Novel Insight Into the Role of CFTR in Lacrimal Gland Duct Function in Mice

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PURPOSE. The role of cystic fibrosis transmembrane conductance regulator (CFTR) in lacrimal gland (LG) function has only recently received some attention, mainly from our group. In the present study, we investigated the potential changes of LG pathology, tear secretion, ocular surface integrity, and fluid secretion in isolated LG ducts from CFTR knockout (KO) mice.

METHODS. Tear production and ocular surface integrity were investigated in anesthetized wild-type (WT) and KO mice using cotton threads and fluorescein staining, respectively. Immunofluorescence was used to localize CFTR protein in the LGs. Ductal fluid secretions evoked by forskolin (10 μM); cell-permeable cAMP analogue (8-bromo cAMP, 100 μM); or carbachol (100 μM) were measured in isolated LG ducts using video-microscopy. Intracellular Ca2+ homeostasis underlying carbachol stimulation was investigated with microfluorometry.

RESULTS. Significant decrease in tear secretion and impaired ocular surface integrity were observed in KO mice. Immunofluorescence demonstrated the predominant presence of CFTR protein in the apical membranes of the duct cells from WT mice. Continuous fluid secretion was evoked by forskolin and 8-bromo cAMP in LG ducts from WT mice, while no secretory response was observed in ducts from KO mice. Carbachol caused similar secretory responses in ducts from WT and KO animals without significant differences in cytosolic Ca2+ signaling.

CONCLUSIONS. Our results suggest the important role of CFTR in LG ductal secretion and in the maintenance of ocular surface integrity, suggesting that CFTR may be a promising target of novel therapeutic approaches in the treatment of dry eye.

Keywords: lacrimal gland, CFTR, lacrimal gland duct, CFTR KO mouse
transgenic mice. Our data strongly suggest that CFTR plays a key role in LG ductal secretion and in the maintenance of ocular surface integrity.

Parts of the results in this manuscript have been presented in abstracts in the Annual Meeting of the Association for Research in Vision and Ophthalmology (Tóth-Molnár E, et al. IOVS 2016;57:ARVO E-Abstract 5222; Ding C, et al. IOVS 2016;57:ARVO E-Abstract 430).

MATERIALS AND METHODS

Animals

CFTR KO mice used throughout our studies were congenic on the FVB/N background. The model was originally generated by Ratcliff et al. and was provided as a gift from Ursula Seidler (Hannover Medical School, Hannover, Germany). Genotyping was performed by RT-PCR. The animals were kept at a constant room temperature of 24°C with a 12 hour light–dark cycle and were allowed free access to specific CFTR chow (C1013, Altromin, Lage, Germany) and drinking solution. Wild-type (WT) refers to the +/+ littermates of the CFTR KO mice. The mice used in this study were 8 to 24 weeks old and 14 to 24 grams (depending on the genotype and age), the sex ratio was 1:1 for all groups.

Animals were narcotized intraperitoneally with ketamine (80 mg/kg) and xylazine (10 mg/kg) and euthanized with pentobarbital overdose (100 mg/kg).

Table. Composition of Solutions Used in the Experiments

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FIGURE 1. Tear secretions of WT and KO mice in 2 age groups. (A) Tear secretion was measured in two age groups in both WT and CFTR KO mice: at 8 to 10 weeks of age and at 20 to 24 weeks of age. Data from both eyes were averaged and evaluated. Tear secretion of CFTR KO mice were significantly lower compared to WTs in both age groups. (B) Secretion results of male and female mice were assessed and evaluated separately in WT and KO animals in both age groups. Sex-based data did not show significant difference in tear secretion either in WT or in KO mice. Data are presented as means ± SEM.

FIGURE 2. Corneal fluorescein staining in WT and CFTR KO mice. (A) Corneal fluorescein staining was measured in two age groups: at 8 to 10 weeks of age and at 20 to 24 weeks of age in both WT and CFTR KO mice. Data from both eyes were averaged and evaluated. Corneal staining scores of KO mice were significantly higher compared to WTs in both age groups. (B) Corneal fluorescein staining scores of male and female mice were calculated separately in WT and KO animals in both age groups. No significant differences were found between males and females either in WT or in KO mice. Data are presented as means ± SEM.
All experiments were conducted in compliance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. The protocol has been approved by the Ethical Committee for the Protection of Animals in Research of the University of Szeged, Szeged, Hungary and conformed to the Directive 2010/63/EU of the European Parliament.

**Solutions and Chemicals**

Media and its supplements (DMEM, McCoy, FCS, glutamine and BSA), carbachol (carbamoylcholine chloride), forskolin and 8-bromo adenosine-3′–5′-cyclic monophosphate (8-bromo cAMP) were purchased from Sigma-Aldrich Corp. (Budapest, Hun-

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**FIGURE 3.** Evaluation of ocular surface integrity of WT and CFTR KO mice at 10 and 24 weeks. Virtually no fluorescence staining could be found in the corneas of WT mice, whereas profound staining were observed in the corneas from KO animals, in both age groups.

**FIGURE 4.** H&E staining of LG from WT and CFTR KO mice. While it appears that there are some increased luminal spaces within acinar cells (arrows) in WT mice, giving the image a less smooth appearance compared to that from KO mice, there are no significant morphologic changes of the LGs, including ducts (arrowheads). Scale bar: 100 μm.
Collagenase was purchased from Worthington Biochemical Corp. (Lakewood, NJ, USA). The composition of solutions used in our studies is summarized in the Table. The pH of standard HEPES-buffered solution was set to 7.4 with HCl at 37 °C. The standard HCO₃⁻/CO₂⁻ buffered solution was gassed with 95% O₂/5% CO₂ at 37 °C. FURA2-AM was purchased from Invitrogen (Waltham, MA, USA).

Measurement of Tear Secretion and Corneal Fluorescein Staining

Tear production was measured in anesthetized mice using phenol red impregnated cotton threads (Zone-Quick, Showa Yakuhin Kako Ltd., Tokyo, Japan) applied into the lateral canthus of both eyes for 5 minutes. Color of the threads turns red in contact with the tears. Wetting length was measured in millimeters under a dissecting microscope.

Ocular surface integrity was evaluated by applying 0.5 l Lo of 5% fluorescein sodium into the conjunctival sac, followed by slit-lamp biomicroscopy (Inami L0198, Tokyo, Japan) through cobalt-blue filter. Images were captured with an anterior segment digital camera (Inami L-0541DC) attached to the slit-lamp. Staining was assessed using the NEI grading system.21 To quantify the staining changes, corneas were divided into five regions and staining was assessed and rated in each region from 0 to 3. Total scores from the five regions were recorded.

Hematoxylin & Eosin (H&E) Staining

Freshly dissected LG tissues, from both WT and KO mice, were fixed in 4% buffered formaldehyde and embedded in paraffin, then 3.5-μm thin serial sections were cut and stained with H&E.

Immunofluorescence

A total of 15-μm thick cryostat sections were rehydrated by washing in tris-buffered saline (TBS, 20 mM Tris-HCl, pH: 7.5, 150 mM NaCl) for 5 minutes, then fixed in 2% paraformaldehyde (PFA). After washing the sections in TBS three times for 5 minutes each, the samples were permeabilized with 0.1% Triton-X in TBS for 10 to 15 minutes. The sections were blocked with 5% FCS in TBS for 1 hour at room temperature followed by an overnight incubation with primary antibody for CFTR (1:100, Alomone Labs, Jerusalem, Israel) at 4°C. The next day the samples were incubated with secondary antibody, Alexa-488 conjugated goat anti-rabbit (1:1000, Abcam, Cambridge, UK) for 1 hour and Hoechst (1:1000, Sigma-Aldrich) for 30 minutes.
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**RESULTS**

**Tear Secretion and Corneal Fluorescein Staining**

Tear secretion was measured in two age groups in both WT and KO mice, at 8 to 10 weeks of age and at 20 to 24 weeks of age. Data from both eyes were averaged and evaluated. Tear secretion result at 8 to 10 weeks of age was 2.47 ± 0.43 mm/5 min (n = 11) in WT mice, and 1.27 ± 0.14 mm/5 minutes (n = 11) in KO mice, while at 20 to 24 weeks of age, tear secretion was 3.86 ± 0.91 mm/5 minutes (n = 11) in the WT group and 1.36 ± 0.14 mm/5 minutes (n = 10) in the KO group. Tear secretion of KO animals in both age groups were significantly lower as compared to their WT littermates (8–10 weeks: P = 0.0008; 20–24 weeks: 0.0004). To study the effect of age (or duration of the disease in KO animals) in tear secretion, results were calculated not only vertically (i.e., separately in two different age groups, comparing WT and KO measurements, see above) but also horizontally, with the comparison of tear secretion in different age groups separately in WT and in KO animals. In WT animals, no significant difference was observed between the secretion data at the age of 8 to 10 weeks and 20 to 24 weeks. Similarly, we could not find statistically significant difference in tear secretion of KO animals measured in different age groups (Fig. 1A).

The potential difference in tear secretion between male and female mice was investigated in WT and in CFTR KO animals in both age groups. Tear secretion results calculated separately in male and in female mice did not show statistically significant difference either in WT or in KO mice (Fig. 1B).

**Measurement of Intracellular Ca^{2+} Concentration**

Intracellular Ca^{2+} concentration [Ca^{2+}]i, was measured using Ca^{2+}-sensitive fluorescent dye FURA 2AM (4–5 µM) as described earlier.22 Changes in [Ca^{2+}]i, were measured using an imaging system (xcellence; Olympus, Budapest, Hungary). We excited 4 to 5 small areas (region of interests: ROIs) of 5 to 10 cells in each intact duct with light at 340 and 380 nm, and the 380/540 fluorescence emission ratio was measured at 510 nm. One [Ca^{2+}]i measurement was obtained per second.

**Statistics**

Kruskal-Wallis test with Dunn method was used for the analysis of tear secretion. A mixed ANOVA model was applied. Effects of the stimulatory compounds (forskolin or carbachol) were taken into account as “fixed effects.” The effect of the individual “duct” and the “duct and effects of forskolin, 8-bromo-cAMP or carbachol” interaction (we assumed that the value of the effect of the stimulatory compounds depend on the individual duct) were taken into account as random effects in the model. Statistical software (SigmaPlot Systat; Software, Inc., London, UK) was used to analyze the data, which were presented as means ± SEM. A value of P < 0.05 was regarded as significant.
Fluorescein staining was evaluated in both WT and KO mice at 8 to 10 weeks of age and at 20 to 24 weeks of age. Data from both eyes were pooled together. Corneal staining score was 1.0 ± 0.66 in WT mice (n = 6) and 6.83 ± 1.16 in KO mice (n = 6) in animals at 8 to 10 weeks of age, while in the 20 to 24 weeks group, the staining was 4.17 ± 0.88 in WT mice (n = 6) and 11.17 ± 1.16 in KO animals (n = 6). Corneal staining scores of KO animals in both age groups were significantly higher in KO mice as compared to their WT littermates (8 to 10 weeks: $P = 0.0002$; 20–24 weeks: 0.0004; Fig. 2A). Staining scores of female and male mice were also calculated separately. We could not find statistically significant difference in corneal fluorescein staining between female and male mice either in WTs or in KO animals (Fig. 2B). Corneal staining images of WT and KO mice at 10 weeks and at 24 weeks of age can be seen in Figure 3.

**H&E Staining of LGs From WT and CFTR KO Mice**

To assess the potential morphologic differences between LGs from KO and WT mice, freshly dissected LGs were processed for H&E staining. LGs of 8- to 10- and 20- to 24-week-old animals were investigated. However, no obvious structural changes have been observed in KO LG tissues as compared to age-matched WT counterparts (Fig. 4).

**Immunofluorescence**

As demonstrated in Figures 5A and 5B, intense CFTR staining could be found most prominently in the apical membranes of LG duct cells from WT animals, although some diffuse staining was also found in acinar cells, mostly within the cytoplasm (Supplementary Video S1). This observation is consistent with previous reports in rat and rabbit, where the presence of CFTR mRNA and protein were demonstrated in acinar and ductal cells, with intense fluorescence staining in the apical membranes of the duct cells. As anticipated, we were unable to detect the presence of CFTR protein in LGs from KO mice (Figs. 5C, 5D).

**Forskolin and 8-Bromo cAMP-Induced Fluid Secretion of Isolated LG Ducts**

Effects of forskolin stimulation on WT and KO LG interlobular and intralobar duct segments isolated from 14- to 24-week-old animals were investigated in HEPES- and in HCO\(_3^-\)/CO\(_2^-\)-buffered solutions. The secretory rates were calculated for the first 10 minutes of stimulation. Forskolin stimulation (10 μM) resulted in a continuous swelling response in WT ducts (secretory rate in HCO\(_3^-\)/CO\(_2^-\)-buffered solution: 176 ± 5 pl/min/mm\(^2\)). In contrast, no forskolin-evoked fluid secretion could be measured in ducts from KO animals (secretory rate in HCO\(_3^-\)/CO\(_2^-\)-buffered solution: 1.9 ± 5.6 pl/min/mm\(^2\)). The secretory responses observed in HEPES-buffered and in HCO\(_3^-\)/CO\(_2^-\)-buffered solutions were similar.

Figures 6A, 6B, and 6C show the luminal volume changes for forskolin stimulation in WT and KO ducts. Overall, forskolin-induced fluid secretion was significantly lower in ducts from KO mice, as compared to WT (in both HEPES and HCO\(_3^-\)/CO\(_2^-\)-buffered solutions: $P = 0.0006$).

Supplementary Videos S2 and S3 demonstrate the effects of forskolin on ductal fluid secretion in WT and KO ducts, respectively.

To further substantiate the secretory effect of elevated cytosolic cAMP level, cell-permeable cAMP analogue 8-bromo cAMP was used. 8-bromo cAMP resulted in a continuous secretion in WT ducts (secretory rate in HCO\(_3^-\)/CO\(_2^-\)-buffer in the first 10 minutes of stimulation: 141 ± 7 pl/min/mm\(^2\)) while no fluid secretory response could be observed in KO ducts (secretory rate in HCO\(_3^-\)/CO\(_2^-\)-buffer in the first 10 minutes of stimulation: 0.5 ± 0.4 pl/min/mm\(^2\)). Similar results were obtained in HEPES-buffered solution. 8-bromo cAMP-induced fluid secretion was significantly lower in KO ducts, as compared to WTs (in both HEPES and HCO\(_3^-\)/CO\(_2^-\)-buffered solutions: $P = 0.0004$; Figs. 7A, 7B). Overall, we could not find statistically significant difference between the secretory rates evoked by forskolin and 8-bromo cAMP either in WT or in KO ducts.

**Cholinergic-Stimulated Fluid Secretion in Isolated LG Ducts**

To examine the role of CFTR in cholinergic-evoked ductal fluid secretion, responses to muscarinic agonist carbachol were investigated in WT and KO LG duct segments isolated from 14- to 24-week-old mice. Rapid secretion could be observed in the first 4 to 5 minutes of carbachol stimulation (100 μM) followed by a slower phase both in WT ducts (secretory rate in HCO\(_3^-\)/CO\(_2^-\)-buffered solution in the first 10 minutes of stimulation: 133 ± 6 pl/min/mm\(^2\)) and in KO ducts (secretory rate in
To investigate the potential difference in [Ca$^{2+}$]i between WT and KO ducts, carbachol-evoked elevation of [Ca$^{2+}$]i was measured in both groups of isolated ducts (Fig. 9). Carbachol dose-dependently elevated the [Ca$^{2+}$]i in both WT (F$_{max}$: 1 μM: 1.19 ± 0.01; 10 μM: 1.67 ± 0.05; 100 μM: 1.76 ± 0.05) and KO duct cells (F$_{max}$: 1 μM: 1.15 ± 0.02; 10 μM: 1.48 ± 0.03; 100 μM: 1.83 ± 0.05) without significant differences between WT and KO ducts.

**Discussion**

Previous reports have shown that CFTR plays an important role in epithelial secretion. Dysfunctional Cl$^-$ and consequent fluid secretion can be observed in the pancreatic ducts, airway epithelia, and salivary glands when CFTR is absent or defective.8–11,25,26 Unfortunately, little is known about the role CFTR may play in LG function, in contrast to the considerable attention paid to the other components of the ocular surface system, the cornea and the conjunctiva.28–31 It has been reported, that CFTR was found on the apical membrane of conjunctival and corneal epithelial cells.32–34 Levin and Verkman found high capacity of CFTR-facilitated Cl$^-$ transport at the ocular surface in mice.35

In the present study, we demonstrated decreased tear secretion and increased corneal fluorescein staining in KO mice in two age groups studied, as compared to age-matched WT mice, suggesting CFTR plays a critical and essential role in tear secretion and in the maintenance of ocular surface integrity. Increased corneal fluorescein staining in the absence of CFTR may reflect the global dysfunction of the lacrimal functional unit including conjunctival, conjunctival, and LG epithelial cells. Our results show that KO mice are a useful model to investigate the role of CFTR may play in lacrimal secretion. As female sex is an established risk factor for dry eye disease, we calculated both the tear secretion results and the fluorescein staining scores separately in female and male mice.36 We could not demonstrate the role of sex in tear secretion and ocular surface integrity which may be explained by the relatively young age of our animals.

Cystic fibrosis can cause wide range of morphologic alterations in the secretory epithelia, including lung, mucosa of the trachea, salivary glands or the pancreas.7,10,11,26 Normal ion and water secretion is required to produce thin, free-flowing mucus. Defective chloride channels can result in reduced fluid secretion causing sticky and thick mucus formation that clogs the ducts and subsequently damages various organs. Our histologic examinations did not reveal any significant morphologic differences between the WT and KO LG tissues either in the 8- to 10-week or in the 20- to 24-week-old group. These histologic results demonstrated that functional deterioration may precede morphologic alterations during the course of disease progression. However, investigation of the duration of the disease in the alteration of LG morphology in CFTR KO mice has strong limitations as shorter life expectancies of KO mice hinder long lasting observations. Further studies are needed in order to clarify potential alterations in LG morphology later in life. In a case report by Alghadayan et al,57 histopathologic examinations of LGs of CF patient who died of pulmonary complications revealed clogged small duct lumens and subsequent degeneration of acinar cells.

Our immunofluorescence data demonstrated the presence of CFTR in both acinar and ductal cells, with the staining most prominent in the apical membranes of ductal cells. Therefore, to further elucidate the role of CFTR in LG function, we have focused our study on the ducts by using our isolated duct segment model described earlier by our laboratory.22 Both HEPES-buffered (nominally HCO$_3^-$-free) and HCO$_3^-/CO_2^-$-buffered solutions were used in the experiments in order to investigate the potential role of HCO$_3^-$ transport in the

**Figure 8.** Effect of carbachol on ductal fluid secretion in mouse ducts isolated from WT and CFTR KO LGs. (A) WT ducts were exposed either to 100 μM carbachol (filled rhombus) or to no agonist (empty triangle). (B) KO ducts were exposed either to 100 μM carbachol (filled square) or to no agonist (empty triangle). Changes in Vr are shown. Data were obtained from six ducts isolated from three different animals in each series and are presented as means ± SEM. (C) Photo series of secreting isolated LG duct segments in response to carbachol stimulation were captured from Supplementary Videos S4 and S5. The secretory responses observed in HEPES-buffered and in HCO$_3^-/CO_2^-$-buffered solutions were similar. The luminal space is marked with blue color.

HCO$_3^-/CO_2^-$-buffered solution in the first 10 minutes of stimulation: 130 ± 5 pl/min/mm$^2$. Similar results were obtained in HEPES-buffered solution. Secretory rates in WT and in KO ducts did not differ significantly either in HEPES-buffered or in HCO$_3^-/CO_2^-$-buffered solutions.

Figures 8A, 8B, and 8C demonstrate the carbachol-induced luminal volume changes in WT and KO ducts.

Supplementary Videos S4 and S5 show the effect of carbachol on ductal fluid secretion in WT and KO ducts.

**Carbachol-Evoked Ca$^{2+}$ Signaling of Isolated LG Ducts**

To investigate the potential difference in [Ca$^{2+}$]i, between WT and KO ducts, carbachol-evoked elevation of [Ca$^{2+}$]i was
secretory processes. The secretory rates were independent from the buffer used (HEPES versus HCO₃⁻/CO₂ buffer) suggesting the predominant role of Cl⁻ transport mechanisms over HCO₃⁻ secreting processes in mouse LG ducts. These findings are in accordance with our previous results derived from rabbit LG ducts.24 As we have shown above, the absence of forskolin or 8-bromo cAMP-stimulated fluid secretion in ducts from KO mice suggests the important role of CFTR may play in LG duct secretion. Lack of cAMP-mediated fluid secretion in KO ducts demonstrates that CFTR may be the only cAMP-dependent transporter on the luminal surface of duct cells in mouse LG. In contrast to our findings from mouse LG ducts, pancreatic ducts isolated from CFTR KO mice has significant secretory capacity for forskolin stimulation. 38 Considering the strong predominance of CFTR protein in LG ducts, CFTR may play a key role in LG secretion through modification of LG fluids while being transported in the ducts. Cl⁻ secretion through CFTR may be a major contributor to the transmembrane electrochemical gradient and subsequent electrolyte and water movements and therefore defects in CFTR may significantly compromise Cl⁻ and water secretion from LG ducts.

Carbachol-evoked fluid secretion and cytosolic Ca²⁺ signaling in WT and CFTR KO ducts did not differ significantly, suggesting the preservation of secretory mechanisms activated by Ca²⁺ mobilizing stimuli in the absence of CFTR protein. Other Cl⁻ channels (i.e., voltage- and Ca²⁺-sensitive Cl⁻ channels (not investigated in the present study) appeared unaffected when CFTR protein is missing.⁵⁹

In recent studies by Flores et al. and Lee et al., small-molecule CFTR activators increased tear secretion in a LG-ablated mouse model of dry eye.⁴⁰,⁴¹ Since LG was absent in this animal model, the enhanced Cl⁻-driven fluid secretion could be from the conjunctival and corneal epithelial cells. Data presented here, however, suggest that CFTR affects not only corneal and conjunctival epithelial cell function, but also LG secretion.

In conclusion, our data demonstrated decreased tear secretion and impaired ocular surface integrity in CFTR KO mice, suggesting the important role of CFTR may play in LG function and in the maintenance of ocular surface integrity. Our functional studies by employing the isolated duct segment model, suggest that CFTR plays a pivotal role in the fluid secretion of LG duct system. Further studies are needed to clarify whether modification of CFTR function may serve as a potential target to stimulate LG secretion and therefore can be an option in treating aqueous deficient dry eye.

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References

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