Simon E. Skalicky

Ocular and Visual Physiology

Clinical Application

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Foreword

It is indeed a privilege to write the foreword to such a useful textbook as *Ocular and Visual Physiology* will become. Most texts on visual physiology are large, complex, and detailed. There is a pressing need for a book that gets to the heart of ocular and visual physiology and provides the student and clinician with the core knowledge in a relevant and practical way. This text succeeds admirably being the result of many hours of careful, painstaking writing that distils complex areas of ocular and visual physiology into the important principles required by the reader.

Its author is well placed to write such a text on ocular and visual physiology. Dr Skalicky has been associated with the Save Sight Institute, Sydney Medical School and Sydney Eye Hospital at many levels. He has been a master's of ophthalmic science student, then a tutor in this course, an ophthalmology trainee, and the professorial senior registrar. Following fellowship training in glaucoma in Cambridge, he has returned and is currently a clinical senior lecturer in the discipline of ophthalmology. He has lectured for many years in our master's course on visual physiology. He is currently completing his PhD at the University of Sydney.

Ocular and Visual Physiology is up to date, based on the author's experience as a student, an ophthalmologist, a researcher, and a teacher of physiology, and bridges the gap between the physiological facts and their relevance to clinical practice in the various visual sciences. An expert has reviewed each chapter to ensure it is accurate, complete, and relevant.

Physiology, being the study of normal function, is one of the cornerstones of basic science required to practice in ophthalmology, optometry, orthoptics, and visual neuroscience. *Ocular and Visual Physiology* will be of great use to both students and practitioners in each of these disciplines.

Sydney, Australia   Peter McCluskey
April 2015

Preface

Ocular and Visual Physiology is a textbook for ophthalmologists, optometrists, orthoptists, and visual neuroscientists throughout the world, in training and beyond. The study of *ocular and visual physiology* is a core discipline for these professions. It describes the means of faithful transmission of visual information from the outside world to the brain, as well as the maintenance of the health of the eye, its supporting structures, and visual pathways. Without a thorough understanding of this subject, clinicians and visual neuroscientists cannot achieve their desired professional level of competency.

There is a crucial need for a textbook such as this that clearly, comprehensively, and succinctly covers all concepts at a high level of detail, yet emphasizes and summarizes the basic themes and core principles that shape our visual system. Although the concepts can be difficult to grasp at first, there is a simple elegance to ocular and visual physiology that describes the relationship between structure and function and is clearly conveyed within this book.

With rapid and exciting scientific progress, the knowledge base of the subject is broad and ever growing. This textbook is based on only the latest publications in peer-reviewed journals that are closely referenced within the body of the text. Occasionally historical papers of great importance are referenced. Where possible human studies are used as primary sources; however, in some circumstances primate or other mammal data are referenced when direct human data is lacking. The level of detail conveyed within the text is high and will satisfy the most avid readers; for a greater in-depth review, readers are invited to consult the primary sources referenced.

Each chapter is summarized with an introductory overview and subdivided using headings and subheadings for clarity and ease of reading. The text contains multiple colored illustrations to help elucidate the concepts. Each chapter is concluded with a Clinical Correlation section to illustrate pertinent clinical scenarios in which the physiology is highly relevant.

For clarity and consistency of structure, this is a single-author textbook. Each of the chapters were independently reviewed and edited by an expert in the field with a clinical or visual scientific academic background. This peer-review process is important to pursue the highest of academic standards intended for this publication.

I would like to extend my grateful thanks to all chapter reviewers for their time and energy in aiding me prepare this work. I am greatly indebted to Associate Professor John Grigg and Professor Peter McCluskey of the Save Sight Institute Sydney University who first suggested the concept of this textbook and then supported my efforts in its creation.

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Part I

The Anterior Eye

Protective Mechanisms of the Eye and the Eyelids

1

Protective Mechanisms of the Eye

Overview

- Several mechanisms exist to protect the eye from external injury.
- Mechanisms of potential damage to the eye include:
  (a) Mechanical insult
  (b) Chemical insult
  (c) Biological insult
  (d) Electromagnetic radiation

Mechanical Insult

1. The orbit (Fig. 1.1)
   - The orbital fat and bony walls support and provide protection for the eye and orbital tissues [1].
   - The orbital fat acts as a semi-fluid padding that cushions the eye.
   - The *inferior* and *medial orbital walls* are thin. They are readily fractured on blunt trauma, providing some shock absorption and orbital decompression to protect the eye from injury [2, 3].
2. The eyelids
   - The eyelids provide a mechanical barrier between the eye and external environment, rapidly closing on *reflexive* or *voluntary blinking* [4].
   - *Cilia* (modified fine hairs) on the eyelid skin are highly sensitive to airborne particles; when stimulated, they elicit a *blink reflex* [5].

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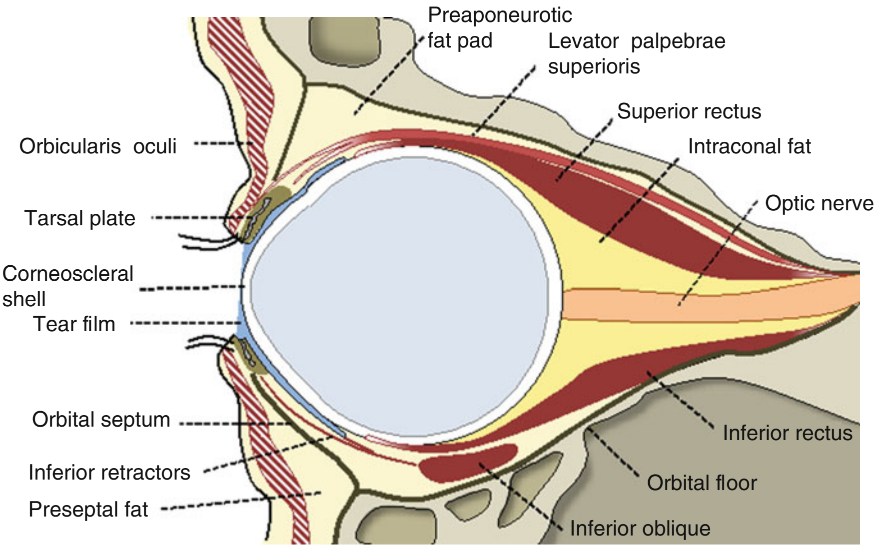

Fig. 1.1 The orbit

3. The corneoscleral shell (see Chap. 3, The Cornea and Sclera)
   - The corneoscleral shell provides *tensile strength* to the globe [6].
   - *Dense corneal innervation* allows for rapid *blink* and *withdrawal reflexes*.
   - Corneal innervation also provides trophic factors that promote epithelial healing [7, 8].

Chemical Insult

1. Eyelid closure
   - Reflex blinking provides *rapid closure* of the eye in response to splash or foreign body sensation.
2. Bell's phenomenon
   - A normal Bell's phenomenon provides involuntary *upward rotation of the globe* on lid closure, removing the cornea from noxious stimuli [9].
3. Tears
   - Tear flow increases dramatically in response to mechanical or noxious stimuli [10].
   - This causes dilution and washout of the irritant.
4. Corneal epithelial barrier
   - The corneal epithelium is 5–7 layers thick with cells adjoined by desmosomes [11, 12].
   - *Tight junctions* (zonulae occludens) surround the most superficial corneal epithelial cells providing a *low conductance barrier* to fluid and solutes [13].

Biological Insult

1. Tear film and conjunctiva (see Chap. 2, The Ocular Surface)
   - The tear film has several bacteriostatic properties [14]:
     (i) Glycocalyx and mucous layer
       - Mucins in the glycocalyx (conjunctival cell membrane-bound mucin) and the mucous layer of the tear film provide a physical barrier to pathogens and can trap microorganisms [15, 16].
     (ii) Aqueous layer
       - The aqueous layer has several antibacterial constituents including secretory immunoglobulin A (IgA), lysozyme, and lactoferrin.
     (iii) Normal conjunctival flora
       - The normal bacterial flora may inhibit survival of more pathogenic species [16].
     (iv) Natural killer cells
       - Present in the conjunctiva, natural killer cells may have a role in restricting the spread of viral infection or tumors.
2. Corneal epithelium and Bowman's layer
   - These act as physical barriers against ocular penetration by microbial pathogens.
3. Descemet's membrane
   - Descemet's membrane is resistant to proteolysis in severe corneal infections, maintaining the integrity of the globe [17].

Electromagnetic Radiation (EMR) Toxicity

- The primary function of the eye is to detect and interpret light information from the external world.
- However, excessive EMR can be damaging to the eye, and several protective mechanisms exist:

1. Eyelid closure
   - The dazzle reflex: bright light induces reflexive blinking.
2. Pupil constriction
   - Rapid pupil constriction in response to bright light limits excessive radiation exposure to the ocular media internal to the iris [18].
3. Light absorption by ocular tissues (Table 1.1)
   - Absorption of nonvisible optic radiation prevents harmful levels of EMR from damaging the eye.
   - The cornea and sclera absorb ultraviolet (UV)-B, UV-C, infrared (IR)-B, and IR-C [19–21].
   - The crystalline lens absorbs UV-A.
   - Antioxidants in the lens and macula prevent excessive UV-induced oxidative damage.

Table 1.1 The electromagnetic spectrum: optical radiation [19–21, 23]

Waveband	Domain	Wavelength (nm)	Absorption by anterior ocular media	Absorption by retinal and choroidal pigments (non-photoreceptor)
Ultraviolet (UV)	UV-C	200–280	Cornea and sclera	
	UV-B	280–315	Cornea and sclera	
	UV-A	315–400	Crystalline lens	
Visible light		400–780		Xanthophylls, hemoglobin, and melanin
Infrared (IR)	IR-A	780–1400		Haemoglobin and melanin
	IR-B	1400–3000	Cornea and sclera	
	IR-C	3000–10,000	Cornea and sclera	

- The yellow macular carotenoid xanthophyll pigments in Henle's fibre layer absorb short wavelength radiation [22]. They minimize blue light incident to the fovea and reduce chromatic aberration and glare.
- Hemoglobin and melanin, principally found in the choroid, absorb excessive light and IR radiation. This results in excessive heat generation; the choroidal circulation acts as a heat sink to dissipate thermal energy [23].

Eyelids

Overview

The eyelids are important for protection and maintenance of normal ocular health and function [24].

1. Barrier function
   - Eyelid closure provides a barrier function elicited by voluntary or reflexive blinking [4, 16].
2. Maintenance of globe position
   - The eyelids apply gentle posterior pressure on the globe to counteract forward pressure from orbital tissues behind the globe.
3. Ocular surface integrity (see Chap. 2, The Ocular Surface)
   - Blinking distributes tears across the ocular surface and promotes drainage of tears via the lacrimal pump mechanism [25, 26].
4. Eyelid glands
   - The eyelid contains glands with secretions that add to the tear film.

Structure

1. Dimensions
   - In adults, the normal interpalpebral fissure height is 8–11 mm; the horizontal palpebral fissure length is 27–30 mm.
   - The upper lid margin rests 1.5–2 mm below the limbus; the lower rests on the limbus [27, 28].
2. Anterior lamella (Fig. 1.2)
   The anterior lamella functions as a single unit, consisting of skin, muscle (orbicularis oculi (OO)), and associated glands [29, 30].
   (i) Skin
      - The eyelid skin is thin, allowing rapid and large movements on eyelid opening and closure.

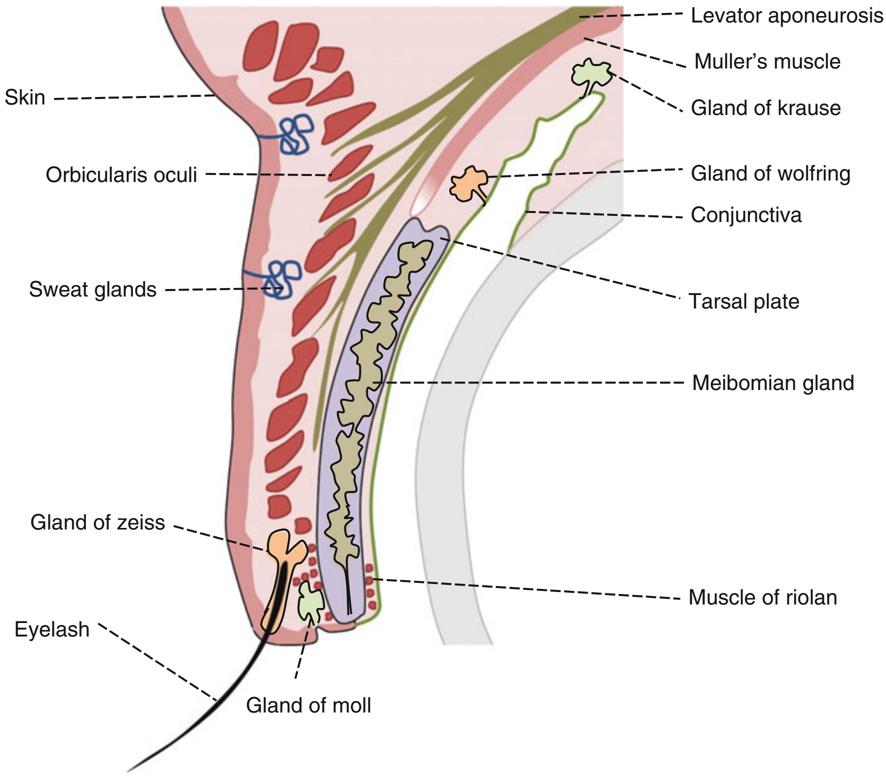

Fig. 1.2 Eyelid anatomy

(ii) Muscle: the orbicularis oculi (Fig. 1.3)
- The orbicularis oculi (OO) is a flat, elliptical muscle surrounding the orbital margin and extending onto the cheek, eyelids, and around the lacrimal sac.
- OO has three functional divisions (Table 1.2) [31, 32].
- Contraction of the OO on blinking aids the lacrimal pump (see Chap. 2, The Ocular Surface) [26].
- The muscle of Riolan, the pretarsal portion of OO adjacent to the lid margin, helps rotate the lashes out during lid closure and releases secretions from Meibomian glands [33].

(iii) Glands
- The glands of Zeiss (modified sebaceous glands) and Moll (modified sweat glands) are found in the anterior lamellae near the eyelash cilia. Both secrete their contents around the lash follicle [27].

(iv) Cilia
- Cilia are modified hairs found on eyelid and lid margin skin that protect the eye from large airborne particles.
- There are 100–150 on the upper lid and 75 on the lower lid and are replaced every 3–5 months.
- Cilia are sensory organs; stimulation results in reflex blinking.

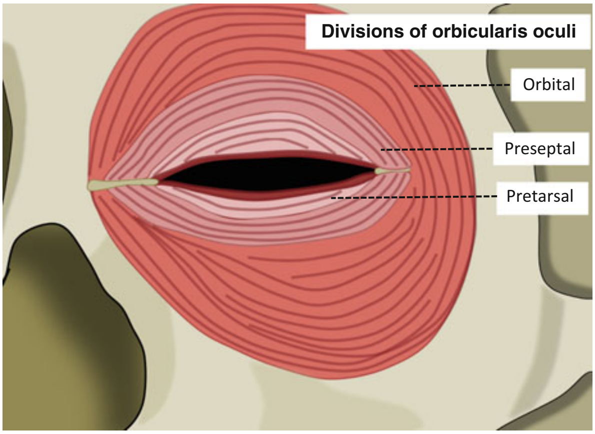

Fig. 1.3 Divisions of orbicularis oculi

Table 1.2 Functional divisions of the orbicularis oculi muscle

Division	Location	Function
Pre-tarsal	Overlying the tarsal plate	Light blink
Pre-septal	Overlying the orbital septum	Blink and sustained closure
Orbital	Outermost portion	Wink and sustained closure

3. Posterior lamella
   The posterior lamella is composed of tarsal plate, conjunctiva, and associated glands [27, 29, 30].
   - The tarsal plate consists of dense fibrous tissue 1–1.5 mm thick and 25 mm wide.
   - In the upper lid the height varies from 8 to 12 mm, in the lower lid 3–4 mm.
   - The tarsal plate provides structural rigidity for the lid and is important for strength and protection.
   - The tarsal plate contains the Meibomian glands, 25 in the upper and 20 in the lower lid.
   - These are holocrine sebaceous glands that produce the lipid layer of the tear film.

Eyelid Movements

1. Opening
   Eyelid movements are linked to gaze, such that the eyelids move up on upward gaze and vice versa.
   - Contracture of the levator palpebrae superioris muscle (innervated by the oculomotor nerve) elevates the upper eyelid approximately 15 mm [34].
   - Muller's muscle (smooth muscle, sympathetically innervated) contributes an additional 1–2 mm of upper lid elevation [35].
   - The lower lid is moved inferiorly (5 mm) by the inferior retractors linked to the inferior rectus and inferior oblique by the capsulopalpebral fascia [30].
2. Closure
   - Closure is due primarily to OO contraction; additionally there is simultaneous levator palpaebrae superioris relaxation [4, 36].
3. Eyelid motor control
   - Eyelid opening and closure is controlled in the frontal cortex close to the oculogyric centers [37, 38].
   - The caudal central nucleus of the oculomotor complex in the midbrain supplies the levator palpebrae superioris [39].
   - Both eyelids obey Hering's law: they are linked as yolk muscles and bilaterally innervated (see Chap. 17, Movements of the Eye) [40].

Blinking

Blinking can be spontaneous, reflex, or voluntary.

- Blinking results from simultaneous:
  (a) Contraction of the eyelid protractors (orbicularis oculi, corrugator, and procerus muscles)
  (b) Relaxation of the eyelid retractors (levator palpebrae superioris and frontalis muscles) [41]

1. Spontaneous blinking [42, 43].
   - This occurs every 3–8 s, lasting 0.3–0.4 s.
   - The spontaneous blink rate is affected by:
     (a) Environment (dry, moist, dust, bright)
     (b) Emotional state (anxiety, concentration)
     (c) Some disease states (e.g., Parkinson's disease) [44]
2. Reflex blinking
   - Reflex blinking occurs rapidly in response to the following stimulus types:
     (a) Tactile: corneal, eyelash, eyelid skin, and eyebrow contact [45]
     (b) Optical: dazzle (bright lights), menace (unexpected or threatening objects) [46]
     (c) Auditory (menace) [47, 48]
   - The tactile blinking reflex is served by a simple neural circuit consisting of the trigeminal nerve (afferent arm) and facial nerve (efferent arm).
   - It can be modified by supranuclear influences.
   - The dazzle reflex is mediated at a subcortical level via the supraoptic nucleus and superior colliculus, while the menace reflex mediated at a cortical level [46].
   - The afferent information for both reflexes is transmitted via the optic nerve.
3. Voluntary blinking
   - The amplitude of voluntary blinking is usually larger than reflex and spontaneous blinking as all three divisions of OO may be used [49–51].

Clinical correlation	
Horner's syndrome	Damage to the sympathetic supply to the eye and orbit results in a partial (1–2 mm) ptosis due to loss of Muller's muscle function [52]
	Additionally the lower lid is elevated and the pupil constricted
Oculomotor (third) nerve palsy	This causes absent levator function, resulting in a complete ptosis [53]
	In addition, there is failure of adduction, failure of elevation and depression, and a dilated pupil
	Often the third nerve palsy is incomplete, and some residual lid opening function, ocular movement, and pupillary constriction are retained
Enhanced ptosis	A ptosis on one side will cause bilateral stimulation of levator function that may mask a contralateral ptosis
	This can be identified by lifting the ptosed eyelid to the normal position: there is less drive for levator stimulation, and the contralateral eyelid may descend [54]
Benign essential blepharospasm	A bilateral, involuntary, spasmodic forced eyelid closure without any other ocular or adnexal cause. It may be unilateral or asymmetric
	It typically presents in the fifth to seventh decade, affecting women more than men
	It is due to the disruption of the normal activation/inhibition pathways resulting in co-contraction of the eyelid protractors with sustained inhibition of the retractors [55]
	It must be differentiated from hemifacial spasm which is typically unilateral and involves lower facial muscles as well as the eyelid protractors. It often has an anatomic cause (e.g., vascular compression of the facial nerve root) [56]

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The Ocular Surface

2

The Tear Film

Overview (Fig. 2.1a)

- The tear film is a highly ordered fluid layer lining the cornea and bulbar and palpebral conjunctiva.
- Abnormal constitution or volume impairs the ocular surface and may reduce corneal transparency [1].
- The tear film has four main functions: *optical, mechanical, nutritional,* and *defensive* [2].

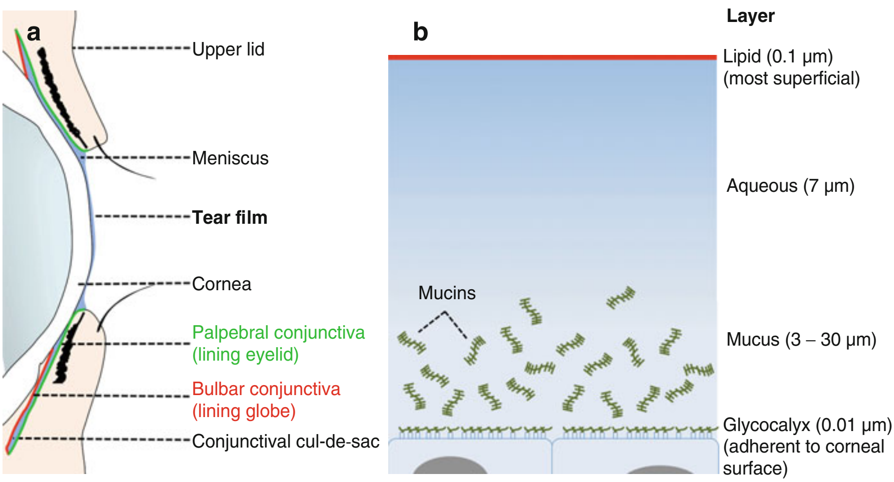

Fig. 2.1 The tear film (**a**) distribution; (**b**) structure

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1. Optical
   - The tear film provides a smooth, regular optical surface for refraction, filling corneal irregularities [3].
   - The air-tear film interface is the most *powerful refractive surface* of the eye.
2. Mechanical
   - The tear film adheres to the bulbar and palpebral conjunctiva ensuring well-*lubricated surfaces* [2].
   - Blinking *flushes debris* and exfoliated cells from the ocular surface out through the tear duct.
3. Nutritional
   - *Oxygen* dissolves in the tear film from air, supplying the avascular cornea [4].
   - *Nutrients* (e.g., glucose) pass from the conjunctival vessels to the cornea via the tear film.
4. Defensive
   - The tear film is the first line of defense against ocular pathogens.
   - It contains *antibacterial constituents* (e.g., secretory immunoglobulin A (sIgA), lysozyme, lactoferrin) and has a *low pH* to maintain an antibacterial environment [5, 6].

Distribution and Flow of Tears

- The tear film has a total volume of 7–10 μL.
- 70–90 % reside in the *upper* and *lower tear menisci*. These are curvilinear collections of tears that line the ocular surface immediately adjacent to the lid margins.
- The tear film drains via the menisci through the *lacrimal puncta* which are apposed to the globe near the inner canthus (See Figs. 2.2 and 2.5a) [7].
- Tears are also stored in the *upper* and *lower conjunctival cul-de-sacs* (*fornices*).
- Normal *basal tear production* rate is 1–2 μl/min; in contrast the *reflex tear rate* is >100 μl/min [8].
- Normal tear volume turnover occurs every 5–7 min.

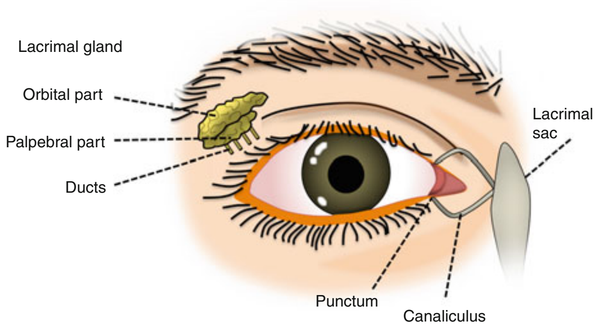

Fig. 2.2 Structure of the lacrimal gland

Structure of the Tear Film [9, 10] (Fig. 2.1b)

From superficial to deep:

- Lipid layer (0.1 μm)
- Aqueous layer (7 μm)
- Mucous layer (3–30 μm)
- Glycocalyx (0.01–0.02 μm)

Lipid Layer

1. Composition, origin, and function (See Fig. 1.2)
   - The lipid layer consists of hydrocarbons, sterol esters, waxy esters, triglycerides, free cholesterol, free fatty acids, polar lipids and proteins [11].
   - It is primarily secreted from *meibomian glands* with additional contributions from the glands of *Moll* and *Zeiss* [12, 13].
   - It is emitted as a liquid spreading over the aqueous on blinking.
   - Polar lipids form the inner surface of the lipid layer, with their charged side facing aqueous [14, 15].
   - Nonpolar lipids spread over the polar lipids.
   - The lipid layer:
     (a) *Inhibits evaporation* of underlying aqueous.
     (b) *Maintains* tear film *stability.*
     (c) *Prevents contamination* with skin lipids (which can destabilize the aqueous).
     (d) *Prevents* tears *spilling* over the eyelid. This occurs because the skin's sebum has mostly nonpolar lipids and tends to repel meibum which has a greater proportion of polar lipids [15, 16].
2. Meibomian glands
   - Meibomian glands are *tubuloacinar glands*, 20–30 per tarsus in number, embedded in the upper and lower tarsal plates.
   - Numerous acini secrete into ducts which converge onto a central vertical channel [13, 17, 18].
   - Lipid-laden acinar cells burst apically releasing their lipid-rich vesicles into the acinar space.
   - The release of the entire cell contents is known as *holocrine secretion*, resulting in a mixture of proteins and lipids termed *meibum* [11].
3. Regulation of meibum secretion
   (i) Neural regulation
     - Meibomian glands are innervated richly by sensory, sympathetic, and parasympathetic nerves [19].
     - However, how these nerves regulate meibum secretion is unknown.