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Diagnostic imaging of the nasolacrimal drainage system. Part I. Radiological anatomy of lacrimal pathways. Physiology of tear secretion and tear outflow

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Excessive watering of the eye is a common condition in ophthalmological practice. It may be the result of excessive production of tear fluid or obstruction and insufficiency of efferent tear pathways. The differentiation between obstruction and insufficiency of the lacrimal pathways is still clinically questionable. In the diagnostic process it is necessary to perform clinical tests and additional diagnostic imaging is often needed. Dacryocystography, with or without the extension of the dynamic phase or subtraction option, still remains the criterion standard for diagnostic imaging of the lacrimal obstruction. It may help to clarify the cause and exact place of the obstruction and provide information for further management, especially surgical treatment. Increasingly, new techniques are used in diagnostic imaging of the lacrimal tract, such as computed tomography, magnetic resonance, and isotopic methods.

Adequate knowledge of the anatomy and physiology of the lacrimal system and the secretion and outflow of tears is the basis for proper diagnostic imaging. The purpose of this paper is to present the exact anatomy of the lacrimal system, with particular emphasis on the radiological anatomy and the current state of knowledge about the physiology of tear secretion and drainage.

MeSH Keywords: Lacrimal Apparatus Diseases • Dacryocystitis – diagnosis • Lacrimal Apparatus – anatomy & histology

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Background

Epiphora is a common condition in ophthalmological practice. It may be the result of an excessive production of tear fluid, or the obstruction or insufficiency of the efferent tear pathways. Diagnosis of the latter problem, as well as differentiation between obstruction and insufficiency of lacrimal pathways, still is clinically questionable. In the diagnostic process, it is necessary to investigate various causes of epiphora and perform additional clinical tests. The ophthalmologist must have a thorough knowledge of anatomy, physiology, and pathophysiology of the lacrimal apparatus in order to make an adequate diagnosis, determine the causes of excessive watering of the eye, and to implement effective medical treatment. In doubtful cases it is necessary to perform additional tests, including radiology and diagnostic imaging. Dacryocystography (DCG), performed as a conventional radiology procedure with the use of contrast media, is considered to be the criterion standard in the diagnosis of lacrimal tracts pathology. Supported by advanced image processing algorithms and high-quality modern contrast media, it enables accurate diagnosis of pathology in small structures such as the lacrimal duct with fewer adverse effects. Both dacryocystography and modern diagnostic methods, which are more commonly used in the lacrimal pathway imaging, can not only provide answers to questions crucial in choosing the appropriate treatment method, but also significantly impact the scope of possible surgical treatment. However, the radiologist must have a broad knowledge on this particular ailment, be able to select an adequate imaging method, have appropriate skills and experience to perform diagnostic procedures, and closely cooperate with the clinician. Good knowledge of radiographic anatomy of the orbit and lacrimal pathways, as well as the physiology of tears outflow, is an essential factor in proper interpretation of test results.

Radiographic Anatomy of the Orbit and Lateral Nasal Wall

The normal anatomical structure of an organ usually determines its physiological efficiency. The visual organ, located mainly within the facial skeleton, consists of an eye and accessory organs. The eye is made up of the eyeball, placed in a 4-sided pyramid known as the orbit, and an optic nerve, which is the only connection between this sense organ and the encephalon. The system of accessory organs is formed by orbital fasciae, eyelids, conjunctiva, the lacrimal apparatus, and muscles of the eyeball. The volume of the orbit is usually about 30 ml, of which the eye occupies only 6–7 ml.

In each orbit, 4 walls, the inlet of the orbit, and its apex, directed medially and posteriorly, can be identified. The floor (inferior wall) of the orbit is formed by the orbital surface of the body of the maxilla, and the anterolateral part of the floor is filled by the orbital surface of the zygomatic bone and the posteromedial part by the orbital process of the palatine bone. In the anteromedial part of the inferior wall, the superior foramen of the nasolacrimal canal, running along the lateral nasal wall, can be found. The nasolacrimal duct, draining tears from the lacrimal sac to the nasopharynx, passes through this bony canal. The inferior ostium of the canal is located on the surface of the inferior nasal concha. The vertically oriented lateral wall of the orbit is formed by orbital surfaces of the zygomatic bone and the greater wing of the sphenoid bone. The orbital roof is composed of the orbital part of the frontal bone and the lesser wing of the sphenoid bone. The depression located in the anterolateral part of the roof is known as the fossa of the lacrimal gland, named after a gland that is situated there [1].

Pathological processes leading to the destruction of the bones forming the scaffold for the lacrimal pathways may cause their blockage. Knowledge of the anatomy of the medial orbital wall is particularly important for the radiologist conducting the assessment of the lacrimal pathways. Its anterior part is formed by the posterior surface of the frontal process of maxilla and the lacrimal bone, while the posterior part is formed by the orbital plate of the ethmoid bone and the lateral surface of the sphenoid bone. The lacrimal bone, which is the smallest bone of the facial skeleton (viscerocranium), plays an important role in the construction of the anterior part of the medial orbital wall. Its orbital surface is divided into 2 parts by the vertical posterior lacrimal crest. The smooth posterior composes the orbital wall. Located in the anterior part, the vertical lacrimal sulcus (which, with the similar lacrimal sulcus of the frontal process of maxilla, forms the fossa of the lacrimal sac), has an average length of 16 mm, width of 8 mm, and depth of 2–4 mm. This depression is usually slightly less narrow in women than in men [2]. The lacrimal sac is located in the superior part of the fossa, while the initial section of the nasolacrimal duct is in the inferior part of the fossa. The posterior nasal crest divides the inferior margin of the lacrimal bone into 2 parts: the posterior part is connected to the orbital process of maxilla, and anterior part descends lower and is connected to the lacrimal process of the inferior nasal concha. Due to that latter connection, the lacrimal bone helps form the nasolacrimal canal (the bony scaffold for the nasolacrimal duct, which begins on the medial orbital wall, runs along the lateral wall of the nasal cavity and enters the inferior nasal meatus just behind the anterior end of the inferior nasal concha. The nasolacrimal canal is formed laterally and anteriorly by the lacrimal sulcus of the frontal process and the body of maxilla, and is formed medially and posteriorly by the lacrimal sulcus of the lacrimal bone and the lacrimal process of the inferior nasal concha. The lacrimal part of the orbiculus oculi muscle attaches to the posterior nasal

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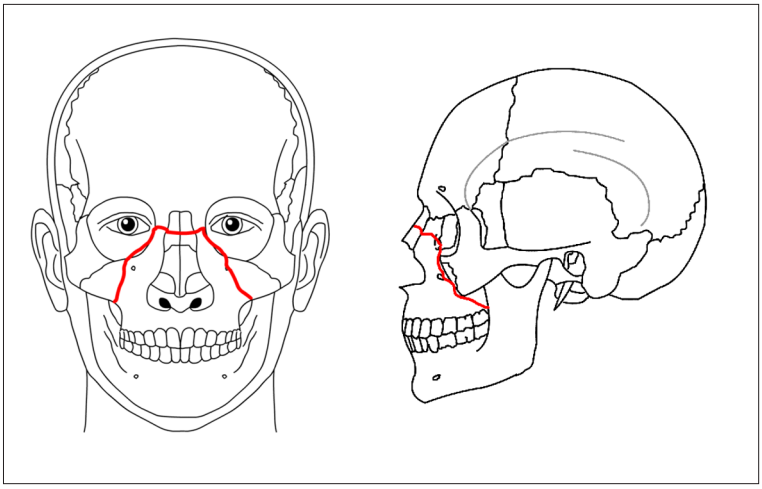

Figure 1. Le Fort fracture, type II scheme. Based on RosarioVanTulpe scheme.

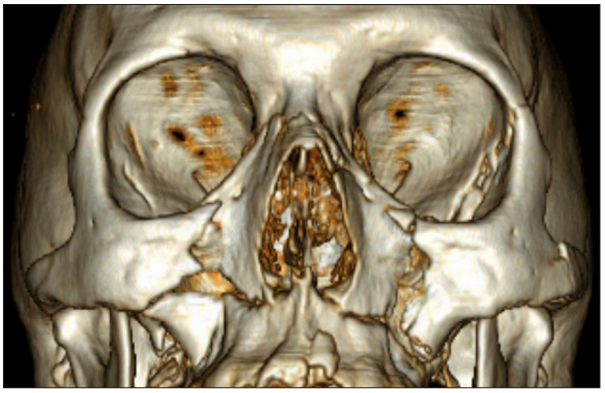

Figure 2. Le Fort fracture, type II. CT volume reconstruction.

crest. Insufficiency of this muscle can be the cause of insufficiency of the tear pump or the insufficiency of lacrimal pathways as a functional block [1,3,4]. Equally important for the radiological diagnosis of the orbit and lacrimal passages is the correct assessment of the sutures fusing the bones of the viscerocranium, especially if trauma of this area is suspected. Looking at the inferior orbital wall, 2 sutures can be seen: one connecting the orbital process of the palatine bone and the maxilla (palatomaxillary), and the other one connecting the zygomatic bone and maxilla (zygomaticomaxillary). The sphenozygomatic suture connects the greater wing of the sphenoid bone and the zygomatic bone on the lateral wall. The connection between the frontal process of the zygomatic bone and the zygomatic process of the frontal bone is formed by the frontozygomatic suture, to which the sphenofrontal suture adheres, slightly medially, forming a horizontal line and the sphenoethmoidal suture on the medial orbital wall. Injuries to these sutures are encountered in Lefort III fractures. In this case, the fissure of the fracture runs through the frontonasal sutures, injuring the medial wall, through the central parts of the orbit, often with injuries of the superior orbital fissure, and through the frontozygomatic and temporozygomatic sutures. In this kind of fracture, the main massif of the viscerocranium with the zygomatic and nasal bones is detached from the cranium as a whole. In Lefort II fractures, injuries of the inferior walls and inferior margins of the orbits near the zygomaticomaxillary sutures, lacrimal bones, nasal bridge, fractures of the frontal processes of maxilla, and lateral walls of the maxillary sinuses occur. Shadowing of the maxillary sinus can also be seen on radiograms. This type of fracture can lead to posttraumatic obstruction of the lacrimal pathways (Figures 1 and 2) [5–9].

Fractures of the medial wall of the orbit are also concomitant with direct injuries of the nasal bone. The fractures are also the effects of blowout trauma, in which a large, round object (e.g., a ball) hits the eyeball directly with great force.

Anatomy of Nasolacrimal Duct

Giovanni Battista Carcano Leone, the Italian professor of anatomy, was the first to provide an adequate description of the nasolacrimal ducts, which he presented in the publication "Anatomici Libri II" in 1574 in Padua. The research was further carried on by the Danish scholar Niels Stensen, who in 1662 produced a reliable study on the structure of the whole lacrimal system [10]. The key function of lacrimal apparatus is to provide sufficient moisturization of the cornea and retina. It consists of secretory and drainage sections. The first section, known as the glandular section, consists of the lacrimal gland and accessory lacrimal glands known as the glands of Krause and Wolfirng, sebaceous glands of Zeiss, and meibomian tarsal gland. The second section consists of lacrimal pathways that commence near the medial angle of palpebral fissure with 2 lacrimal puncta – the upper and lower – located on the summits of the lacrimal papilla. Accessory glands, which are 40 up to 50 in number, are mainly found in the superior fornix of the conjunctiva. Only a few of them, usually 5–6, are found in the inferior fornix of the conjunctiva [3].

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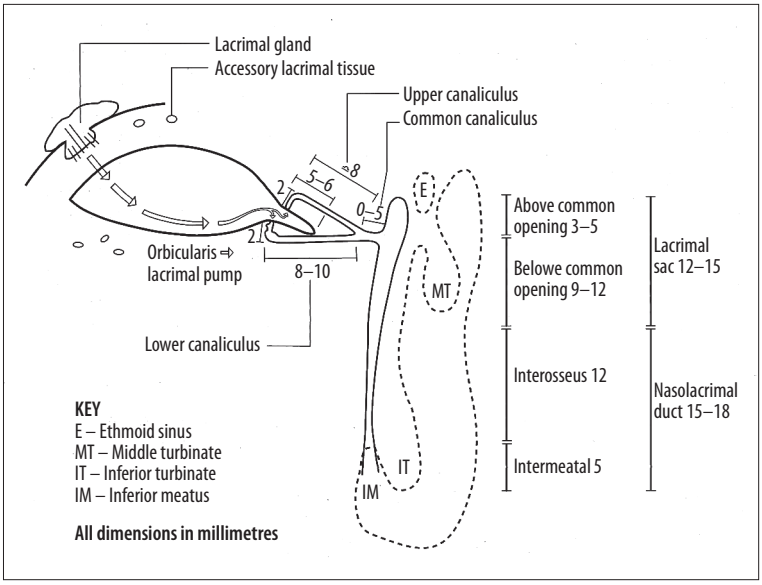

Figure 3. Lacrimal system shapes and sizes. With kind permission of Jane Olver, Color Atlas of Lacrimal Surgery, Oxford, 2002.

Lacrimal gland

The lacrimal gland is located in the superolateral part of the orbit, above the lateral angle of the eyelids. The tendon of the levator palpebrae superioris muscle divides the gland into a visibly larger superior part, known as the orbital, with dimensions of 20×12mm. It lies in the fossa of the lacrimal gland, which is a small depression in the orbital surface of the frontal bone, right under the zygomatic process. The much smaller inferior part, known as the palpebral, is located near the superior fornix of the conjunctiva and can be seen after unrolling the superior eyelid. In normal conditions, the lacrimal gland is not visible on a viscerocranium radiogram because osseous structures, which produce a much stronger shadow, effectively shade its more subtle shadow. The situation can differ if there are lumpy changes in the lacrimal gland. When low-voltage (less than 70 kV) radiation is used, the radiogram may show a subtle shadowing, which is the basis for further testing. Nowadays, magnetic resonance and computer tomography are used to image such pathologies. Ten to 12 excretory glands come out of the lacrimal gland and drain into the lateral part of the superior fornix of the conjunctiva [11].

Anatomy of the conjunctival sac and eyelid margins

Eyelids, formed by movable folds of facial skin, protect the eyeball, covering it from the front. Their function is to provide protection from mechanical injuries and to keep the cornea and conjunctiva of the eye constantly moisturized. In both superior and inferior eyelids, the anterior (cutaneous) and posterior (conjunctival) surfaces can be distinguished. Both surfaces bind with each other on their 2-mm-width free margins, forming anterior and posterior edges of the eyelid. Orifices of the tarsal glands, located in the tarsal plate (the connective tissue scaffold of the eyelids) are positioned near the posterior edge. The eyelids meet each other on both ends of the palpebral fissure, forming the lateral and medial angles of the eye. The conjunctiva, which lines the posterior palpebral surface and the anterior surface of the eyeball, forms the common conjunctival sac. Tears, secreted by lacrimal glands, do not flow down unobstructed on the corneal surface, but are spread over it by blinking, with support of the groove formed by the anterior surface of the eyeball and free margin of the eyelids, known also as the rivus lacrimalis [12]. Some tears evaporate, other gather in the lacrimal lake, surrounding the lacrimal caruncle situated in the medial angle of the eye. The normal structure of margins of the eyelids determines the physiological distribution of tear film and normal tear drainage. Small anatomical abnormalities or excessively loose eyelids cause lacrimal passage obstruction.

Anatomy of lacrimal passages

The key function of the lacrimal apparatus is to maintain adequate cornea and conjunctiva moisturization, but also to provide the correct the balance between inflow and outflow of tears to the lacrimal sac. This specific tear balance guarantees normal function of the cornea, which mainly refracts light rays in the vision process. The lacrimal fluid produced by the lacrimal glands is spread across the surface of the cornea and conjunctiva and penetrates through lacrimal puncta into the lacrimal drainage system formed by lacrimal canaliculi, the lacrimal sac, and nasolacrimal ducts. Lacrimal system shapes and sizes are presented in Figure 3. Lacrimal puncta and canaliculi form the upper part of the lacrimal pathways (the so-called upper lacrimal pathways). Its lumen is lined with stratified cuboidal epithelium. The lacrimal sac and nasolacrimal ducts compose the lower floor of the lacrimal drainage system (the so-called

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lower lacrimal pathways), whose interior membrane is formed by double-layered columnar epithelium.

Lacrimal puncta

Tears are drained down from the conjunctival sac through lacrimal pathways to the inferior nasal meatus and then to the nasopharynx. The entrance of the lacrimal pathways is formed by 2 small (0.2–0.3 mm in diameter) orifices, known as the upper and lower lacrimal puncta. Lacrimal puncta placed on small papillae lacrimalis near the posterior palpebral edge continue into upper and lower lacrimal canaliculi, then they converge into the common canaliculus, which enters the lacrimal sac. Tear fluid drains from the lacrimal sac to the nasopharynx through the nasolacrimal duct, which enters the inferior nasal meatus behind the anterior margin of the inferior nasal concha. Lacrimal puncta are located 6 mm lateral to the medial angle of the eye on the papillae lacrimalis [2]. The papillae region is relatively less vascularized than the surrounding tissues; therefore, lacrimal puncta can be seen microscopically, as less intensely pink spots. When eyelids close, puncta meet each other and simultaneously submerge in the lacrimal lake. When eyelids open, the lower lacrimal punctum is seen approximately 1 mm lateral to the upper one. Normal positioning of the puncta plays an important role in efficiency of the whole lacrimal drainage system, and their abnormal location can lead to epiphora. Walls of the puncta are strengthened with a fibrous connective tissue ring. Orbicularis oculi muscle fibers surround the papilla lacrimalis, directing its apex posteriorly and medially [10].

Lacrimal canaliculi

Lacrimal puncta, forming the opening of the lacrimal pathways, lead to the lacrimal canaliculi. They are separated by short folds of mucous membrane that act as valves protecting the canaliculi lumen from moving its content back into the conjunctival sac. The valves are called alternatively, after names of their discoverers, the valves of Bochdalek or Foltz. During contrast examination, cannulas inserted into lacrimal puncta and the microscopic size of the structures significantly limit the ability to assess these valves. The initial sections of the lacrimal canaliculi run about 2 mm vertically and then spread their lumen, forming the ampulla of the lacrimal canaliculus, and bend medially into the horizontal part. The length of the horizontal segment varies from 6 to 10 mm [2,13]. The distal upper and lower canaliculi sections run along the eyelid margins medially towards the lacrimal sac. In contrast imaging of lacrimal pathways, it can be seen that the upper lacrimal canaliculus is usually slightly shorter then the lower and runs straighter, at the angle of 25–30 degrees down towards the lacrimal sac. The lower canaliculus, however, is in a more horizontal position and usually leans down at the angle of 10–15 degrees. The average width of the canaliculi lumen is about 0.5–0.6 mm [11], but their diameter can increase by up to 3-fold. Their elastic thin walls, strengthened partially by the delicate orbicular eye muscle (Riolan's muscle) fibers, enable that. The ability of the canaliculi and lacrimal sac lumen to alter the diameter is the main lacrimal drainage supporting mechanism, known as the lacrimal pump. During eyelid closure, the distal part of the canaliculi lumen constricts (Horner's muscle) and has compressing influence on the tear fluid (Venturi effect). When eyelids open the lumen dilates, causing the absorption of fluid (a suction effect called the Bernoulli effect). The lower canaliculus is the main way for tears to drain from the conjunctival sac and 80–90% of the total tear fluid drains down that way. Therefore, even the smallest dysfunction at this level of the lacrimal pathway can lead to pathological lacrimation. The ability to dilate the lumen and straighten the canaliculus by palpational, lateral eyelid movement is very important in both diagnostic and treatment process, as it allows the insertion of instruments [14,15].

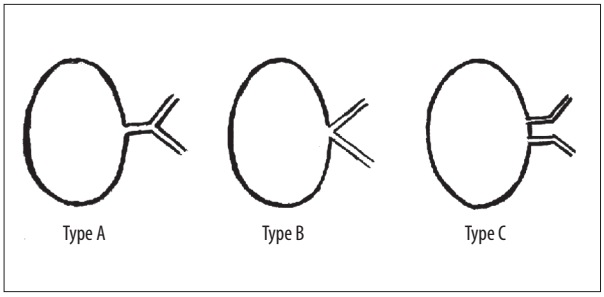

Figure 4. Anatomical types connecting the upper and lower canaliculi to the lacrimal sac. Based on Yazici B, Yazici Z. Frequency of the common canaliculus. A radiological study. Arch Ophthalmol, 2000; 118: 1381–85.

Lacrimal canaliculi can enter the lacrimal sac in several ways. The most common way is when the upper and lower canaliculus join to form a common canaliculus of 2–5 mm in length, which then enters the small recess of the lateral wall of the lacrimal sac, known as the sinus of Maier. It is currently assumed that this structure of the upper section of lacrimal apparatus is typical for 90% of population, and in the remaining 10% there is the separate ostium of the upper and lower canaliculus [2,13,16]. Meanwhile, Turkish studies found that 94% of the general population have the common canaliculus (type A), while only 2% have a separate ostium of the upper and lower canaliculus (type C). The remaining 4% have a common ostium of upper and lower canaliculus that join in the lacrimal sac wall without forming a common canaliculus (type B) [17]. Anatomical types connecting the upper and lower canaliculi to the lacrimal sac are presented in Figure 4.

The common canaliculus is usually short and in most cases runs in a straight line, medially and from back to front, then

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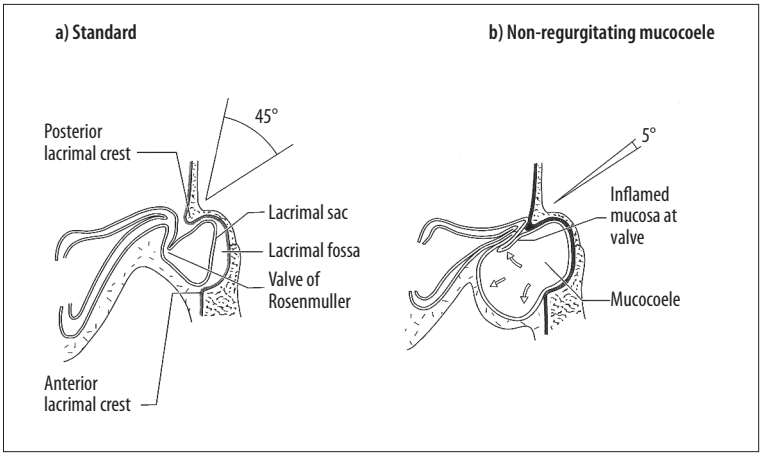

Figure 5. Mucocele formation diagram. With kind permission of Jane Olver, Color Atlas of Lacrimal Surgery, Oxford, 2002.

enters the lacrimal sac at a sharp angle. At the junction between the common canaliculus and the lateral wall of the lacrimal sac, a sharp flexure of the common canaliculus forms 2 short mucous membrane folds (upper and lower), which form a type of valve. The upper fold, known also as the posterior, is called the valve of Rosenmueller, while the lower fold is the valve of Huschke [18]. The anatomical structure of this particular ostium is suspected to be the cause of lacrimal sac mucocele formation. When tears accumulate in the lacrimal sac due to impaired drainage into the nasolacrimal duct, the hydrostatic pressure in the sac increases, leading to valve fold pressure and permanent closure of the common canaliculus ostium. The mechanism of lacrimal sac mucocele formation is presented in Figure 5.

Lacrimal sac

The lacrimal sac is located in the fossa within the medial orbital wall. It is separated from the orbit by the orbital septum, which attaches to anterior surface of the upper and lower eyelid tarsal plates and superiorly and inferiorly connects with the orbital margins. The orbital septum takes part in every movement of the eyelids. It lies directly under the orbicularis oculi muscle and closes the orbital aditus, separating the orbital fat body from the front. The central part of the lacrimal sac is anteriorly and posteriorly covered by the medial palpebral ligament, which divides into 2 tracts: anteriorly attached to the anterior lacrimal crest, and posteriorly fixed to the posterior lacrimal crest. The lateral end of the medial palpebral ligament stabilizes the palpebral tarsal plates. The superior part of the sac, protruding above the ligament tracts, is called the fornix. Depending on the position of the lacrimal sac against the ligament, the high, normal, and low locations can be distinguished.

The canaliculi and the lacrimal sac can alter lumen width due to the significant mobility of the orbital septum, the lacrimal part of the orbital muscle of the eye fibers, and medial palpebral ligament. By dilating and constricting, they determine the function of the tear pump, working as a lift-and-force pump. Contrary to the lacrimal canaliculi, the lacrimal sac expands during eyelid closure and contracts when the eyelids open. The sac is about 12.5 mm (6–14 mm) in length, 2.5 mm (1–4 mm) in diameter. The, oblique AP diameter is about 4 mm (1–6 mm) and volume is 0.1 ml [19]. Some researchers consider that the normal width of the sac in AP projection is up to 5 mm [10]. Others claim that every width exceeding 4 mm in AP projection should be considered to be pathological widening [2,14,19]. Normal size of the sac is still disputed.

The wall of the lacrimal sac is formed by screw-shaped elastic connective tissue. Delicate and prone to stretching, the sac walls are strengthened by the lacrimal part of the orbicularis oculi muscle (Horner m.) fibers. The sac wall has no interior muscle fibers.

Slightly above the inferior margin of the orbit, the distal part of the lacrimal sac narrows its infundibular lumen and continues into the nasolacrimal duct. This distal narrowing of the sac is correlated with the existence of the mucous membrane fold, known as the valve of Krause, which separates the sac from the nasolacrimal duct.

The nasolacrimal duct (NLD)

The nasolacrimal duct is the integral extension of the lacrimal sac. It divides into 2 parts: the upper (orbital) part, located in the fossa (the depression of the medial orbital wall) of the lacrimal sac, and the lower part, located in the bony canal of the nasolacrimal duct. This division is particularly important because of the available diagnostic methods used in lacrimal pathway examinations. Ultrasound imaging can be used in the diagnosis of the orbital part and the lacrimal sac, while the lower part can only be assessed using X-ray or endoscopic techniques. The lacrimal sac in some patients with high position the sac can be imaged in its entirety by ultrasound.

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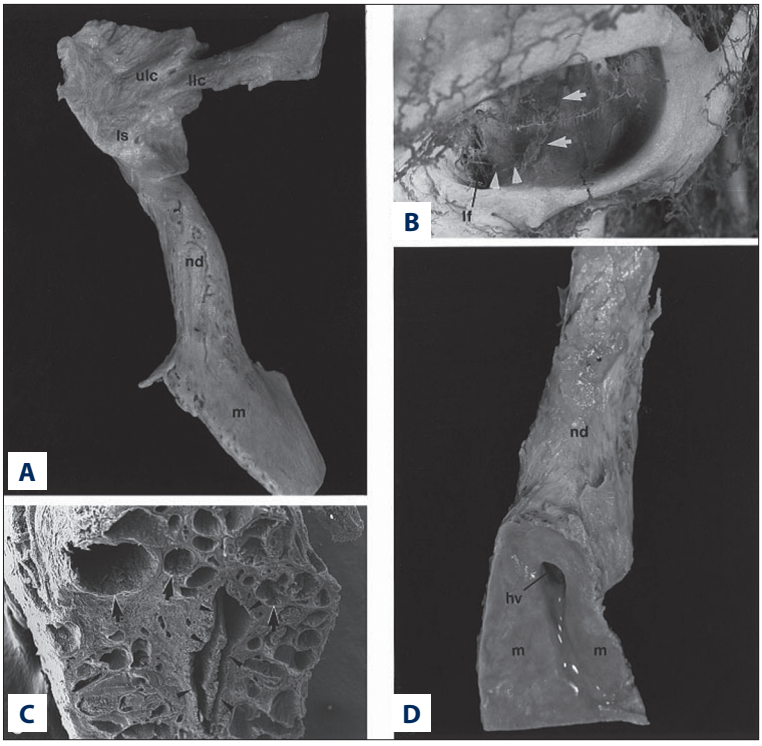

Figure 6. (**A**) Dorsal view of the lacrimal system of a right eye (male, 68 years) removed from its bony canal. (**B**) Corrosion vascular cast of a right orbit. *Arrows* mark the ophthalmic artery with a branch (*arrowheads*) to the lacrimal fossa (lf). (**C**) Scanning electron microscopic photograph of a horizontally sectioned lacrimal system. Wide-lumened blood vessels (*arrows*) surround the lumen of the lacrimal passage (*arrowheads*). (**D**) Medial view of the lower part of the lacrimal system of a right eye (female, 72 years) removed from its bony canal. ulc, upper lacrimal canaliculus; llc lower lacrimal canaliculus; ls, lacrimal sac; nd, nasolacrimal duct; m, mucous membrane of the nose; hv, Hasner's valve, opening of the nasolacrimal duct into the inferior meatus of the nose. Magnification: (**A**) 32; (**B**) 31; (**C**) 37.5; (**D**). With permission of prof. F.P. Paulsen and Association for Research in Vision and Ophthalmology. Paulsen FP, Thale AB, Hallmann UJ et al: The Cavernous Body of the Human Efferent Tear Ducts: Function in Tear Outflow Mechanism, IOVS, 2000; 41(5)

The nasolacrimal duct runs along the lateral wall of the nasal cavity and enters the inferior nasal meatus behind the anterior end of the inferior nasal concha. In its course, it runs inferolaterally and posteriorly. On the radiogram of the facial skeleton in AP projection, the path of the duct is marked by the line connecting the medial angle of the eye with the first/second upper molar tooth. The important aid in finding the inferior ostium of the duct is the position of the uncinate process, which is located just behind the NLD ostium. The distance between the NLD and the ostium of the maxillary sinus is very small – approximately 4 mm. In the widening of the maxillary sinus ostium the uncinate process is removed during the first stage of the procedure. In such cases the close vicinity of the NLD is also important due to the possibility of its damage [20]. The length of the nasolacrimal duct ranges between 13 and 28 mm (on average, 21–22 mm), and its transverse [AP] and oblique diameter is 1–4 mm, with average values of 2.3 mm and 2.8 mm, respectively. The length of the orbital part depends on the lacrimal sac location. If it is located high, it can measure up to 10 mm, while if it is low, the duct can begin in the bony canal. The usual length of the orbital part is 5–7 mm [21].

Japanese research has established that there are individual differences in spatial lacrimal pathway locations. The positioning of the long axis of the lacrimal sac and the nasolacrimal duct against the frontal plane of the orbit was examined. In 72% of subjects the nasolacrimal duct directs more superficially than the long axis of the lacrimal sac, while in 28% it directs posteriorly against the long axis of the sac. It was shown that the difference in the spatial lacrimal pathways has an impact on the performance of the lacrimal system drainage and can also affect the frequency of obstruction of lacrimal pathways [22].

The nasolacrimal duct is considered to be an anatomical continuation of the lacrimal sac structures. The duct wall is formed by helical-shaped collagen fibers, spun together with the thick lattice of venous sinus capillaries and tiny arterioles. Similarly to the lacrimal sac, the mucous membrane of the duct is lined with double-layered columnar epithelium. The integrity of the mucous membrane, with numerous vascular plexi in the NLD wall plays, an important role in the tear drainage regulation. Tear fluid components are constantly absorbed by the epithelium during passage through the nasolacrimal duct and are then transported into the thick sinus capillaries plexus, located in the wall of the inferior section of the lacrimal pathways. Excessive build-up of fluid in the vessels leads to edema of the mucous membrane, constriction of the duct lumen, and even to its temporary closure. Due to its specific construction, the NLD wall is compared to the cavernous body structure (Figure 6) [23].

Functional Anatomy of the Lacrimal Pathways

Production of normal tear film depends on the correct functioning of the rivus lacrimalis, which is the adherence of the

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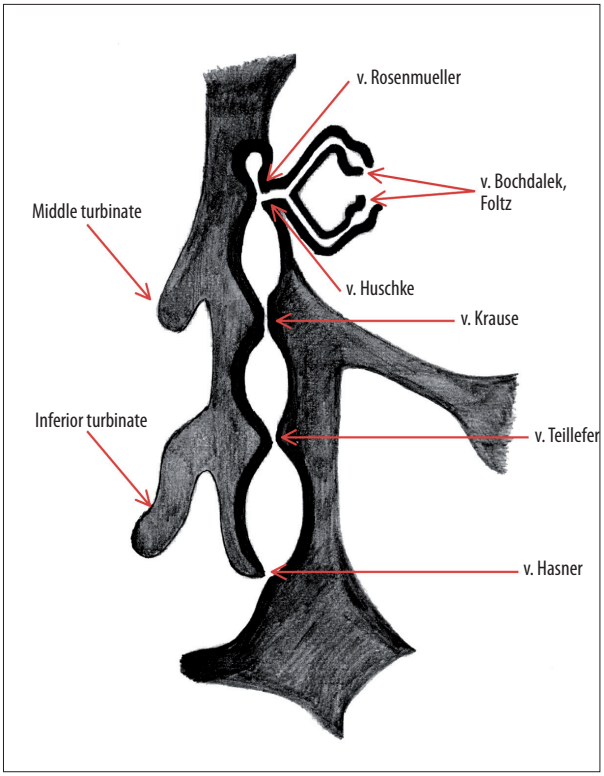

Figure 7. Valves arrangement diagram of nasolacrimal drainage system. Based on Warwick R. Anatomy of the Eye and Orbit, 7th ed. Philadelphia: WB Saunders, 1976; 232.

free palpebral margin to the eyeball surface. Its excessive relaxation can lead to abnormalities in tear drainage.

The normal location of the lacrimal puncta and maintenance of their patency determines correct drainage of the conjunctival sac. When eyelids close, the puncta should contact each other and be immersed in the lacrimal lake. The majority of the tear fluid (90%) is drained by the lower lacrimal canaliculus, through the lower lacrimal punctum; therefore, this place requires special attention in the diagnostic process.

The mucous membrane folds form a type of valve in the lacrimal pathways and their main function is to block the backward tear outflow. They are also a barrier that limits the spread of the pathological processes in the lacrimal system. Valves of the lacrimal puncta (the valves of Bochdalek and Foltz), the valves of the ostium of canaliculi to lacrimal sac (the valves of Rosenmuller and Huschke), the valve of Krause (where the sac continues into the nasolacrimal duct), and the valve of Teileffer (in the central part of the nasolacrimal duct), which were presented above, are not permanent and form only a partial obstacle to tear fluid reflux. Only the valve of Hasner, located at the end part of the nasolacrimal duct, is a functional barrier for the backward tear outflow, mostly from penetrating the lacrimal pathways with the nasal cavity contents. The arrangement of nasolacrimal drainage system valves arrangement is shown in Figure 7.

Lack of outflow of the lacrimal sac contents into the conjunctival sac is the result of the valve of Rosenmuller fold activity. It is especially important in the formation process of the mucocele, and lacrimal abscess. This mechanism is shown in Figure 5.

The transverse folds of the mucous membrane in the lacrimal pathways are the natural lumen constriction. The majority of obstructions originate at the level of valves built by those folds. Obstructions of the lacrimal pathways occur in most cases at the valve of Kause level, which is where the lacrimal sac continues into the nasolacrimal duct.

Congenital abnormalities of the lacrimal system most often refer to the obstruction at the level of Hasner's valve and occur in 6–20% of newborns [14,26].

The tear pump is considered to be the most important among all tear drainage supporting mechanisms. The lacrimal part of the orbicularis oculi muscle attaches to the posterior lacrimal crest of the lacrimal bone, surrounding the posterior wall of the lacrimal sac. Insufficiency of this muscle is one of the causes of tear pump insufficiency or lacrimal pathways insufficiency in the form of a functional block [1,3,4,14]. Normal lacrimal sac and NLD functioning depends both on motoric and secretive activity of the mucous membrane and vascular plexi of structures that tightly surround the sac and the NLD. Lower lacrimal pathways tear flow is mostly determined by interactions between mucin produced by mucosa, TFF, AQP, and mucous membrane microvilli activity [24].

Physiology of tear secretion and drainage

Tears are a mixture of secretions of the main lacrimal gland, accessory glands of Wolfring and Krause, tarsal glands of Meibom, conjunctival goblet cells, and cells of the nasolacrimal duct epithelium.

The lacrimal gland and the accessory glands secrete the amount of tears that is indispensable for the adequate cornea and conjunctiva moisturization. At rest, with no additional stimulation, approx. 1.5–2.0 ml of tears per day is produced. Increased involuntary secretion occurs in response to stimuli that affect the optic nerve (bright light), trigeminal nerve (direct conjunctiva or cornea irritation), or in response to mental stimuli. If the main lacrimal gland is activated, the volume of secreted tears can increase by 100 times. The increased activity of the parasympathetic system stimulates the secretion. Secretory parasympathetic fibers are derived from the facial nerve through nervus intermedius, travel alongside the greater petrosal nerve, branches of pterygopalatine ganglion and zygomatic nerve, and arrive at

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the lacrimal gland. Sympathetic system activity decreases tear production, providing, however, its permanent secretion at the basic level. Sympathetic fibers originate from the superior cervical plexus of the sympathetic trunk and arrive at the gland via the plexus of the internal carotid. Sensory nerves originate from the lacrimal nerve [28]. Sympathetic system stimulation, mostly via α1-receptors pathway (phenylephrine), constricts blood vessels in the nasolacrimal duct wall, reducing the cavernous bodies filling and dilating the lacrimal drainage passages lumen. It is currently considered to be the main mechanism that ensures lacrimal pathway patency. Experiments with use of the selective á1-blockers show that they have a strong dilating impact on the NLD, but little effect on the lacrimal sac lumen. This proves the influence of the level of sinus vessels filling on the lacrimal passages lumen and the similarities between the nasolacrimal duct wall structure and cavernous body. It also confirms that the lacrimal sac lumen is surrounded by weaker sinus vessel lattice than is the nasolacrimal duct lumen. Choline antagonists, however, do not cause any significant changes in NLD and lacrimal sac diameter. This indicates the main role of the sympathetic system in lacrimal pathways lumen regulation [29,30].

Tear fluid contains mostly water and a little of salt (1%), protein (0.6%), and lipids (0.1%). The meibomian glands produce the lipid component of the tear fluid that influences tear film stability. Its synthesis depends on many neuronal, hormonal, and vascular factors. Tear fluid is a liquid, easy to spread, surface-active agent. The gland secretion composition can vary due to changes in the level of sex hormones, mainly androgens, and activity of lipases produced by bacteria. Changes in the composition of meibomian gland secretion can lead to the tear film destabilization [31].

Lacrimal sac and the nasolacrimal duct mucous membrane cells produce many of the components of the innate immune response. During inflammation they are the first line of defense. The epithelium cells produce many substances with antimicrobial properties such as lysozyme, lactoferrin, phospholipase A2, and peptides. The mucous, produced by goblet cells of conjunctiva and epithelium cells of the mucous membrane of the nasolacrimal duct, contains macromolecular glycoproteins in the form of mucins: MUC1, MUC2, MUC3, MUC5AC, MUC5B, and MUC7. Those glycoproteins are most frequently combined with the TFF (Trefoil Factor Family) peptide group, produced in the lower lacrimal pathway epithelium in the form of TFF1 and TFF3 [17–19,32]. Mucins and TFF peptides are structural components of precipitation extracted from the lacrimal passages. It has not yet been verified whether the presence of those substances is caused by their participation in precipitation forming initiative process or is a response to the existing pathological process [33].

Humoral response components, mostly α-immunoglobulin, produced by B and T lymphocytes of epithelium cells, can also be found in the nasolacrimal duct secretion. Lymphocytes are elements of the immune system cells, abundant in epithelium of lacrimal drainage pathways. They often cluster into larger groups, forming lymphatic follicles. Those follicle conglomerates with surrounding epithelial and subepithelial tissue of the lacrimal passages are called mucosa-associated lymphoid tissue (MALT). The same tissue in the nasolacrimal duct mucosa is called tear duct-associated lymphoid tissue (TALT). Reactive centers of lymphocytes multiplication located in endothelium bind with marginal cells, forming a kind of “lymphatic epithelium” [34–37].

Conclusions

There are many mechanisms that support the tear drainage from the lacrimal sac. Tears are spread across the cornea surface by eyelid movement. Normal anatomy of the eyelid margins determines the correct tear film passage. Minor defects in the position of eyelid margins or lacrimal puncta against eyeball surface result in epiphora, despite maintained lacrimal passages patency. Tears automatically drain out of the conjunctival sac due to capillary forces of lacrimal puncta, which suck up the liquid into the lacrimal canaliculi.

The strongest tear fluid passage support mechanism is the tear pump, stimulated by orbicularis oculi muscle contraction. The tear pump activates when the pretarsal and preseptal muscles close the eyelids. When eyelid margins touch each other, the tears accumulate in the palpebral fissure line, forming the external extra-palpebral canal. Contraction of muscles in the lateral angle of the eye moves canal contents towards the medial angle of the eye, directing it to the lacrimal lake. When the palpebral part of orbicularis oculi fibers (located in the canaliculi wall) contracts, then the lacrimal puncta submerges in the lacrimal lake, contracts the canaliculi wall, and visibly shortens their length, which induces pumping force towards the sac. The lacrimal sac, contrary to the lacrimal canaliculi, dilates when eyelids close as a result of Horner’s muscle contraction and forms space for the fluid flowing out of the canaliculus, and simultaneously generates the sucking force. When eyelids open, the sac lumen constricts and imposes the force that pumps tears to the nasolacrimal duct. Numerous valves and helical structure of the mucous membrane with many transverse folds prevent backflow of tears. Helical mucous membrane structure in the lacrimal pathways plays an additional role in the tear passage regulation, strengthening motoric properties of mucosa. Contraction and relaxation of wall muscle fibers and better, or smaller filling of the thick lattice of blood vessels surrounding the duct lumen, result in tightening and relaxing the mucous membrane helix and thereby quicken the passage.

The lacrimal sac (especially the nasolacrimal duct) is surrounded by a thick lattice of blood vessels, similar in structure to minor

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venous sinuses (Figure 6). Recent research confirms that both the drainage system and the secretory part of the nasolacrimal ducts play decisive roles, not only in the immune system, but also in tear passage. In this context, integrity of the mucous membrane as a mucin and TFF peptides source, with numerous vascular plexi in the lacrimal pathway wall, plays an important role in tear drainage regulation. Recent studies have shown the presence of aquaporins (AQP), which are albuminous membranous canals that act as selective pores, in the nasolacrimal duct epithelium. AQP transport water, glycerine, and other micromolecular substances permeable through the cell membrane, including TFF peptides, from the nasolacrimal ducts [38].

Tear fluid components are constantly absorbed by epithelium while they pass through nasolacrimal ducts and are then transported to the system of blood vessels surrounding the lacrimal sac, especially the nasolacrimal duct. This system is similar to the plexus of the thick lattice of venous sinus vessels. Increased or decreased flow of blood through the vessels, located in the sac and duct wall, results in expansion or contraction of the sinuses volume and, consequently, increased or decreased pressure in the lower lacrimal pathways lumen. The mechanism by which the sinus vessels are more or less filled with blood leads to opening or closing of the nasolacrimal duct lumen, thereby regulating tear drainage. Pathological processes leading to hyperemia of the lower lacrimal pathways walls result in narrowing, patency impairments, or full obstruction of the lacrimal passages. Single-lumen narrowing sometimes also causes valves to be incorrectly described [12,39,40].

Gravity is another tear drainage-supporting mechanism in the lacrimal pathways, but it has no significant effect on the dynamic passage and plays only a supplementary role.

In the evaporation process about 10–20% of the produced tear volume is lost. The main factor protecting against tear fluid loss is the lipid layer of the tear film, produced by meibomian glands. Its dysfunction may increase tear loss via evaporation by up to 10-fold [41].

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