The Cavernous Body of the Human Efferent Tear Ducts: Function in Tear Outflow Mechanism

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PURPOSE. To determine the structure and function of a system of large blood vessels integrated in the bony canal between the orbit and the inferior nasal duct.

METHODS. Thirty-one dissected lacrimal systems of adults were analyzed by using gross anatomy, histology, and electron microscopy as well as corrosion vascular casts.

RESULTS. More than two thirds of the bony canal between orbit and inferior nasal duct is filled by a plexus of wide-lumened veins and arteries. The vascular system is embedded in the wall of the lacrimal sac and nasolacrimal duct and is connected to the cavernous tissue of the inferior turbinate. The concept of a canalicular pump was supported by anatomic studies, high-speed photography, scintillography, and intracanalicular pressure measurements. Some hypotheses have also assumed an active pump mechanism to explain the function of the human lacrimal sac. Other investigators suggest that physical factors such as gravity, respiration, absorption, and evaporation may play a role in tear drainage through the lacrimal system.

CONCLUSIONS. The surrounding vascular plexus of the lacrimal sac and nasolacrimal duct is comparable to a cavernous body. While regulating the blood flow, the specialized blood vessels permit opening and closing of the lumen of the lacrimal passage, effected by the bulging and subsiding of the cavernous body, and at the same time regulate tear outflow. Other functions such as drainage of absorbed tear fluid components and a role in immunologic response are under discussion as well. Malfunctions in the cavernous body may lead to disturbances in the tear outflow cycle, ocular congestion, or total occlusion of the lacrimal passages. Variations in the conditions for swelling of the cavernous tissue may have led to the (mistaken) description of valves in the lacrimal passage.

(Technical appendix)

Tear flow is caused by forces that are not completely understood. Various mechanisms have therefore been proposed to explain the drainage of tears. An active mechanism has been recognized as an essential factor in lacrimal drainage since the observation of epiphora in cases of facial palsy. This mechanism was investigated by Frieberg and Rosengren who found evidence for a canalicular pump. The concept of a canalicular pump was supported by anatomic studies, high-speed photography, scintillography, and intracanalicular pressure measurements. Some hypotheses have also assumed an active pump mechanism to explain the function of the human lacrimal sac. Other investigators suggest that physical factors such as gravity, respiration, absorption, and evaporation may play a role in tear drainage through the lacrimal system.

Although the physiology of lacrimal drainage has been under study for more than a century, the pathophysiology of functional lacrimal drainage insufficiency is still not understood (i.e., cases of epiphora despite patent lacrimal passages found when syringing).

As early as in 1866, Henle described a vascular plexus surrounding the lumen of the lacrimal sac and the nasolacrimal duct. This network of large vessels is connected caudally with the cavernous body of the nasal inferior turbinate. Although more than two thirds of the bony canal between orbit and inferior turbinate are occupied by this wide-lumened vascular plexus, textbooks of anatomy do not mention its existence. The purpose of this study was to investigate the structure of the vascular system in the human efferent tear ducts and in particular to obtain insights into its clinical function.

MATERIALS AND METHODS

Thirty-one lacrimal systems (17 male, 14 female, aged 29–92 years) obtained during surgical procedures and four heads of adults (2 male, 2 female, aged 58–65 years) obtained from cadavers donated to the Department of Anatomy, Christian Albrecht University of Kiel, Germany, were prepared. Material from surgical procedures was obtained with the permission of the medical ethics commission and used in accordance with the Declaration of Helsinki. Limited information was available on the specimens; however, the specimens were obtained from individuals free of recent trauma, eye or nasal infections, and diseases potentially involving or affecting lacrimal func-
tion. Except for the size of the removed lacrimal systems, there were no individual differences or differences in freshly obtained material versus the material obtained from fixed bodies.

Light Microscopy
For analysis by light microscopy, 15 lacrimal systems (8 male, 7 female, aged 29–92 years) were fixed in 4% formalin, decalcified in 20% EDTA as required, dehydrated in graded concentrations of ethanol, and embedded in paraffin. Sections (7 \( \mu \)m) in three planes were stained with toluidine blue (pH 8.5), azan, resorcin-fuchsin-thiacine picric acid, and using Goldner staining. The slides were examined by microscope (Axiophot; Zeiss, Oberkochen, Germany).

Scanning Electron Microscopy
For scanning electron microscopy 16 lacrimal systems (9 male, 7 female, aged 29–77 years) were cut either horizontally or longitudinally or processed without cutting. The preparations were then fixed in 2.5% glutaraldehyde for 1 week and macerated with HClO or NaOH to remove cellular components. All tissue blocks were then impregnated with 2.5% tannic acid for 2 days. Postfixation in 2% OsO\(_4\) for 4 hours was followed by dehydration in ethanol and drying in a critical point dryer. Preparations were coated with gold and analyzed by scanning electron microscope (Philips, Kassel, Germany).

Corrosion Vascular Casts
For corrosion vascular casts, the bony cranium and brain were removed from four heads of donor cadavers. The right and left ophthalmic arteries were exposed. Cannulae were introduced into these arteries, and the external and internal carotid arteries were ligated. Ten milliliters of casting resin mixture (Mercox CL-2B and MA, Dainihon Ink Chemical, Tokyo, Japan; or Acrifix 190 Katalysator 20, Fa.; Röhm, Darmstadt, Germany) were injected through each cannula under hand pressure. After the resin had polymerized, the eyes were removed from the orbit, and the heads were transferred to plastic containers. To obtain completely macerated specimens, the organic material was removed with 5% potassium hydroxide solution and maintenance of a maceration temperature of 40°C. Maceration was then continued in distilled water at a temperature of 40°C. Finally, the specimens were air dried. In two heads (1 male, 1 female, both aged 63) the vascular system of the efferent lacrimal ducts were removed from the bony canal, sputter coated, and viewed under the scanning electron microscope.

RESULTS
Macroscopic Morphology
The fossa lacrimalis contains the lacrimal sac and the proximal part of the nasolacrimal duct. Figure 1a shows a prepared tear duct system that is removed from its bony canal. The lower and the upper lacrimal canaliculi lead to the lacrimal sac beneath the fornix. The lacrimal sac passes into the nasolacrimal duct, which runs into the inferior meatus of the nose with Hasner’s valve (Fig. 1d). Bony attachments are located medially in the fossa lacrimalis.

Figure 1. (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) \( \times 2 \); (b) \( \times 1 \); (c) \( \times 7.5 \); (d) \( \times 3 \).
Light Microscopy

The lacrimal sac and nasolacrimal duct are surrounded by a vascular plexus connected to the cavernous body of the inferior turbinate (Figs. 2a, 2b). The sac, flattened above but more rounded where it joins the duct, is enclosed in an osseofibrous cavern formed by the lacrimal fascia bridging the lacrimal fossa (Fig. 2a). The duct is embedded in a bony canal formed by the maxilla and the lacrimal bone (Fig. 2b). More than two thirds of the bony canal between orbit and inferior turbinate are occupied by the vascular plexus.

Subepithelially, the lamina propria consists of collagen bundles as well as elastic and reticular fibers arranged in a helical pattern and encloses some mixed glands with excretory canals that open at the surface of the epithelium. Thick-walled, muscular arteries located near the periosteum, or in contact with it, give off branches that run vertically through the lamina propria. Segments of these arteries consist of an additional layer of longitudinally arranged smooth muscle cells (arrows). Its tunica intima has acquired an incomplete layer of longitudinal smooth muscle fibers. Toluidine blue staining. m, maxillary bone; ol, os lacrimale; l: (a, c, d) lumen of the lacrimal sac; (b) lumen of the nasolacrimal duct; (f) lumen of the anastomosis with erythrocytes; lf, lacrimal fascia; O, orbit after enucleation; e, epithelium; tm, tunica media with circular arranged smooth muscle cells. Magnification, (a, b) ×3.8; (c) ×57; (d, e) ×114; (f) ×228.
The diameter between the lacunae varies between 0.2 and 0.6 mm. In most cases, the tunica intima contains a thin subendothelial layer, whereas the tunica media is sparingly developed, and the adventitia is clearly visible as a broad band of connective tissue. Valves are not seen inside the lacunae. At numerous places, the lacunae consist of a markedly developed musculature (Fig. 4a, 4b). Venous lacunae are connected to veins situated near bone. Some veins of the vascular plexus are situated close to the wall of the bony canal and are connected to intraosseous veins of the maxilla or the lacrimal bone. Between the arteries and veins are numerous arteriovenous anastomoses characterized by the presence of epi-

**FIGURE 3.** Capacitance veins. (a) Cross section of some convoluted venous lacunae (cv), which are called capacitance veins. Erythrocytes are visible in the lumen of the veins. Some seromucous glands (s) are localized between the veins. Azan staining. (b) Transverse section of convoluted venous lacunae in a resorcin-fuchsin-thiacine picric acid staining. Loose connective tissue is visible between the veins. (c) Scanning electron micrograph of convoluted venous lacunae. Their lumens are opened by maceration with HClO. (d) Scanning electron micrograph of a corrosion vascular cast showing convoluted venous lacunae. ct, connective tissue between the blood vessels. Magnification, (a) ×57; (b) ×29; (c) ×68; (d) ×45.

**FIGURE 4.** Throttle veins. (a) Cross section of a venous lacuna. Arrows: muscle fibers of a markedly developed tunica media. Goldner staining. (b) Transverse section of a venous lacuna. Arrows: muscle fibers that are circularly arranged around the lumen of this so-called throttle vein. Goldner staining. (c) Scanning electron micrograph of a specialized (throttle) vein. In the wall of the vein numerous recesses are localized between a network of connective tissue fibers (ctf) in which smooth muscle cells are normally embedded. The muscle cells have been removed by a maceration process. (d) Scanning electron micrograph of a corrosion vascular cast of a venous lacuna (cv), or so-called capacitance vein. The lumen of the vein is narrowed in its middle segment (arrows). Such a segment is termed a throttle vein. lu: (a) lumen of the blood vessel; (b) lumen of venous lacuna; (c) lumen of the throttle vein. Magnification, (a) ×228; (b) ×359; (c) ×95; (d) ×312.
Numerous arteriovenous anastomoses (arrowed) having the form of short bridges are localized between branches of arteries (a) and convoluted venous lacunae (cv). (b) Transverse section of a arterio (a) -venous (v) anastomosis (arrowed). Toluidine blue staining. (c) Arterio (a) -venous (v) anastomosis (arrowed) in the form of a short bridge. (d) Cross section through a vein with two orifices of arteriovenous anastomoses (arrowed). Toluidine blue staining. Magnification, (a) ×37; (b, d) ×114; (c) ×98.

The specialized blood vessels may facilitate closure and opening of the lumen of the lacrimal passage by swelling and shrinkage of the cavernous body. Swelling occurs when the barrier arteries are opened and the throttle veins closed. Filling of the capacitance veins occurs at the same time with closure of the lumen of the lacrimal passage. By contrast, closure of the barrier arteries and opening of the throttle veins reduces the blood outflow from these veins with resultant shrinkage of the blood vessels we found were specialized arteries, venous lacunae, and veins. The arteries contained two muscle layers. They are known from skin, esophagus, and ovary as well as the lower anterior spinal artery and are called barrier arteries according to the German term Sperrarterien. Their function is to reduce or interrupt the blood supply to the downstream blood vessels. The arteries split just beneath the epithelium into superficial arcading branches. A dense network of capillaries arises from these branches to supply blood to seromucous glands of the lamina propria and also to bring nutritive substances to the epithelium. The blood from the capillary network is collected by short postcapillary venules that drain into widely convoluted venous lacunae. These blood vessels are called capacitance veins because of their probable ability to store large amounts of blood. Segments of the capacitance veins are sometimes narrowed. The tunica media of these segments contains a muscle layer of helically arranged smooth muscle cells that effects closure of the segment. In agreement with the nomenclature of the nose these appliances are called cushion veins, which are also termed throttle veins in the English literature and are referred to as Polstervenen, Sperrvenen, or Drosselvenen in the German literature. They can reduce or interrupt venous blood outflow and allow large amounts of blood to accumulate inside the capacitance veins. Finally, blood is collected by large veins that drain the blood out of the lacrimal passage. Furthermore, arteriovenous anastomoses are seen to connect branches of the arteries with capacitance veins.

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cavernous body and dilatation of the lumen of the lacrimal passage. Arteriovenous anastomoses provide for direct blood flow between arteries and venous lacunae. Thus, the subepithelial situated capillary network can be avoided, and rapid filling of capacitance veins is possible when the shunts of the arteriovenous anastomoses are open.

The occurrence of cavernous tissue in various hollow viscera such as at the entrance to the esophagus, the uterine tube, the vagina, and the anus is well known.\textsuperscript{21,22} Based on its yielding characteristic, the vascular plexus allows both obstruction and, simultaneously, rapid passage of solid and liquid components.

In the efferent tear duct barrier arteries, capacitance veins and throttle veins facilitate closure and opening of the lumen of the lacrimal passage by swelling and shrinkage of the cavernous body with consecutive regulation of tear outflow.

The possibility has been discussed that tear fluid is absorbed by the epithelial lining before it reaches the nose.\textsuperscript{23,24} In this context, the cavernous body could play a role in drainage of the reabsorbed fluid. Moreover, contact times between tear fluid and mucosa may be regulated by the swelling of the cavernous body.

Moreover, our findings lead to the assumption that the valves in the lacrimal sac and nasolacrimal duct described in the past by Rosenmüller, Hanske, Aubaret, Beraud, Krause, and Taillefer may be based on different swelling states of the cavernous body and must therefore be considered speculative.

Drainage of tears certainly involves a number of different mechanisms. A decisive role is played by capillary attraction,\textsuperscript{2,4,6–8} aided by contraction of the lacrimal part of the orbicularis muscle with blinking\textsuperscript{4,5,10–13} and distension of the sac, as well as a passive wringing out of the sac because of its medial attachment and helically arranged fibrillar structures.\textsuperscript{13}

The results of our study suggest that the cavernous body of the lacrimal passage is the morphologic correlate of a further mechanism that affects tear outflow. When the net outflow of blood from the cavernous body is less than the inflow, the mucosa expands and functionally decreases the tear outflow through the efferent tear duct system. This mechanism acts, for example, to provide protection against foreign bodies that have entered the conjunctival sac: Not only is tear fluid production increased by the lacrimal gland, tear outflow is also interrupted by the swelling of the cavernous body to flush out the foreign body and protect the efferent tear ducts themselves. Moreover, the pathophysiology of functional lacrimal drainage insufficiency (i.e., patients with epiphora despite patent lacrimal passages found during syringing), can be explained by this mechanism: Malfunctions in the different blood vessels of the vascular bed may lead to disturbances in the tear outflow cycle, ocular congestion, or total occlusion of the lacrimal passages. Such malfunctions may be caused by acute diseases, such as allergic conjunctivitis, hay fever, or rhinitis, or chronic conditions such as stenoses after dacryocystitis or dacryolithiasis. Further, in most patients persistent epiphora after dacryocystorhinostomy can be explained by destruction of the surrounding cavernous body.

It can be concluded that the cavernous body of the lacrimal passage plays an important role in tear outflow. Further investigations are needed to evaluate the function of the cavernous body in different pathologic conditions of the efferent tear ducts, especially in dry eye syndrome. It will be interesting to find out whether there is an absorption of tear fluid components in the efferent tear ducts, and if so, which components of tear fluid are absorbed.

\section*{Acknowledgments}

The authors thank Sonja Seiter, Karin Stengel, and Regine Worm for excellent technical assistance; Heidi Waluk and Heide Siebke for photographic work; Rolf Klaws for excellent support with the corrosion vascular casts; and Michael Beall for correcting the English.

\section*{References}

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