Physiology of Lacrimal Drainage

16

Ali Riza Cenk Çelebi and T. Metin Önerci

Keywords

Lacrimal pump system • Krehbiel's effect • Bernoulli principle • Microciliation • Siphon effect • Capillarity

Core Messages

- There are many factors contributing to lacrimal elimination, but the most important mechanism is canalicular and sac pump mechanism.
- Canalicular pump is probably more important than the sac pump because following DCR, tears are still drained through the canaliculi to the nose.
- The pressure gradient between the canaliculi and the sac cannot be produced if the canaliculus is slit open. Therefore, the lacrimal canaliculi should be preserved and should not be damaged.
- Tear elimination is equivalent through the upper and lower canalicular systems. Therefore, attention should be given not to damage both the upper and lower canaliculus.

The lacrimal drainage system works to remove those tears secreted into the palpebral aperture to cover the cornea at a rate of 1.2 µl/min with a total 24-h secretory volume of approximately 10 ml (Hurwitz 1996). The tear film travels across the surface of the globe and eyelids, enters the puncta/ampulla, passes through the canaliculi, and enters the lacrimal sac/nasolacrimal duct/nasal passages. With blinking (orbicularis muscle contraction), the closure of palpebral aperture starts from lateral and proceeds to medial. This action propels the tears medially toward the lacrimal lake (Hurwitz 1996).

Factors contributing to lacrimal elimination may include:

- Evaporation of tears from the ocular surface
- Capillary attraction of the tears
- Reservoir drainage into the lacrimal sac (so-called Krehbiel flow)
- Siphon effect
- Microciliation and absorption of tears by the lacrimal sac mucosa

A.R.C. Çelebi, MD (✉)
Ophthalmology Clinic,
Niğde State Hospital,
Feridun Zeren Street,
Niğde 51000, Turkey
e-mail: arcenkcelebi@gmail.com

T.M. Önerci, MD
Department of Otorhinolaryngology,
Faculty of Medicine,
Hacettepe University,
Ankara, Turkey

T.M. Önerci (ed.), *Nasal Physiology and Pathophysiology of Nasal Disorders*,
DOI 10.1007/978-3-642-37250-6_16,

- Bernoulli’s principle and Venturi tube effect
- Physical forces such as gravity
- Canalicular and sac pump mechanism

16.1 Factors in Tear Flow

16.1.1 Evaporation

Much of the tears is lost by direct evaporation from the ocular surface. Low humidity and wind increase this loss. According to Schirmer almost half of the secreted tears were lost by evaporation (Hurwitz 1996).

16.1.2 Capillarity

Capillarity or capillary action is the ability of a liquid to flow in a narrow tube without assistance of gravity. This effect can be seen in the drawing of liquids in a thin tube or in porous materials such as paper. Capillary action can be noticed for the drainage of tears from the eye. The small canaliculi may act like a capillary tube. The canaliculi may draw tears through the punctum and transfer tears through the canaliculi. The fact that trauma to the canaliculi and loss of capillarity does not cause loss of function indicates that capillarity is not the only factor in drawing tears through the punctum (Hurwitz 1996).

16.1.3 Krehbiel Flow

Krehbiel flow is the flow of the tears from the punctum through the canaliculus due to changes of pressure within the lacrimal sac owing to the effect of the orbicularis tonus on both canaliculi and tear sac when the lids are open (Hurwitz 1996; Ahl and Hill 1982).

16.1.4 Siphon Effect

The word siphon refers specifically to a tube in an inverted U shape which causes a liquid to flow uphill, above the surface of the reservoir, without pumps, powered by the fall of the liquid as it flows down the tube under the pull of gravity, and is discharged at a level lower than the surface of the reservoir. It is important that while the siphon must touch the liquid in the (upper) reservoir (the surface of the liquid must be above the intake opening), it need not touch the liquid in the lower reservoir and indeed there need not be a lower reservoir – liquid can discharge into midair.

16.1.5 Microciliation and Reabsorption

The internal wall of the lacrimal canaliculi is lined by a stratified epithelium. Epithelial cells are faced by microvilli. The facing of epithelial cells by microvilli gives hints of reabsorption of lacrimal fluid inside the lacrimal ducts (Paulsen et al. 1998). Due to this reabsorption in the nasolacrimal sac and duct, the amount of tears leaving the nasolacrimal duct orifice in the nose is less than the amount of tears entering the puncta.

16.1.6 Bernoulli’s Principle and Venturi Tube Effect

The relationship between the velocity and pressure exerted by a moving liquid is described by the Bernoulli’s principle: as the velocity of a fluid increases, the pressure exerted by that fluid decreases. The Venturi effect is similar to Bernoulli’s principle. The velocity of the fluid increases as the cross-sectional area decreases, with the static pressure correspondingly decreasing. According to the laws governing fluid dynamics, a fluid’s velocity must increase as it passes through a constriction to satisfy the principle of continuity, while its pressure must decrease to satisfy the principle of conservation of mechanical energy. An equation for the drop in pressure due to the Venturi effect may be derived from a combination of Bernoulli’s principle and the continuity equation.

The canaliculi narrow close to the common canaliculus, and the common canaliculus is a larger structure. Bernoulli principle and Venturi tube effect may play a role in the flow through the canaliculi. According to Venturi tube effect, narrowing of the canaliculi from lateral to medial increases the speed of flow from lateral to medial and according to Bernoulli's principle movement over a low pressure area creates a suctional effect. Bernoulli's principle may also play a role in the lacrimal system at the nasal cavity sucking tears from the valve of Hasner area into the nose in addition to the ampulla and just distal to the common internal punctum (Sisler 1982).

16.2 Tear Flow and Elimination

16.2.1 Flow from the Lacrimal Lake Through the Puncta

The tears enter the puncta with three mechanisms (Hurwitz 1996):

1. A negative pressure would develop inside the punctum to suck the tears.
2. The small canaliculi may act as capillary tubes and would suction the tears through the small capillary tubes. However, capillarity is not the only factor in drainage because a slit canaliculus where capillarity has been destroyed usually functions well for other reasons.
3. Krehbiel's effect (Reservoir drainage into the lacrimal sac) Krehbiel suggested that even in the resting phase of the blink cycle, tears pass from the punctum through into the canaliculus. This may be due to changes of pressure within the lacrimal sac owing to the effect of the orbicularis tonus on both canaliculi and tear sac when the lids are open. However, if a DCR is performed, this effect may not be seen and therefore it is probably not the intracanalicular suction that is causing this effect, but sac suction (Hurwitz 1996; Ahl and Hill 1982).

16.2.2 What Canalicular System Is More Important for Tear Elimination: Upper or Lower?

Although it is believed that upper canalicular system is unimportant, experimental and clinical studies show that tear elimination is equivalent through the upper and lower canalicular systems (White et al. 1989; Daubert et al. 1990; Linberg and Moore 1988; Meyer et al. 1990). Surgeons should thus give equal consideration to a patient with lacerations of either the upper or lower canaliculus. Studies by White et al. (1989) and Daubert et al. (1990) have demonstrated equal tear flow between the upper and lower canalicular systems using radioactive dacryoscintigraphy flow studies. Meyer et al. (1990) studied fluorescein dye disappearance in 20 subjects and found that 90 % of patients showed minimal or no impairment with monocanalicular (either upper or lower) obstruction.

16.2.3 Flow Through the Canaliculi into the Sac

Although multiple mechanisms may contribute to lacrimal outflow, present evidence suggests that the most important factor is the active palpebral-canalicular pump. It has long been noted that the blinking mechanism readily drains tears even with the head held in an inverted position. When the palpebral blink mechanism is impaired, however, epiphora is common, such as in patients with facial paralysis.

16.2.4 Lacrimal Pump

There are two most popular lacrimal pump theories: one suggested by Jones (1973) and the other by Doane (1981). More recently, Becker (1992) proposed a tricompartmental model of the lacrimal pump, which in many ways is similar to the Doane model. The lacrimal pump models agree that eyelid closure results in a squeezing of the canaliculi with the nasal movement of tears into the lacrimal sac. The models diverge, however, in the analysis of the changes in the lacrimal sac pressure with eyelid closure and opening.

The first "lacrimal pump" theory is based on classic anatomic studies by Jones (1973), describing tendinous and muscular insertions exerting their action on and around the lacrimal sac. The Jones theory for this lacrimal pump involves three components:

1. The deep heads of the pretarsal orbicularis muscle (Horner's muscle)
2. The deep head of the preseptal muscle (Jones' muscle)
3. The lacrimal diaphragm (fascia around the sac)

The tensor tarsi (Horner's) muscle originates on the posterior lacrimal crest and divides to surround the canaliculi. It then becomes continuous with the pretarsal portions of the orbicularis muscle. Since some fibers of this muscle run in a parallel and sometimes spiral manner, the contraction of the muscle can draw the papillae of the puncta in a medial direction. This narrows the ampullae and shortens the canaliculi (Jones 1957). The Horner's muscle around the canaliculi pumps tears from the punctum through to the sac (Ahl and Hill 1982).

An additional strand of orbicularis muscle from the preseptal area inserting into the lacrimal fascia and posterior lacrimal crest (the deep head of the preseptal orbicularis muscle) was described by Jones and this muscle is named as Jones' muscle. According to Jones the muscular pull of this preseptal orbicularis muscle (Jones' muscle) on the lacrimal sac draws the lateral wall of the nasolacrimal sac laterally and creates a negative pressure within the sac (Jones 1956).

With blinking, contraction of the deep preseptal orbicularis fibers (Jones' muscle) draws the lateral wall of the nasolacrimal sac laterally, creating a negative pressure within the sac and allowing the inspiration of tears into the sac. The tears are forced along the canalicular system by contraction of the deep head of the pretarsal muscle (Horner's muscle). When the orbicularis relaxes and the eyelid opens, the sac collapses, forcing tears down the nasolacrimal duct. At the same time, the canaliculi open, siphoning tears into their lumen. Closing the eyelids again pushes and propels the accumulated tears into the lacrimal sac (Jordan et al. 2012).

Doane suggested a different mechanism of tear propulsion through the system. He noted that the puncta came together during the early phases of eyelid closure and occlusion of the puncta occurred as a first step in the tear pump. He postulated that contraction of the pretarsal orbicularis oculi muscle exerts lateral traction on the lacrimal sac wall, compresses the ampulla, and shortens the canaliculi, causing a pressure increase in the canaliculi propelling tear fluid within the canaliculi toward the lacrimal sac (i.e., positive pressure is created during a blink in both the canaliculi and the nasolacrimal sac as a result of muscle contraction occurring in the pretarsal and preseptal orbicularis fibers) (Jordan et al. 2012; Doane 1981). Doane further theorized that as the tension increases on the lacrimal fascia to open the fundus of the sac, the inferior portion closes more tightly, preventing aspiration of air from the nose. As the eyelids open, the puncta initially remain closed by the opposing lid until the end of the opening movement and a partial vacuum forms within the membranous lacrimal conduit. As the eyelid-opening phase of the blink continues, the two lacrimal puncta open and expose the adjacent lacrimal lake to this partial vacuum. Tears rapidly flow into the canaliculi during the 1– 3-s interval immediately after the blink. Once again, the canaliculi fill with fluid so that the pumping action of the next blink can continue the lacrimal elimination cycle. With relaxation of the deep head of the preseptal orbicularis muscle, elastic recoil of the lacrimal fascia collapses the lacrimal sac, expelling any fluid within the sac down into the now patent nasolacrimal duct. Thus the collapsing lacrimal drainage conduit was believed to push the tears through the system into the nose without the suction phase postulated by Jones (Doane 1981). To date, most evidence supports the Doane model (Burkat et al. 2006).

Becker observed that the superolateral wall of the lacrimal sac, which is attached to the deep head of the preseptal orbicularis, moved laterally with lid closure and medially with lid opening. The inferior half of the lateral wall of the lacrimal sac moved medially with lid closure and laterally with lid opening. Becker suggested a tricompartment model of the lacrimal pump that incorporates these findings. With lid closure, the orbicularis muscle contracts, compressing the canaliculi and pulling the superior half of the lateral wall of the lacrimal sac laterally. This creates a lower pressure in the superior sac, allowing tears to be propelled from the canaliculi into the sac. At the same time, the inferior half of the lateral sac wall moves medially, creating a positive pressure in the inferior sac and nasolacrimal duct, thus forcing tears down the duct into the nose. With lid opening, the orbicularis muscle relaxes, allowing the canaliculi to open and the superior half of the lateral sac wall to move medially. The resulting negative intracanalicular pressure allows tears to flow from the lacrimal lake into the canaliculi, and the higher pressure in the superior sac closes the valve of Rosenmüller and forces tears from the superior to inferior sac and proximal nasolacrimal duct. At the same time, the inferior half of the lateral sac wall moves laterally, resulting in a negative pressure in the inferior sac and nasolacrimal duct (Becker 1992). These observations are in agreement with Doane's model, with the overall lacrimal sac pressure increasing with eyelid closure and reducing with eyelid opening.

These proposed lacrimal sac pumping mechanisms are based on anatomic studies and likely do not have a large role in normal lacrimal elimination, because the system functions quite well with the lacrimal sac completely open, as is the case after dacryocystorhinostomy (DCR). This shows that the canalicular pump is more important than the sac pump (Hurwitz 1996).

16.2.5 Flow from the Sac to the Nose

The flow of tears from the sac down through the duct has been postulated to be a siphoning effect and a gravitational effect. The fact that tears will flow through the lacrimal system even when one is standing on his head, means that it does not only depend on the gravitational effect but some other active mechanisms as well. The filling of the sac and the increasing pressure in the sac force the tears down through the duct. Each blink expels the fluid through the canaliculi to the sac and the sac expels the fluid to the duct (Hurwitz 1996).

16.3 Other Factors on Tear Flow

16.3.1 Effect of Respiration

It was postulated that respiration also plays a role in drainage of tears from the duct into the nose and that Bernoulli's principle has some effect on this function. However since the duct narrows as it approaches to the Hasner valve, Bernoulli's effect is minimal. On the other hand after DCR operation common canaliculus opens directly into the nose, and respiration and Bernouilli's principle plays a much more important role in these operated cases (Nik et al. 1984).

16.3.2 Valves

The function of the valves is to prevent or decrease the retrograde flow of tears and/or air currents. The most important valve is Hasner valve which is located at the lower end of the nasolacrimal duct. Hasner valve prevents air currents from within the nose being drawn up into the lacrimal duct (Hurwitz 1996).

Rosenmüller valve is located at the common internal punctum and prevents backflow from the sac into the canaliculi. This valve is not a real valve but it functions like a valve because of the anatomic angulation of the canaliculi and common canaliculus. This valve is especially important after DCR operation to prevent backflow of the tears from the nose into the canaliculi (Corin et al. 1990).

Although other valves at the punctum, the ampulla, and at the junction of the nasolacrimal sac and duct have been described in the literature, these are mainly mucosal folds and do not have much function.

16.3.3 Clinical Principles Derived from the Physiologic Information

The palpebral-canalicular pump mechanism in lacrimal elimination is the major mechanism. The canalicular pump is probably more important than the sac pump because following DCR tears are still drained through the canaliculi to the nose. In facial nerve paralysis, tears will not drain into the nose because orbicularis muscle is not functioning and cannot operate the canalicular pump although there is a patent opening. Therefore, the lacrimal canaliculi should be preserved and should not be damaged. Repeated instrumentation

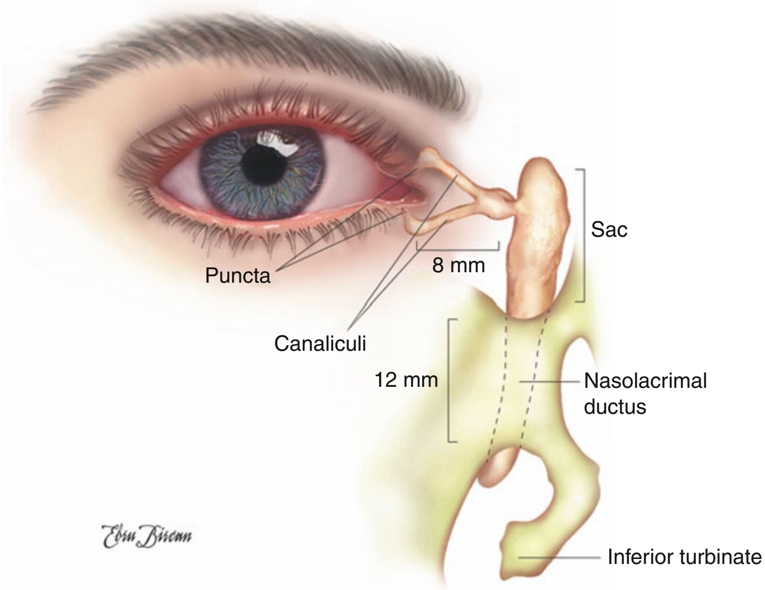


Fig. 16.1 Normal anatomy of the nasolacrimal system (Courtesy of TESAV)

of the lacrimal system or nasolacrimal duct probings may injure the canaliculi and thus permanently impair lacrimal elimination. It is very difficult to restore scarred fibrosed canaliculi. On the other hand, the pressure gradient between the canaliculi and the sac cannot be produced if the canaliculus is slit open. This information should caution clinicians against performing overly aggressive procedures on the lacrimal outflow system (Myron and Clinton 2006).

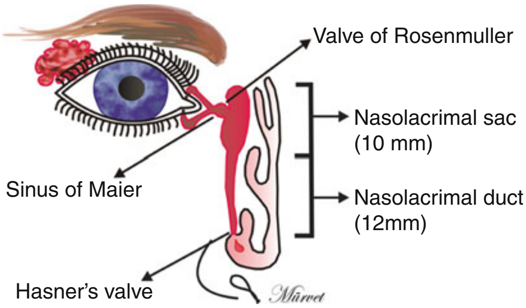


Fig. 16.2 Schematic representation of the nasolacrimal system (Courtesy of TESAV)

Conclusions

There are many factors which are important in lacrimal drainage system. The palpebral-canalicular pump mechanism in lacrimal elimination is the major mechanism. The canalicular pump is probably more important than the sac pump because following DCR tears are still drained through the canaliculi to the nose. Damage to the canaliculi should be avoided since the damage of the canaliculi impairs the lacrimal elimination. After DCR operation the physiology changes and some physiologic mechanisms may play a more important role. Tear elimination is equivalent through the upper and lower canalicular systems. Therefore, attention should be given not

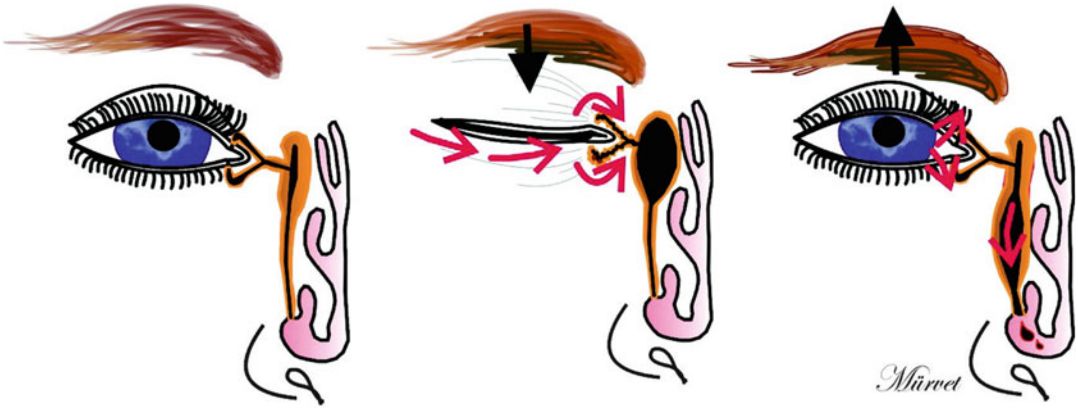
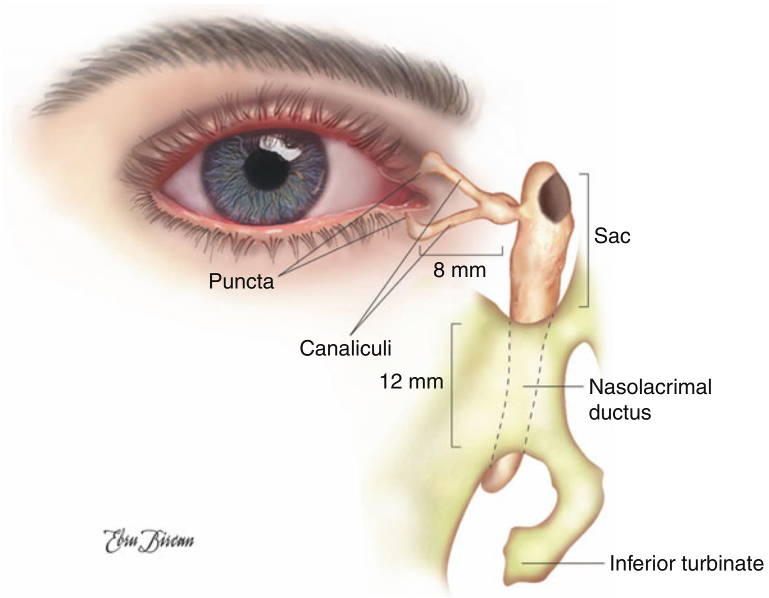


Fig. 16.3 The palpebral-canalicular pump mechanism in lacrimal elimination (Courtesy of TESAV)

Fig. 16.4 Sump syndrome. If the rhinostomy opening is made too high during DCR operation, the drainage system will not function properly (Courtesy of TESAV)



to damage both the upper and lower canaliculus (Figs. 16.1, 16.2, 16.3, 16.4).

References

Ahl NC, Hill JC. Horner's muscle and the lacrimal system. Arch Ophthalmol. 1982;100:488–93.

Becker BB. Tricompartment model of the lacrimal pump mechanism. Ophthalmology. 1992;99:1139–1145.

Burkat CN, Hodges RR, Lucarelli MJ, et al. Physiology of the lacrimal system. In: Tasman W, Jaeger EA, editors. Duane's foundations of clinical ophthalmology, vol. 2. Philadelphia: Lippincott Williams&Wilkins; 2006. Chapter 2a.

Corin S, Hurwitz JJ, Jaffer N, Botta EP. The true canalicular angle: a mathematical analysis. Ophthal Plast Reconstr Surg. 1990;6:42–5.

Daubert J, Nik N, Chandeyssoun PA, et al. Tear flow analysis through the upper and lower systems. Ophthal Plast Reconstr Surg. 1990;6:193–6.

Doane MG. Blinking and the mechanics of the lacrimal drainage system. Ophthalmology. 1981;88: 844–51.

Hurwitz JJ. Physiology of the lacrimal drainage system. In: Hurwitz JJ, editor. The lacrimal system. Philadelphia: Lippincott-Raven Publishers; 1996. p. 23–8.

Jones LT. Epiphora: its relation to the anatomic structures and surgery of the medial canthal region. Trans Pac Coast Oto-Ophthalmol Soc. 1956;37:31–46.

Jones LT. Epiphora. II. Its relation to the anatomic structures and surgery of the medial canthal region. Am J Ophthalmol. 1957;43:203–212.

Jones LT. Anatomy of the tear system. Int Ophthalmol Clin. 1973;13:3–22.

Jordan DR, Mawn L, Anderson RL. Surgical anatomy of the ocular Adnexa: a clinical approach. San Francisco: American Academy of Ophthalmology; 2012. p. 30–8. 1st ed. 1996.

Linberg JV, Moore CA. Symptoms of canalicular obstruction. Ophthalmology. 1988;95:1077–9.

Meyer DR, Antonello A, Linberg JY. Assessment of tear drainage after canalicular obstruction using fluorescein dye disappearance. Ophthalmology. 1990;97:1370–4.

Myron T, Clinton DM. Lacrimal drainage system. In: Tasman W, Jaeger EA, editors. Duane's clinical ophthalmology, vol. 4. Philadelphia: Lippincott Williams & Wilkins; 2006. Chapter 13.

Nik NA, Hurwitz JJ, Ching SH. The mechanism of tear flow after DCR and Jones' tube surgery. Arch Ophthalmol. 1984;102:1643–6.

Paulsen F, Thale A, Kohla G, et al. Functional anatomy of human lacrimal duct epithelium. Anat Embryol. 1998; 198:1–12.

Sisler HA. One-way flow in the lacrimal drainage system: determinants from the basic sciences. Ann Ophthalmol. 1982;14:76–77.

White WL, Glover AT, Buckner AB, et al. Relative canalicular tear flow as assessed by dacryoscintigraphy. Ophthalmology. 1989;96:167–9.