# OPHTHALMOLOGY

## PRINCIPLES AND CONCEPTS

FRANK W. NEWELL

SEVENTH EDITION

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## principles and concepts

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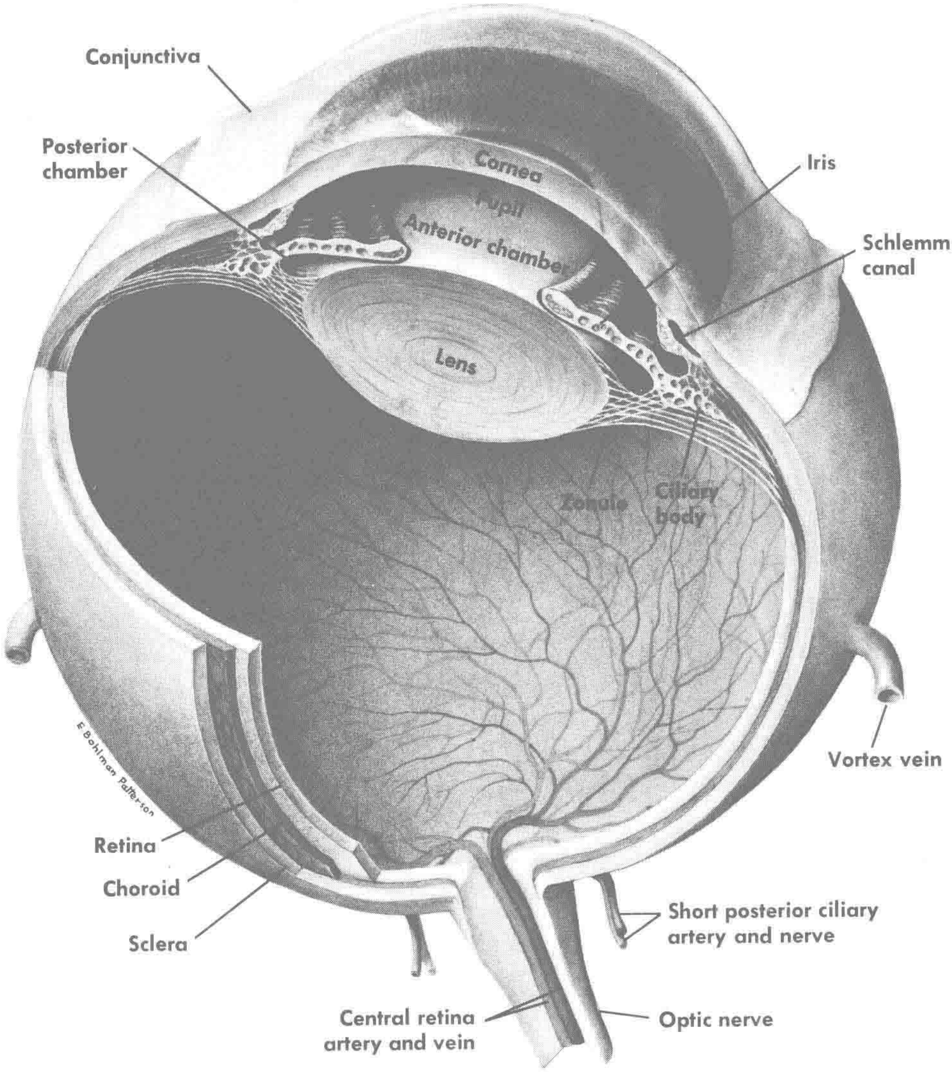


## THE HUMAN EYE

To

**Frankie T., Arien,**

**and Johnny R.**

# PREFACE

Ophthalmology has advanced remarkably in the 26 years since the first edition of this textbook was published. A host of ophthalmic practitioners limit themselves to a particular disorder or surgical procedure. Surgery using the microscope has become routine, intraocular lenses have replaced the heavy spectacles used to correct aphakia, computed perimetry is widespread, and diagnosis is aided immeasurably by new laboratory and radiologic tests. Yet in many ways the diagnosis and treatment of ophthalmic disorders are not different than they were a quarter of a century ago. The physician still relies upon a careful history and examination, and most ocular disorders are amenable to simple diagnostic and therapeutic steps. Examination of the eye remains helpful in the diagnosis and treatment of a variety of systemic disorders.

I believe now, as I did when I first planned this book, that an introduction to ophthalmology is not so complicated a topic that its elements are beyond the comprehension of a single author. Thus, it does not seem appropriate to require a student to understand a topic so obscure that a standard textbook requires many authors. Hence, this rarity in current medical teaching, a textbook written by one author. I have tried to simplify the study by bringing to students the earlier lessons of anatomy, physiology, pharmacology, pathology, and medicine.

As before, the audiovisual department of The University of Chicago Hospitals has been particularly helpful. I have freely used the photographic files of the Department of Ophthalmology and Visual Science of the University of Chicago. The staff of the *American Journal of Ophthalmology* has provided exceptional assistance. I am particularly grateful to the Managing Editor, Mary Borysewicz, and to the Assistant to the Editor, Laureen Kott.

**Frank W. Newell, M.D., M.Sc. (Ophth.)**

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PART I

# BASIC MECHANISMS

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# ANATOMY AND EMBRYOLOGY

## ANATOMY

Dissection of a fresh animal eye readily reveals the interrelationship of the intraocular tissues and the organization of the eye as a multichambered, nearly spherical structure. The surface anatomy is easily studied in a living subject by direct inspection, using a small penlight for illumination and a +20 diopter lens for magnification.

### THE EYE

The eye (frontispiece) rests upon a fascial hammock, in the front half of the cavity of the orbit, surrounded by ocular muscles, fat, and connective tissue. Only its anterior aspect is exposed, and it is protected by the bony orbital rim. Attached to the eye are four recti and two oblique muscles. These are innervated by the oculomotor (N III), trochlear (N IV, superior oblique muscle), and abducent (N VI, lateral rectus muscle) cranial nerves, which enter the orbit through the superior orbital fissure in the posterior orbit. The ophthalmic branch of the trigeminal nerve (N V) that transmits sensory fibers from the upper face and the eye enters the cranial cavity through the superior orbital fissure. The optic nerve, which transmits visual impulses, leaves the orbit through the optic foramen, which also transmits the ophthalmic artery and the sympathetic innervation of the eye. The exposed anterior one third of the eye consists of a central transparent portion, the cornea, and a surrounding white portion, the sclera. The sclera is covered with the bulbar conjunctiva, which is continuous with the palpebral conjunctiva that lines the inner surface of the protective tissue curtains, the eyelids. The lacrimal gland is located in the upper outer portion of the bony orbit.

The anterior pole of the eye is the center of curvature of the cornea. The posterior pole marks the center of the posterior curvature of the globe, and it is located slightly temporal to the optic nerve. The geometric axis is a line connecting these two poles. The equator encircles the eye midway between the two poles (Fig 1–1).

The anteroposterior diameter of the normal eye, measured by ultrasonic methods, is about 22 to 26 mm. The circumference is between 69 and 81 mm. In the average eye (24 mm in length), the equator, on the surface of the sclera, is 16 mm posterior to the corneoscleral limbus. The posterior pole is 32 mm behind the corneoscleral limbus. Internally the anterior termination of the sensory retina (ora serrata) is approximately 5.75 to 6.5 mm posterior to the termination of the Descemet membrane and endothelium of the cornea (Schwalbe line) (Fig 1–2). The retina extends further forward on the nasal side of the eye than on the temporal aspect, thus accounting in part for the more extensive visual field temporally. The optic nerve leaves the eye nasal to the posterior pole.

The globe has three main layers, each of which is further divided. The outer supporting coat consists of the transparent cornea, the opaque sclera, and their junction, the corneo-

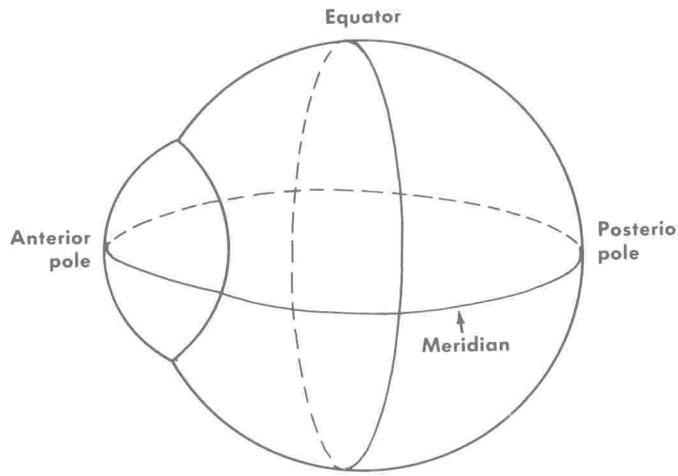


**FIG 1–1.**
Principal coordinates of the eye. The visual line that connects an object in space with the fovea centralis does not correspond exactly to the geometric axis, which connects the anterior to the posterior pole.

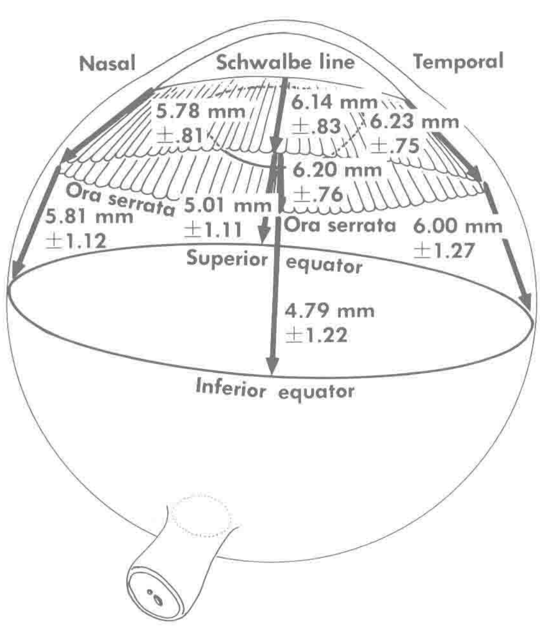


**FIG 1–2.**
Relationship of the ora serrata (junction of the ciliary body and retina) and the line of Schwalbe (peripheral margin of Descemet membrane). Measurements are in millimeters from the internal surfaces in the four principal meridians. Average measurements and standard deviations are shown. The average internal diameter at the equator is 24.08 ± 0.94 mm. Surgical instruments are introduced into the vitreous cavity about 3 or 4 mm posterior to the corneoscleral limbus, and 1 or 2 mm anterior to the ora serrata. (Redrawn from Straatsma BR, Landers MB, Kreiger AE: *Arch Ophthalmol* 1968; 80:30. Copyright 1968, American Medical Association.)

scleral limbus or sulcus. The middle layer, or uvea, is composed of the iris, which contains a central opening—the pupil; the ciliary body, which secretes aqueous humor and supports the crystalline lens; and the choroid, which nurtures the adjacent retina. The inner layer consists of the retina, which is composed of two parts, a sensory portion and a single layer of retinal pigment epithelium.

The lens is a transparent structure located immediately behind the iris and supported in position by a series of fine fibers, the zonule. These fibers are attached to the ciliary body and the capsule of the lens.

The eye encloses three chambers: (1) the vitreous cavity, (2) the posterior chamber, and (3) the anterior chamber. The *vitreous cavity*, by far the largest, is located behind the lens and zonule and is adjacent to the sensory retina. The *posterior chamber* is minute in size and is bounded by the lens and zonule behind and the iris in front. The *anterior chamber* is located between the iris and the posterior surface of the cornea and communicates with the posterior chamber through the pupil. Aqueous humor is secreted by the ciliary processes into the posterior chamber and passes through the pupil into the anterior chamber. The aqueous humor leaves the anterior chamber through the trabecular meshwork that opens into the canal of Schlemm, an endothelium-lined channel that encircles the anterior chamber.

## Outer coat

The outer coat of the eye consists of relatively tough fibrous tissues shaped as segments of two spheres: the sclera, with a radius of curvature of about 13 mm, and the cornea, with a radius of curvature of about 7.5 mm. The white, opaque sclera constitutes the posterior five sixths of the globe, and the transparent cornea provides the anterior one sixth of the globe. The junction of the cornea and the sclera, the corneoscleral limbus, contains the trabecular meshwork and the aqueous humor drainage system, the canal of Schlemm, which is an important functional and anatomic area.

**The sclera.**—The sclera is a dense, fibrous, collagenous structure that comprises the posterior five sixths of the eye. Anteriorly, it forms the "white" of the eye and is covered with a richly vascular episclera, the fascia bulbi (Tenon capsule), and the conjunctiva. The delicate blood vessels of the episclera are visible anteriorly through the transparent conjunctiva. Posteriorly, the sclera is connected by loose, fine collagen fibers to the dense fascia bulbi (Tenon capsule).

The sclera has two large openings, the anterior and posterior scleral foramina, and numerous smaller openings through which nerves and blood vessels pass. The sclera is perforated 3 mm medial to the posterior pole by the posterior scleral foramen, the canal through which the optic nerve and central retinal vein leave the eye and through which the central retinal artery enters the eye. The canal is cone-shaped and measures 1.5 to 2.0 mm in diameter on the inner surface of the sclera and 3.0 to 3.5 mm on the outer surface. The posterior scleral foramen is bridged by a sievelike structure, the lamina cribrosa (Fig 1–3), the most posterior portion of which is formed by scleral fibers. The anterior portion, rich in elastic tissue, is derived from the choroid and Bruch membrane.

The anterior scleral foramen is bridged by the transparent cornea. The periphery of the anterior sclera foramen is a transitional area, the corneoscleral limbus. On its inner surface is the scleral spur, to which the longitudinal

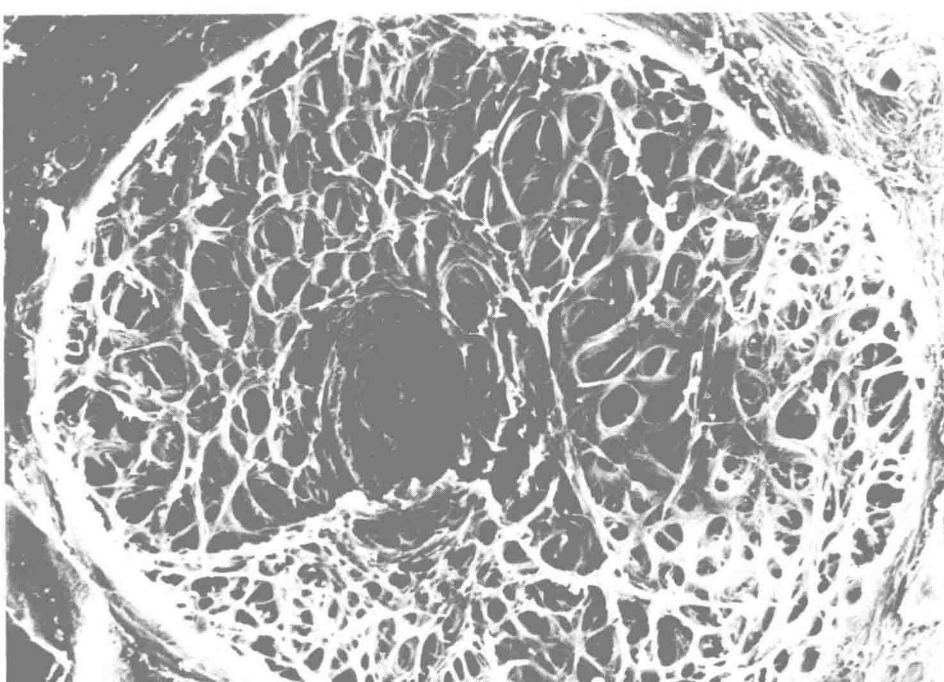

**FIG 1–3.**
Scanning electron micrograph of the human posterior scleral foramen viewed from the vitreous cavity. It is bridged by a sievelike structure, the lamina cribrosa. (From Miller NR: *Walsh and Hoyt's Clinical Neuro-ophthalmology*, ed 4, vol 1. Baltimore, Williams & Wilkins, 1982. Used by permission.)

portion of the ciliary muscle (N III) is attached. Slightly anterior to this is the canal of Schlemm, through which aqueous humor exits from the eye.

About 4 mm posterior to the equator of the eye in the region between the recti muscles are the openings for the vortex veins that are the collecting channels for choroidal veins. In the area surrounding the optic nerve, the sclera is perforated by the long and short ciliary nerves and the long and short posterior ciliary arteries. About 4 mm posterior to the corneoscleral limbus and just anterior to the insertions of the recti muscles, the anterior ciliary arteries pierce the sclera at sites sometimes marked with a dot of uveal pigment. Occasionally a loop of a long ciliary nerve surfaces on the sclera and returns to the ciliary body. Uveal melanin marks the loop as a small pigmented dot 2 to 4 mm from the corneoscleral limbus.

The sclera is thickest (1.0 mm) in the region surrounding the optic nerve, where the meningeal coverings (mainly dura mater) of the optic nerve blend into the sclera. It is thinnest (0.3 mm) immediately posterior to the insertions of the recti muscles.

***Structure.***—The sclera (Fig 1–4) has three layers: (1) the episclera, (2) the scleral stroma, and (3) the lamina fusca.

The *episclera* is the outermost layer. It is a moderately dense, vascularized connective tissue that merges with the scleral stroma and sends connective tissue bundles into the fascia bulbi (Tenon capsule). The anterior portion of the episclera has a rich blood supply that may become markedly congested in inflammation. The episclera and the fascia bulbi are attenu-

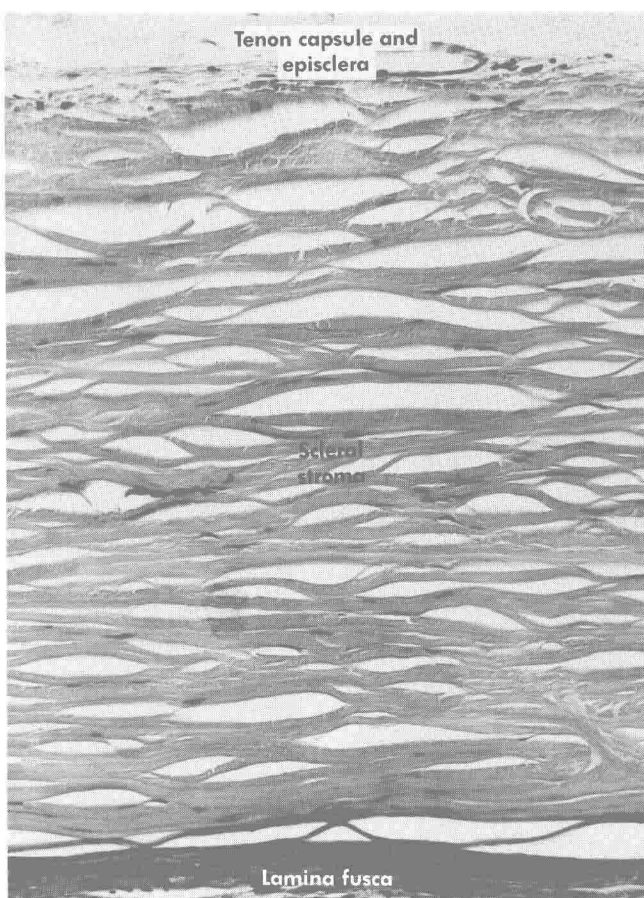


**FIG 1–4.**
Transverse section through the sclera anterior to the equator of the eye. (Masson trichrome; ×160.)

ated behind the ocular equator; this accounts for the relative avascularity of the posterior sclera.

The dense *scleral stroma* consists mainly of bundles of typical collagen fibers (Fig 1–5) that vary in diameter from 10 μm to 16 μm and in length from 30 μm to 140 μm. The fibers are oriented parallel to the corneoscleral limbus to form an interlacing basketlike weave in that region. In the region of the insertion of the extraocular muscles, they become more meridional, apparently in response to mechanical stresses induced by traction of the ocular muscles and intraocular pressure. The sclera is white because of the variable diameter and irregular arrangement of the collagen fibers of the stroma. When the water content of the sclera (usually between 65% and 70%) is reduced to less than 40% or increased to more than 80%, the sclera becomes transparent.

The *lamina fusca*, the innermost layer of the sclera, is located next to the choroid, which provides many melanocytes that give it a brown color. Fine collagen fibers blend with

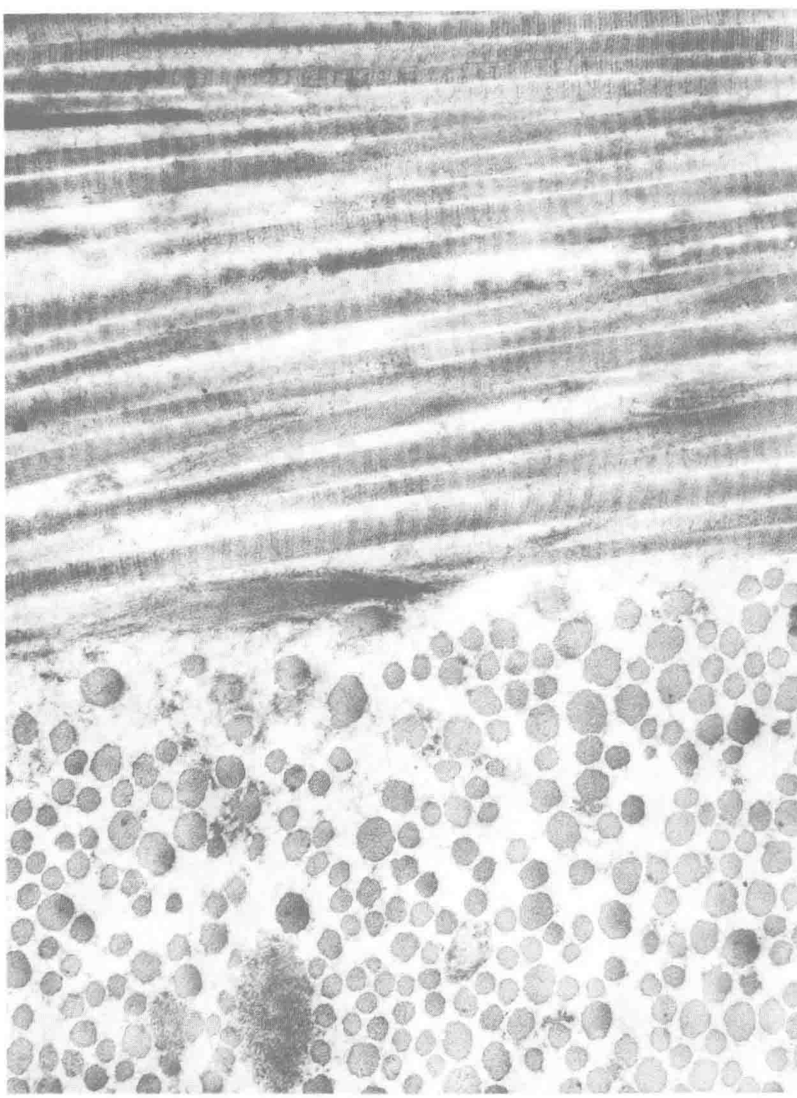

**FIG 1–5.**
Transmission electron micrograph of scleral stroma showing collagen bundles. Collagen fibrils in the lamellae are of variable diameters and much more irregularly arranged than those of the cornea. (×45,000.) (Courtesy of Ramesh C. Tripathi, M.D.)

the choroid and form delicate connections between the sclera and the choroid.

***Blood supply.***—The blood supply of the scleral stroma is provided by the episcleral and choroidal vascular networks. Anterior to the insertions of the recti muscles, the anterior ciliary arteries form a dense episcleral plexus. These vessels become congested in "ciliary injection." Small branches of the long and short posterior ciliary arteries supply the scleral stroma posterior to the recti muscles.

***Nerve supply.***—The posterior sclera is innervated by branches of the short ciliary nerves that enter the sclera close to the optic nerve. The long ciliary nerves provide sensory innervation anteriorly. Because of the generous innervation, inflammations of the sclera may be extremely painful.

**The cornea.**—The cornea is the transparent anterior one sixth of the eye. Its anterior peripheral margin merges with the sclera and is covered with conjunctiva. Its internal margin terminates at the trabecular meshwork. Anteriorly, the cornea measures about 10.6 mm vertically and about 11.7 mm horizontally; the peripheral conjunctival covering makes exact measurement difficult. Internally the cornea is circular with a diameter of 11.7 mm. The central optical portion is 0.52 mm thick with nearly parallel anterior and posterior surfaces. It thickens to about 1.0 mm at the periphery. Corneal growth is complete in humans at about 6 years of age. The radius of curvature of the convex anterior surface is 7.8 mm, and the radius of curvature of the concave posterior surface is 6.2 to 6.8 mm. The cornea separates air, with an index of refraction of 1.00, and aqueous humor, with an index of refraction of 1.33, and is the main refracting structure of the eye. Variations in the radius of curvature in different corneal meridians cause astigmatism.

***Structure.***—The cornea (Fig 1–6) has three layers: (1) an anterior layer, the epithelium and its basement membrane; (2) a middle layer, the substantia propria (stroma) and its anterior condensation, Bowman zone; and (3) a lining layer, the mesothelium (endothelium) and its basement membrane (Descemet membrane) which separates the endothelium from the stroma (Table 1–1).

The *epithelium* is 50 μm to 90 μm thick and covers the stroma anteriorly. It is continuous

A

B

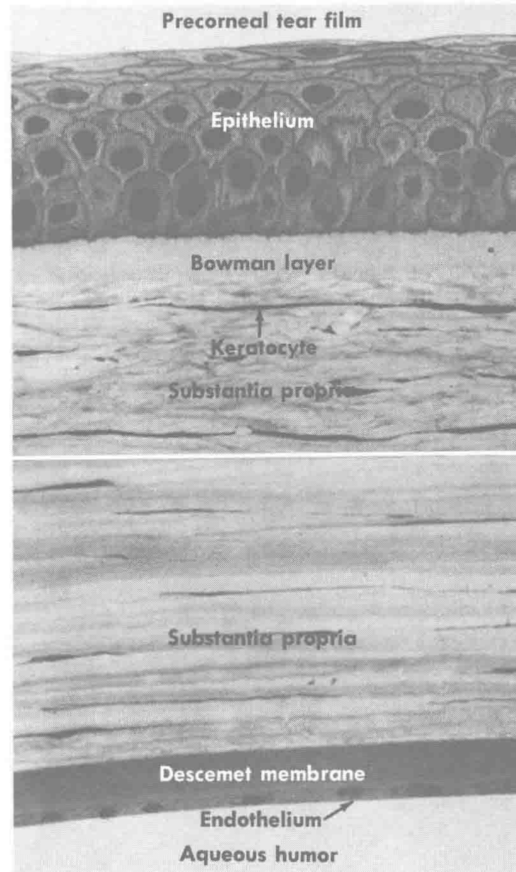


**FIG 1–6.**
Cross section of the axial area of the cornea. The *substantia propria* constitutes 90% of the thickness. **A**, the basement membrane of the epithelium is firmly adherent to the *Bowman zone*, the anterior condensation of the substantia propria. **B**, the lamellae of the posterior substantia propria are much more regularly arranged than those of the anterior substantia propria. (×500.) (Courtesy of Ramesh C. Tripathi, M.D.)

with the epithelium of the conjunctiva. It is composed of stratified squamous epithelium, five to six cell layers thick. It has an outermost layer two to three cell layers thick, a midzone layer formed by two or three layers of polyhedral cells (wing cells), and an inner single layer of tall, columnar, basal germinal cells that rest upon a thin basement membrane. The epithelial cells form in the deepest layer, become progressively flatter, and are shed from the superficial layer 7 days later. The superficial squamous cells (Fig 1–7) have many microvilli. These cells are flat, have horizontal nuclei, and

**TABLE 1–1.**
Layers of Cornea and Sclera

- I. Precorneal tear film
  - A. Oil layer (from meibomian glands)
  - B. Aqueous layer (from lacrimal glands)
  - C. Mucoid layer (from goblet cells)
- II. Cornea
  - A. Epithelium
    - 1. Surface cell layer
    - 2. Wing cell layer
    - 3. Basal cell layer (columnar cells)
    - 4. Basement membrane
  - B. Stroma
    - 1. Anterior condensation (Bowman zone)
    - 2. Lamellar stroma
  - C. Mesothelium (endothelium)
    - 1. Descemet membrane (basement membrane) between endothelium and stroma
- III. Sclera
  - A. Episclera
  - B. Scleral stroma
  - C. Lamina fusca

are joined to each other with desmosomes that prevent aqueous solutions (such as tears) from penetrating the cornea. As superficial cells age, they lose their interdigitations and disintegrate or are swept away by the eyelids during blinking. Wing cells in the midzone are polyhedral with a convex anterior surface, parallel with the surface of the cornea, and a concave posterior surface. Those immediately adjacent to the inner columnar epithelium have round nuclei that become successively flatter as the cells approach the surface of the cornea. The cells are joined together from base to apex by desmosomes (maculae adherentes). The basal cells in the deepest layer are tall and columnar in shape. They have a flattened base that rests on the basement membrane to which it is attached by hemidesmosomes. Their interdigitating lateral cell borders are joined by desmosomes. The cells often show mitosis. The basement membrane is positive to periodic acid–Schiff stain (PAS) and is firmly attached to the underlying anterior condensation of the substantia propria (Bowman zone) by irregular filaments. After injury, these attachments may take as long as 6 weeks to be reestablished.

The *substantia propria* (Fig 1–8), or stroma, constitutes 90% of the corneal thickness. Its anterior portion, the Bowman zone (Bowman membrane or layer to the light microscopist), is made up of randomly oriented collagen fibers that form an acellular region resistant to deformation, trauma, and the passage of foreign bodies or infecting organisms. Once damaged, its typical architecture is not restored and causes corneal scarring and an irregularity in corneal thickness that results in irregular astigmatism.

The stroma is composed of lamellae of collagen fibrils of uniform diameter and regular spacing that extend the entire width of the cornea. They have a periodicity typical of embryonic collagen. In the posterior cornea, the lamellae are of almost equal thickness; they become more irregular in the anterior portion. All fibers within a lamella are parallel—but at a right angle—to fibers in the adjacent lamellae. They are enmeshed in glycosaminoglycans. Scattered throughout are fixed, long, and flat cells known as keratocytes or corneal corpuscles, which function as fibroblasts do in other tissues. There are also a few wandering cells (leukocytes and macrophages).

The posterior surface of the stroma is lined with a loosely attached PAS-positive glassy membrane, the Descemet membrane, the basement membrane of endothelial cells. The Descemet membrane is composed of collagen fibers different from those of the corneal stroma and arranged in a hexagonal pattern. After injury the membrane regenerates readily (but not its endothelial cells in humans) and may form glass membranes that extend into the anterior chamber. The Descemet membrane terminates abruptly at the periphery of the cornea to form the line of Schwalbe, the anterior border of the trabecular meshwork.

The *endothelium* of the cornea is a single layer of mesothelium (Fig 1–9). The apices of the endothelial cells are in direct contact with the aqueous humor and have occasional microvilli. The cells are tightly bound together with desmosomes (maculae adherentes); near the apical region a terminal bar is constantly present. The cells contain large oval nuclei and are rich in intracellular organelles. The endothelium is responsible for the deturgescence (dehydration) of the corneal stroma. Injury to the endothelium (or epithelium) results in edema of the corneal stroma. The corneal endothelium does not regenerate in adult humans.

At the corneal periphery, the Bowman zone