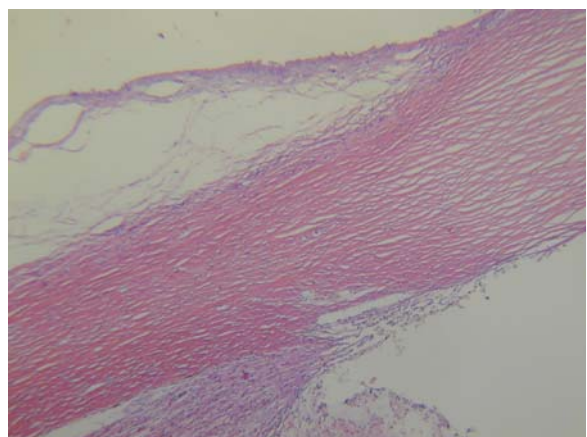


Figure B245. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H023

Sample: 2

Age: --

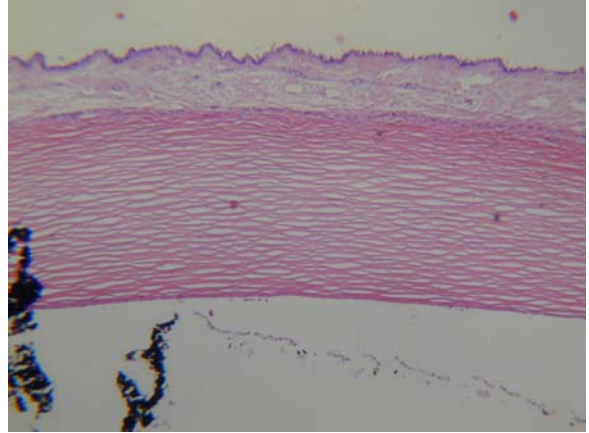


Figure B246. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

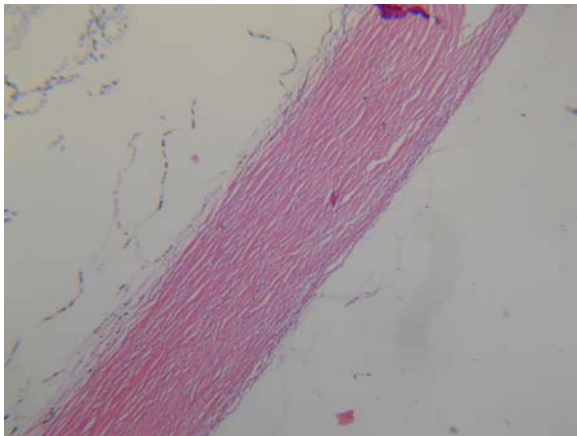


Figure B247. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

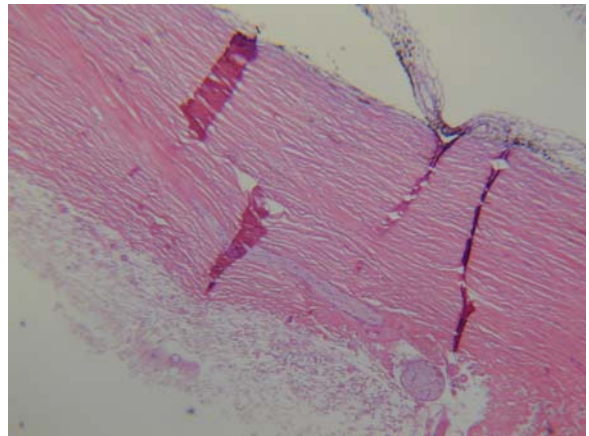


Figure B248. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

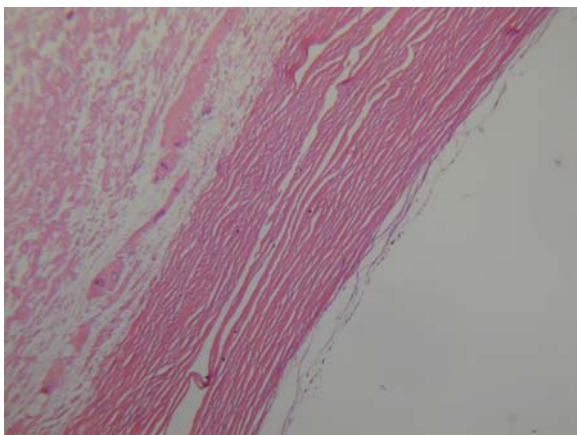


Figure B249. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

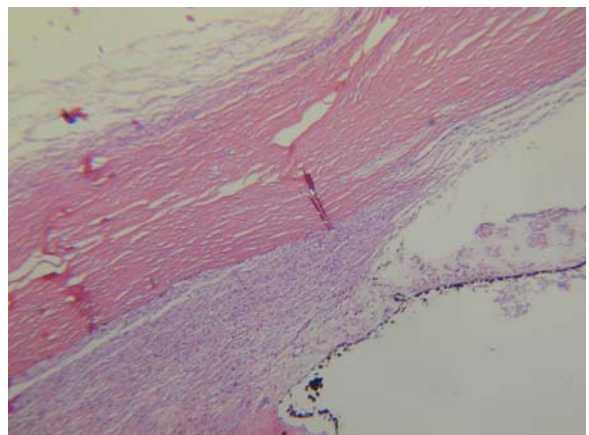


Figure B250. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H024

Sample: 1

Age: 73



Figure B251. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

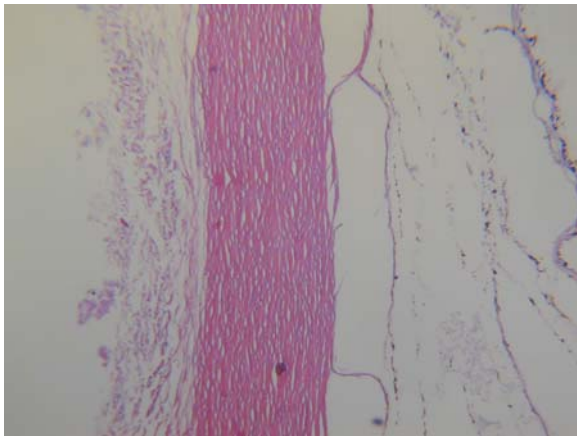


Figure B252. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

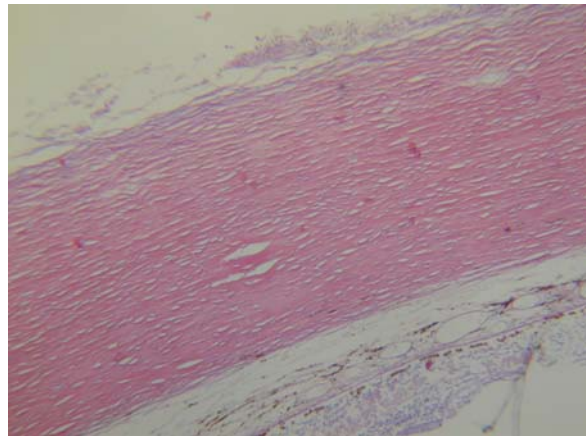


Figure B253. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

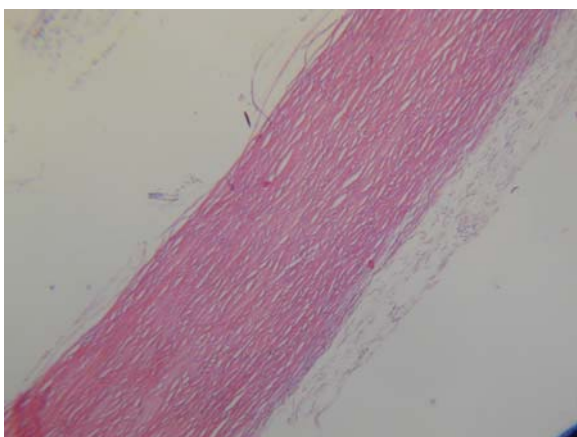


Figure B254. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

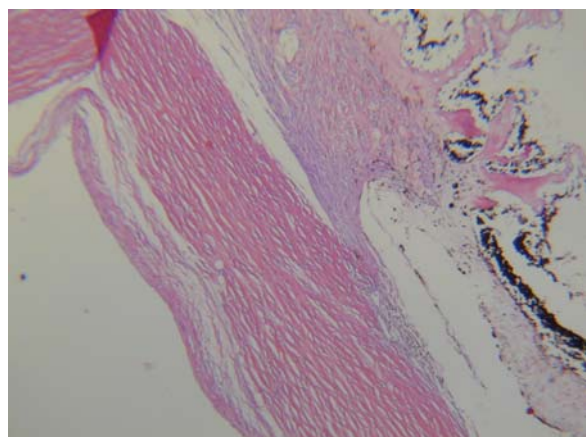


Figure B255. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H024

Sample: 2

Age: 73

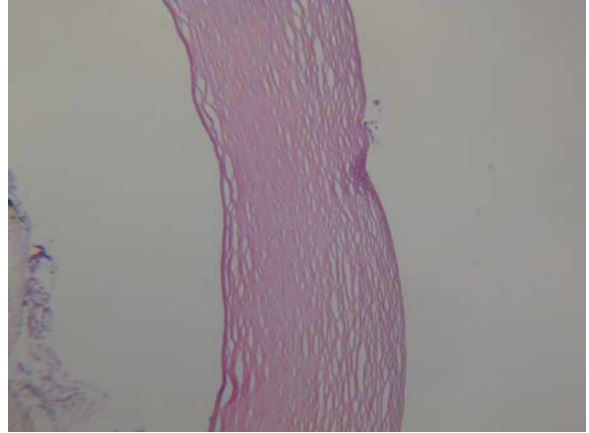


Figure B256. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

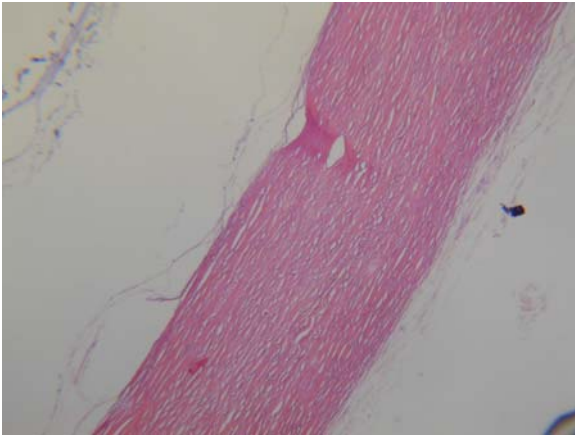


Figure B257. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

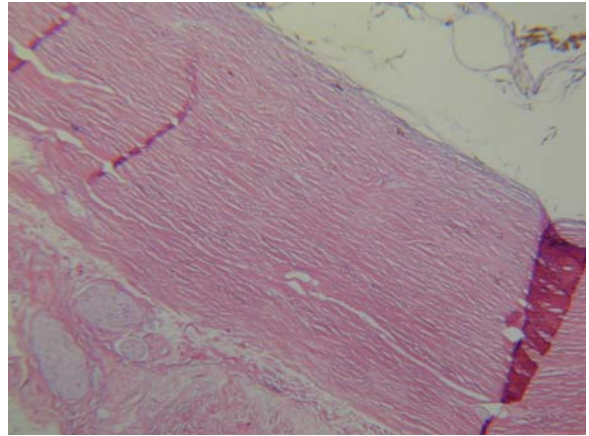


Figure B258. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

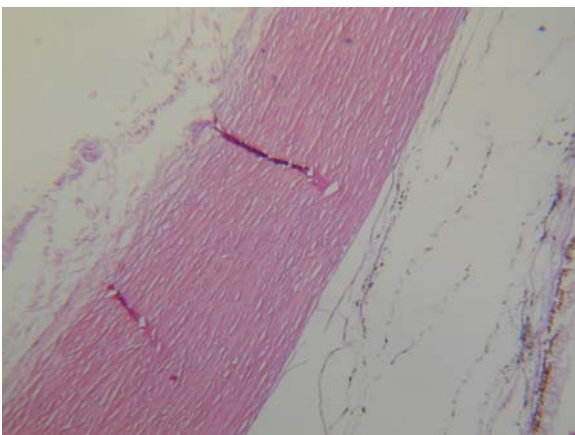


Figure B259. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

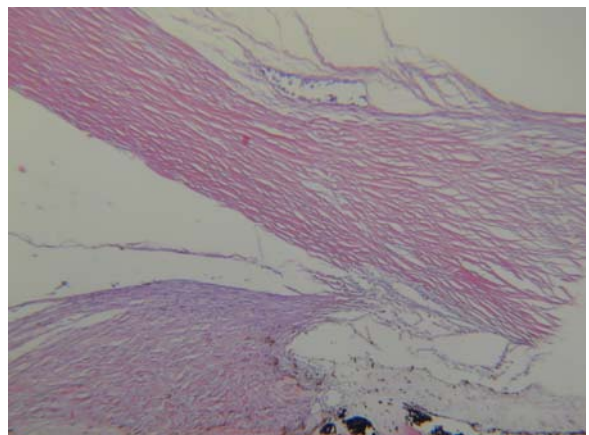


Figure B260. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H025

Sample: 1

Age: 72

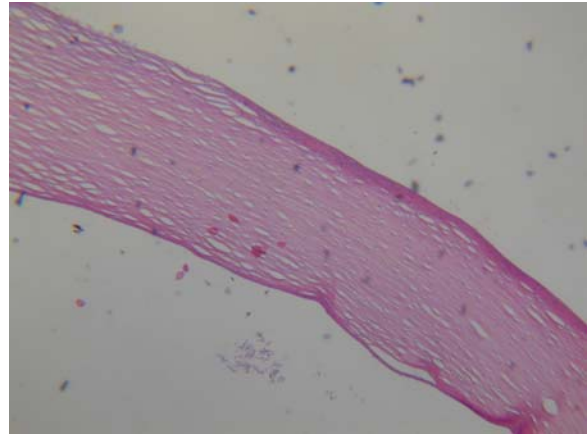


Figure B261. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

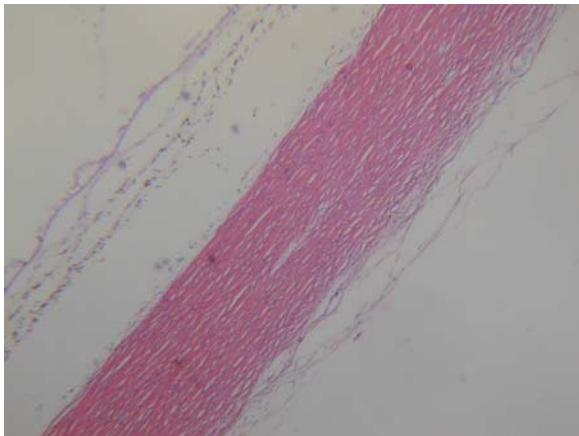


Figure B262. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

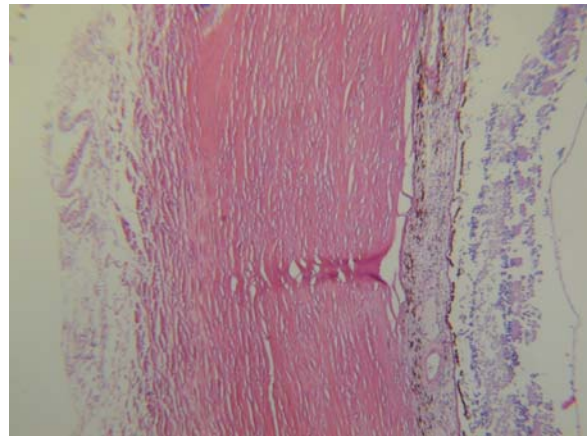


Figure B263. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

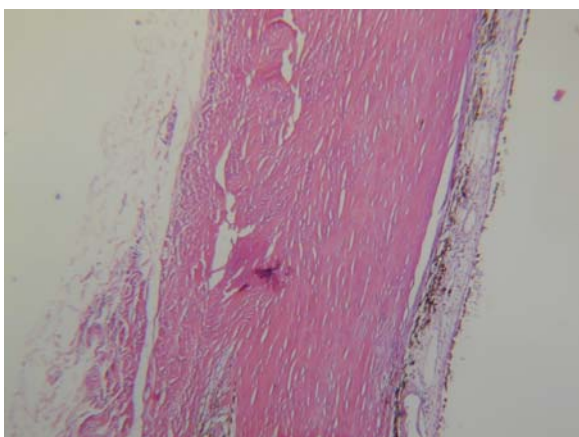


Figure B264. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

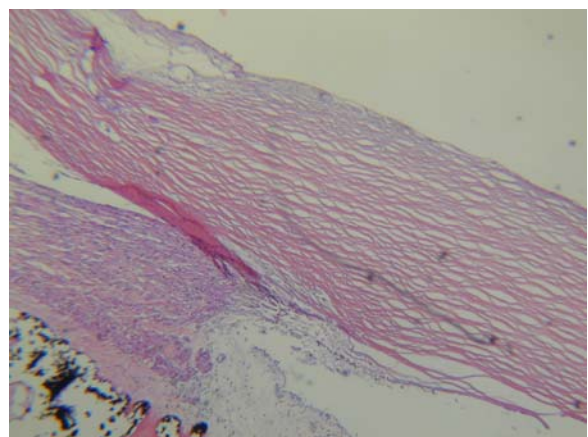


Figure B265. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Eye: H025

Sample: 2

Age: 72

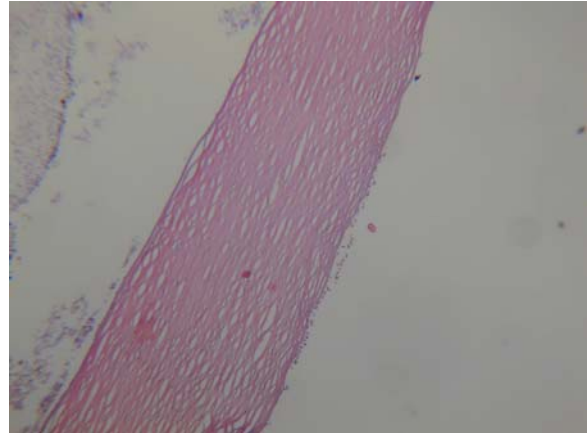


Figure B266. Histological sagittal cross section of the cornea of a human eye stained using H & E and paraffin embedded.

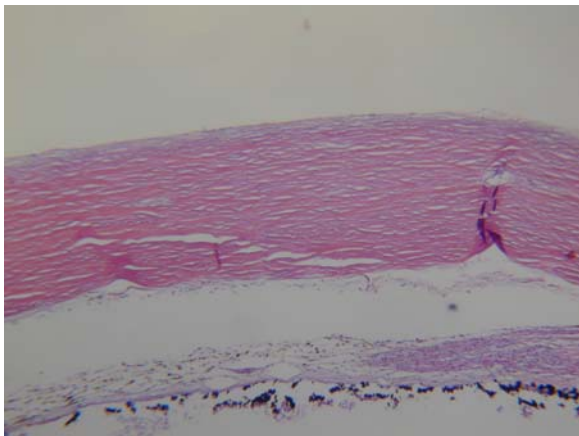


Figure B267. Histological sagittal cross section of the sub-rectus sclera of a human eye stained using H & E and paraffin embedded.

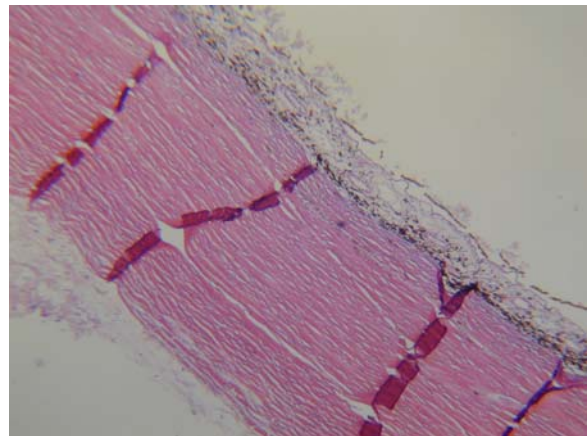


Figure B268. Histological sagittal cross section of the posterior sclera of a human eye stained using H & E and paraffin embedded.

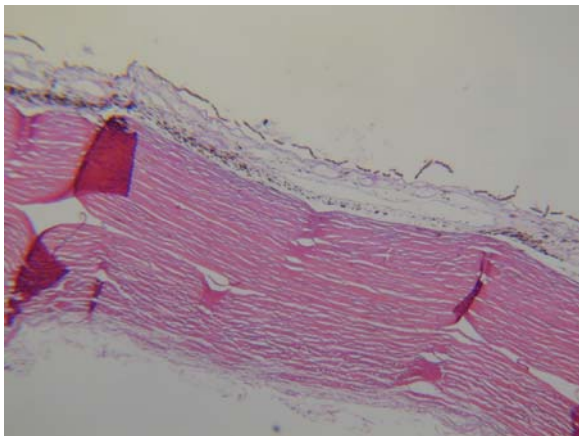


Figure B269. Histological sagittal cross section of the pre-rectus sclera of a human eye stained using H & E and paraffin embedded.

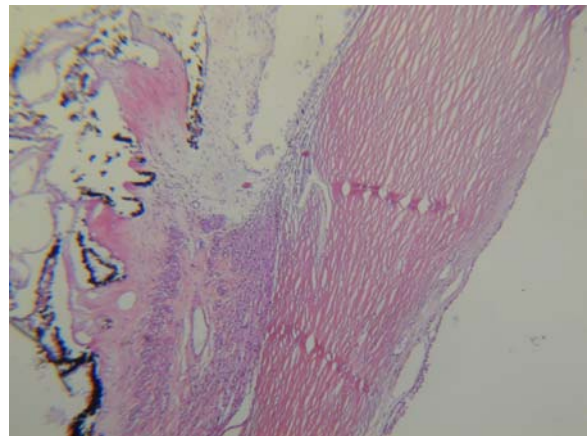


Figure B270. Histological sagittal cross section of the sclera at the limbus of a human eye stained using H & E and paraffin embedded.

Vita

Amber Lorraine Rath

Amber Lorraine Rath was born in Chula Vista, California on the 19th of March 1981 to Doug and Becky Rath. She has a younger sister, Heather, and a younger brother, Kyle. She attended Olympic High School in Charlotte, NC, and where she lettered each year in Softball and Tennis. She graduated with numerous honors including Valedictorian in June of 1999. She went on to graduate with honors from The University of North Carolina at Charlotte with a Bachelor's Degree in Mechanical Engineering and a minor in Mathematics in May of 2003. While a student there, she attended Cambridge University in the United Kingdom for a semester and interned at Siemens-Westinghouse Turbine and Generator Plant. She was in the University Bands all four years, and graduated from the University Honors Program. She also led missionary trips to Haiti and Mexico with the United Christian Fellowship Chapter. During the summer of 2003 she moved to Virginia where she became a member of the Impact Biomechanics Laboratory and then the Center for Injury Biomechanics. The research that she conducted there focused on investigating human tolerance to impact loading by combining experiments using human surrogates with statistical analyses to develop human impact injury criteria. She has been published in automotive safety, biomechanical, and medical journals and conferences. She received the Phi Kappa Phi, National Graduate Fellowship as well as the Jean B. Duerr and Pratt Scholastic Fellowship from Virginia Tech. She will obtain her Master's degree in Mechanical Engineering with a Biomedical Engineering Option and a Certificate in Engineering Education at the Virginia Polytechnic Institute and State University on the 13th of May 2005. Under the guidance of Stefan Duma, she has plans to pursue a Ph.D. in Biomedical Engineering through a distance learning program offered by the Virginia Tech – Wake Forest School of Biomedical Engineering and Sciences. Ultimately, she would like to be a professor in engineering as well as establish her own research program. She will marry Matthew Bonivtch on June 25, 2005, and will change her name to Amber Lorraine Rath Bonivtch. During her free time, Amber likes to play French horn, watch movies, listen to music, play sports, and enjoy the outdoors.

Further information can be obtained by writing to her permanent address:

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Charlotte, NC 28278

Amber Lorraine Rath