Graefe's Arch Clin Exp Ophthalmol (1998)
236:674–678

CLINICAL INVESTIGATION

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Functional anatomy of the human efferent tear ducts: a new theory of tear outflow mechanism

Received: 23 January 1998
Accepted: 27 March 1998

This study was presented at the 95th annual meeting of the Deutsche Ophthalmologische Gesellschaft, Berlin, 20–23 September 1997

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Abstract ● Background: The mechanism of lacrimal drainage under physiological conditions is controversial. The aim of this study was to analyze the three-dimensional architecture of human efferent tear ducts from functional and clinical points of view. A new theory of tear outflow is discussed. ● Methods: Thirty-two prepared lacrimal systems of adults were examined by histological, immunohistochemical and scanning electron microscopic techniques. ● Results: The wall of the lacrimal sac is made up of collagen bundles, elastic and reticular fibers arranged in a helical pattern. Wide luminal vascular plexus are embedded in this helical system and connected to the cavernous tissue of the inferior turbinate in the region of Hasner's valve. Immunohistochemical analysis showed evidence of type I and type III collagen as well as chondroitin 4- and 6-sulfate. ● Conclusion: With blinking, the lacrimal part of the orbicularis muscle contracts. The fornix of the sac moves in a cranial-lateral direction. Thus the lacrimal sac distends and may be ''wrung out'' due to its medial attachment and helically arranged fibrillar structures. The vascular plexus may play an important role in the absorption and drainage of lacrimal fluid.

Introduction

Tear flow from the lacrimal sac to the cavum nasi is caused by forces that are not completely understood. Many studies have emphasized the role of the canaliculi and relegated the lacrimal sac to a minimal or even passive role in the lacrimal pump mechanism. The aim of this study was to analyze the three-dimensional structure of human efferent tear ducts from functional and clinical points of view. A new theory of tear outflow is proposed.

Material and methods

Fourteen lacrimal systems of adults (nine males, five females, aged 57–81 years) obtained from bodies donated to the anatomical institute were prepared. Limited information was available on the specimens; however, they were taken from individuals free of recent trauma or disease that might involve or affect lacrimal function. The specimens were fixed in 4% formalin, embedded in paraffin and sectioned in three planes. Sections (7 μm) were stained with toluidine blue (pH 8.5), alcian blue (pH 1), Heidenhain's azan stain, resorcine-fuchsine-thiazine-picric acid and by the method of Gomori accoding to Romeis [13].

Immunohistochemical investigations of extracellular matrix components were performed on eight cryosections of unfixed material (four males, four females, aged 47–78 years), frozen in liquid nitrogen. Polyclonal antibodies against collagen type I (Biochrom, Berlin, Germany) and collagen type III (Bio-Science, Emmenbrücke, Switzerland) as well as monoclonal antibodies against chondroitin-4-sulfate (Chemicon International, Temecula, Calif., USA), chondroitin-6-sulfate (Chemicon International) and keratan sulfate (Bio-Science, Emmenbrücke, Switzerland) were used. For scanning electron microscopy, ten efferent tear duct systems (six males, four females, aged 52–87 years) were fixed in 2.5% glutaraldehyde for 1 week and macerated with HClO to remove cellular compartments. All tissue blocks were impregnated in 2.5% tannic acid for 2 days. A counterfixation in 2% OsO_4 for 4 h was followed by dehydration in ethanol and drying in a critical point dryer. They were then coated with gold and analyzed with a Philips scanning electron microscope.

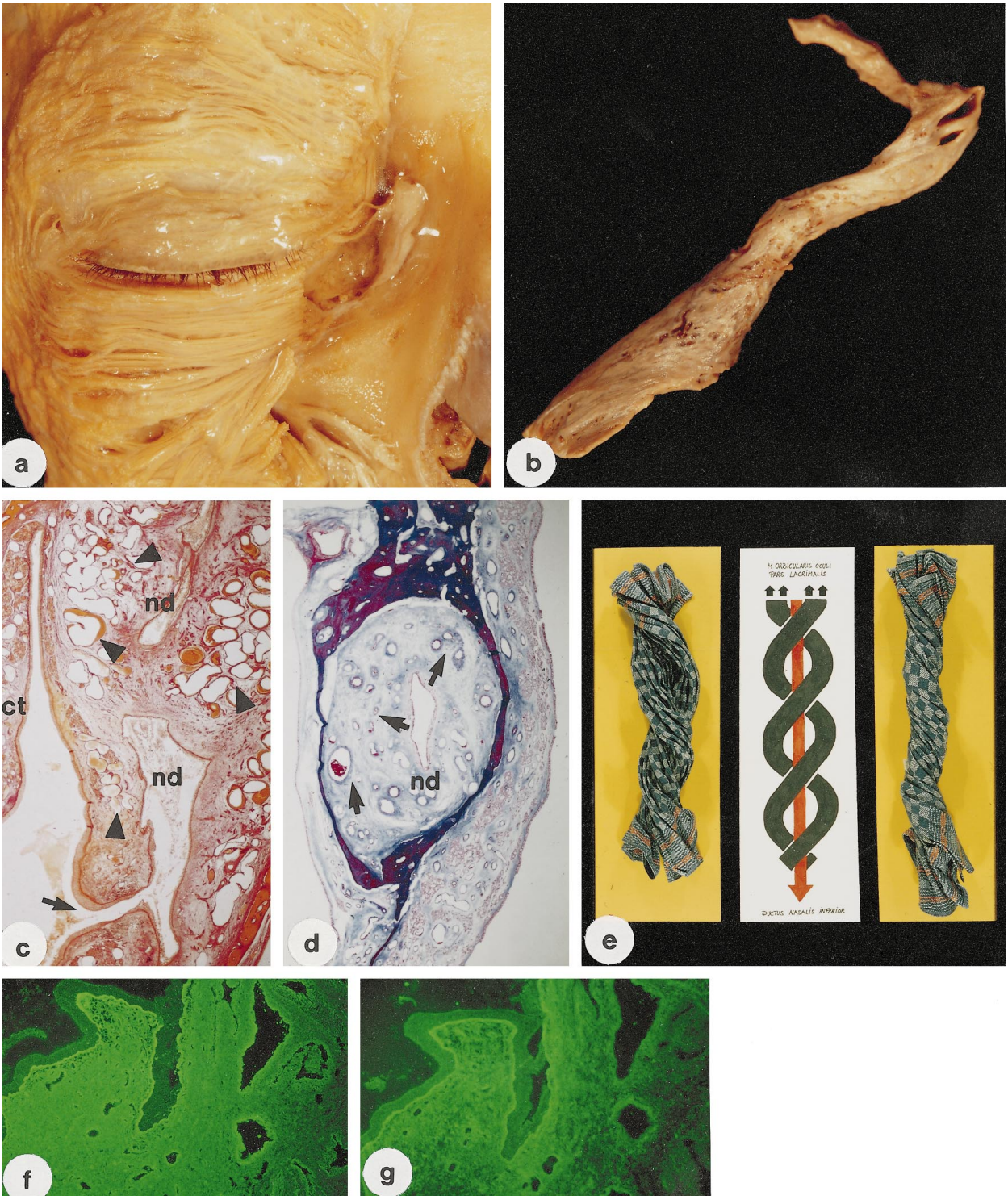

Fig. 1 **a** Macroscopic view of a prepared right lacrimal sac and duct in situ (male, 65 years). **b** Macroscopic view of a prepared left efferent tear duct system (female, 57 years) after maceration with HClO. **c** Transverse section of a nasolacrimal duct in the region of Hasner's valve (*arrow*) in a resorcine-fuchsine-thiazine-picric acid staining. Note the large capacitance vessels (*arrowheads*) around the nasolacrimal duct (*nd*) which are connected to the ''cavernous tissue'' (*ct*) of the inferior turbinate. **d** Cross-section of a nasolacrimal duct (*nd*) (female, 67 years) in an azan staining. More than two-thirds of the surrounding bony canal is filled by vascular plexus (*arrows*). **e** The arrangement of collagen and elastic fibers in a schematic view. If the nasolacrimal duct distends while blinking it will be ''wrung out'' due to the screw-shaped arrangement of the collagen bundles. **f** Immunohistochemical analysis of type I collagen. Type I collagen makes up the main part of the extracellular matrix in the wall of the nasolacrimal duct. **g** Immunohistochemical proof of type III collagen. Strong immunoreactivity is visible in the subepithelial layer

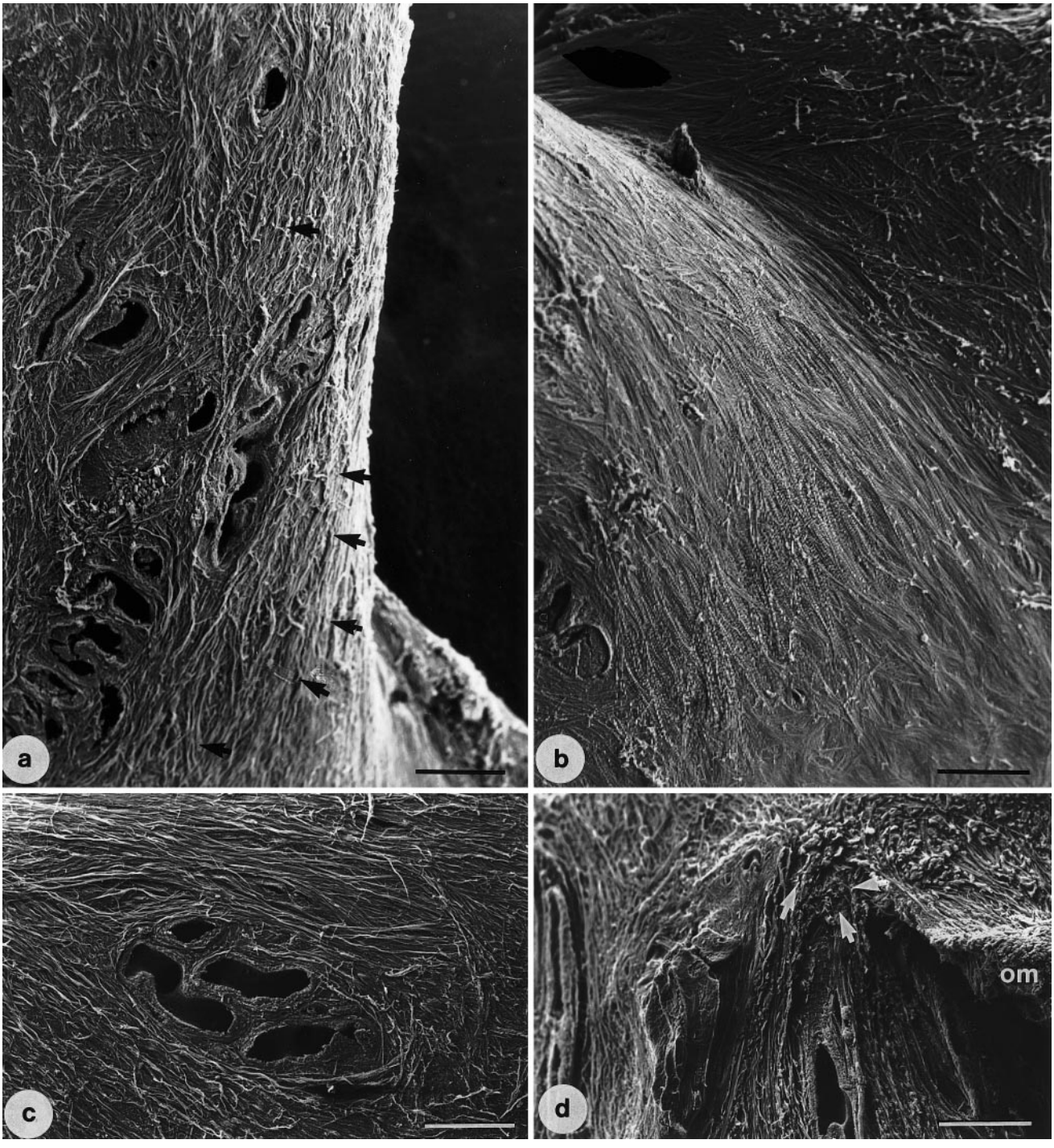

Fig. 2 **a** SEM photograph of the outer surface of a nasolacrimal duct. Note the helically arranged collagen fibrils (*arrows*). **b** SEM photograph of the outer surface of a nasolacrimal duct at higher magnification at a lower position than Fig. 2a. Note the ''screw-shaped'' arrangement of the collagen fibrils. **c** SEM photograph of vascular plexus in the wall of the nasolacrimal duct. Wide luminal arteries and veins are embedded in the helical system of collagen bundles. **d** SEM photograph of the fornix of the lacrimal sac. In this region the nasolacrimal system is attached to the orbicularis muscle (*om*) by fibrillar structures (*arrows*). *Bar* 550 µm

Results

The fossa lacrimalis contains the lacrimal sac and the proximal part of the nasolacrimal canal. Figure 1a shows a prepared tear duct system in situ. The lower and the upper lacrimal canaliculi lead to the lacrimal sac beneath the fornix. The lacrimal sac passes into the nasolacrimal duct running into the inferior meatus of the nose with Hasner's valve (Fig. 1b). Bony attachments are located medial in

the fossa lacrimalis. The lacrimal sac and duct are surrounded by a network of large capacitance vessels which are connected to the ''cavernous tissue'' of the inferior turbinate. Figure 1c demonstrates a horizontal section through the nasolacrimal duct at a lower position. The duct is embedded in a bony canal formed by the maxillar and the lacrimal bone. The relation between the lumen of the lacrimal sac and the complex venous system is rendered visible by azan staining (Fig. 1d). More than two-thirds of the bony canal between orbit and inferior turbinate is filled by venous plexus. Histologically, the venous endothelium is surrounded by circularly arranged muscular fibers which permit regulation of blood flow. The wall of the lacrimal sac is made up of collagen bundles, elastic and reticular fibers arranged in a helical pattern (Fig. 2a, b). In this helical system fibers run screw-shaped from the fornix to the outlet of the nasolacrimal duct. Figure 2a, b shows the outer surface of the lacrimal sac freed from the bony attachments. Fibroelastic and muscular elements of attachment are situated rostral to the fornix (Fig. 2d). In this region the lacrimal sac is attached to the orbicularis oculi muscle by fibrillar structures. Normally the veins are located directly beneath the bone. Wide luminal plexus of veins and arteries are embedded or enclosed in the helical fibrillar system (Fig. 2c). Immunohistochemical analysis confirmed the presence of collagen type I and type III (Fig. 1f, g) in the wall of the efferent tear duct system. Bundles of type I collagen fibrils make up the main part of the extracellular matrix (Fig. 1f). Strong immunoreactivity of collagen type III can be demonstrated in the subepithelial layer (Fig. 1g). Antibodies against chondroitin-4-sulfate, chondroitin-6-sulfate and keratan sulfate revealed these glycosaminoglycans to be a major component of the extracellular matrix in the efferent tear duct system.

Discussion

Tear flow from the saccus lacrimalis to the cavum nasi is caused by forces that are not completely understood. Some hypotheses propose an active pump mechanism for the function of the human lacrimal sac [7, 9]. Certainly in a facial palsy, tears will not be pumped through the lacrimal system. Even with a Jones tube in place, there will be a decrease in tear flow if the orbicularis muscle function is insufficient [10]. Fernandez-Valencia and Gomez Pellico [2] concluded that the saccus lacrimalis is subject to two muscular vectors that are activated during the contraction of the musculus orbicularis oculi. While the muscle contracts, the saccus lacrimalis is dilated, raising the fornix and pulling at the anterior face. When contraction ends, the saccus recovers its original volume. Other authors suggest that physical factors such as gravity, respiration, absorption and evaporation might play a role in draining tears through the lacrimal system [5, 6, 8, 10, 15]. Brienen and Snell [1] postulated that the main, and presumably the sole, force that impels lacrimal flow from the conjunctival sac is the pressure brought about by closing of the eyes. In all, probability, their expansions and contractions are secondary consequences of pressure fluctuations in the conjunctival sac. Jones [7] analyzed the anatomical structures of the medial palpebral ligament and the palpebral part of the orbicularis oculi muscle. He introduced the concept of the lacrimal pump system which functions with blinking and might be responsible for lacrimal drainage. Rosengren [14] showed that during blinking movements the canaliculi are compressed and a uniform volume of lacrimal fluid is squirted into the lacrimal sac. The small canaliculi may act as capillary tubes [4, 7]. Lacrimal fluid is attracted by capillarity into the lacrimal puncta, and with closing of the eyelids the contraction of the preseptal muscle creates a negative pressure and sucks the tear fluid into the sac. Even the role of gravity is not clear, since Hurwitz [4] concluded that gravity does have a significant role in the transport of tears. Support for the existence of a canalicular pump system on lid closure also came from experimental work carried out by other workers [3]. Rohen [12] and Paulsen et al. [11] discussed the possibility that tear fluid is absorbed by the lining epithelium before it reaches the nose. This would explain the large network of capacitance vessels surrounding the nasolacrimal duct. Tear fluid is absorbed through the mucosa and will be drained by the microcirculation of the venous plexus. Another reason for the occurrence of an extensive network of large luminal vessels at this location could be a regulating function for tear flow. When the net outflow of blood is less than the inflow, the mucosa expands and functionally decreases the tear outflow through the efferent tear duct system.

Drainage of tears certainly occurs by different mechanisms. The results of our study suggest another possible explanation. We postulate a new theory of tear outflow depending on anatomical configurations described above: With blinking, the lacrimal part of the orbicularis muscle contracts. The fornix of the sac moves in a cranial-lateral direction. Thus the lacrimal sac distends and may be ''wrung out'' passively because of its medial attachment and helically arranged fibrillar structures (Fig. 1e). Venous plexus and arteries embedded in this helical system may play an important role in absorption and drainage of lacrimal fluid.

Acknowledgements We would like to thank Mrs. R. Worm and Mrs. K. Stengel for their expert technical assistance.

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