Cold-Sensitive Corneal Afferents Respond to a Variety of Ocular Stimuli Central to Tear Production: Implications for Dry Eye Disease

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PURPOSE. To investigate the response characteristics of the corneal afferents that detect ocular conditions critical to the activation of the “afferent limb” of the lacrimation reflex.

METHODS. In isoflurane-anesthetized male rats, trigeminal ganglia were explored extracellularly in vivo to identify the corneal neurons that can be activated by ocular stimuli important to lacrimation. After verifying their receptive field loci to be restricted to the cornea, neural response properties were characterized with a variety of stimuli, such as drying and wetting of the cornea, by applying and removing artificial tears, temperature changes (35°C–15°C and 39°C–51°C), menthol (10–100 μM), and hyperosmolar solutions (NaCl, sucrose; 297-3014 mOsm), applied to the ocular surface.

RESULTS. A specific type of corneal afferent was identified that responded to drying of the ocular surface. These neurons were classified as innocuous “cold” thermoreceptors by their responses to steady state and dynamic temperature changes applied to the cornea. In addition to drying and slight cooling (<1°C) of the corneal surface, these neurons were excited by evaporation of tears from the ocular surface and hyperosmolar tears. Moreover, these neurons were activated by noxious thermal stimulation and menthol applied to the corneal surface.

CONCLUSIONS. These results demonstrate that innocuous “cold” corneal thermoreceptors are activated by drying of the ocular surface and hyperosmotic solutions, conditions that are consistent with a role in tear production. The authors hypothesize that the dysfunction of these corneal afferents and the lacrimation reflex pathway they activate lead to some forms of dry eye disease. (Invest Ophthalmol Vis Sci. 2010;51:3969–3976) DOI: 10.1167/iovs.09-4747

Dry eye disease (DED) is a chronic disorder that results in part from inadequate or altered tear film on the anterior ocular surface. Earlier studies have shown that sensory stimulation of the cornea and conjunctiva is essential in initiating the lacrimation reflex in humans.1,2 Several types of corneal and conjunctival afferents have been identified.3–6 Activation of two classes of corneal primary afferents, polymodal and mechanoreceptive neurons, elicits reflex tearing, blinking, and pain. The neural regulatory mechanisms responsible for maintaining normal tear film, through basic (basal) tear production, are still unknown. Understanding these regulatory mechanisms is especially important because dysfunction of the corneal sensory nerves7–10 and of the neurons in the central nervous system11 involved in basic tearing has been hypothesized to contribute to the pathogenesis of DED. Because the “cold” sensitive corneal thermoreceptors are the only sensory afferents that exhibit spontaneous activity, it was speculated that the discharge of these afferents is necessary for the production of basic tears. However, the detailed response properties of these neurons to ocular stimuli important to lacrimation have not been examined. Furthermore, a previous study13 reported the existence of neurons in the rostral spinal trigeminal nucleus caudalis that monitor the fluid status of the ocular surface and modulate tear production in rats. Because the evoked tears are produced and blocked, respectively, by glutamate and muscimol injections into the vicinity of these neurons, which previously were shown to project to superior salivatory and facial nuclei, it was hypothesized that these neurons form a central component of the lacrimation reflex circuit. However, it has not been determined what specific cornea afferents activated these central neurons.

The present study identifies and characterizes the primary afferent neurons innervating the cornea that respond to the types of ocular stimuli that will produce tears and, therefore, may serve as the “afferent limb” of the lacrimation reflex. We report that these corneal afferents can be classified as cold neurons, and we discuss the potential contribution to and significance of these afferents to DED.

METHODS

Surgery and Recordings

Under 2.0% to 2.5% isoflurane anesthesia, the femoral vein and artery of male Sprague-Dawley rats were catheterized, respectively, for fluid injections and mean arterial pressure (MAP) recordings. Each animal was placed in a stereotactic instrument that held its head firmly with mouth and ear bars, and the tracheal tube was connected to a ventilator after tracheostomy. A partial craniotomy was performed to expose the brain overlying the left trigeminal ganglion (TG). Animals were artificially respirated (Rodent Ventilator Model 683; Harvard Apparatus, Boston, MA), and the end tidal CO₂ was monitored with a CO₂ analyzer (4%–5%; CWE, Ardmore, PA). Core temperature was maintained at 37°C to 38°C with a feedback-controlled regulator. Just before the recordings, the isoflurane concentration was decreased to and maintained at 1.25% to 1.5% throughout the experiment. After checking for noxious stimulation-evoked withdrawal reflexes, pancuronium bromide (0.6 mg/kg/h) was infused continuously before and during electrophysiological recordings. Any significant elevation in MAP resulted in an increased concentration of isoflurane. A tungsten microelectrode (5–9 MΩ; FHC, Bowdoin, ME) was lowered into the left TG to search for a spontaneously active neuron after amplification and discrimination of the neural signals (BAK Electronic, Inc., Mt. Airy,

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MD). Discriminated spike outputs, MAP, and temperatures during the corneal thermal stimulation were acquired and analyzed (Micro 1401 mKII and Spike2, v5.19; Cambridge Electric Design Ltd., Cambridge, UK). Neurons that responded to room temperature saline solution applied to the eye with a brief (<4 s duration) burst of activity were isolated. Receptive fields (RFs) were identified on the cornea with an ice-cooled dental metal probe (tip diameter, ~1 mm). A bipolar silver electrode was placed on the RF to activate the nerve terminal of the neuron (A360 and Pulsemaster A300; WPI Inc., Sarasota, FL) to measure afferent conduction velocity (CV). The CV was calculated by dividing the conduction distance by the latency of the action potential to electrical stimulation of the RF. The average conduction distance from the center of the cornea to the center of TG was 17.5 mm (n = 3). Based on the calculated CV, neurons were categorized as either Aβ (1.5–15.0 m/s) or C-fibers (<1.5 m/s).13 At the end of the experiment, each animal was euthanized with sodium pentobarbital (200 mg/kg, IP). The experimental protocol was in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and was approved by the IACUC at the University of New England.

## Dry and Wet Corneal Stimulation

After determining the afferent fiber type, the discharge rate of each unit was recorded during two conditions of corneal fluid status. The dry corneal condition (5 minutes) occurred when the cornea was moistened with 20 μL rat artificial tears (ATs) with a sterile pipette.16 This volume was sufficient to cover the entire anterior ocular surface. The dry corneal condition (1 minute) occurred after the ATs were removed with a piece of filter paper.

### Chemical Stimulation

Chemical stimuli (i.e., menthol, NaCl, sucrose) were applied to the ocular surface in 20-μL drops immediately after removal of ATs with filter paper and were left on the cornea for approximately 1 minute. Chemical solutions were then washed off by flushing the eye with copious amounts of ATs (~4 mL).

### Thermal Stimulation

Thermal stimuli were applied to the corneal surface with a Peltier-based thermal stimulator (TSAII; Medoc Ltd., Ramat Yishai, Israel), which was oriented to the ocular surface and the thermode surface, keeping it moist and bathing the nerve terminals. In addition, this method kept the position of the thermal probe constant relative to the cornea, thus providing consistent temperatures throughout a number of stimulus applications. Two temperature stimulation protocols were used: a steady state temperature series and a dynamic temperature series. In the steady state temperature series, cooling stimuli were presented to the cornea beginning with a 35°C adapting temperature followed by consecutive 2°C incremental decreases in temperature to a final temperature of 15°C, with each temperature lasting for 60 seconds (see Fig. 3). After the cooling stimulus sequence, a warming series back to 35°C was presented, also in 2°C steps. In the dynamic temperature stimulus series, 4°C step ramp cooling or heating stimuli were applied to the cornea from the adapting temperature of 35°C to 15°C or to 51°C, respectively (see Fig. 4). Each stimulus ramp lasted 20 seconds, with an inter-stimulus period of 20 seconds, except for the noxious heat stimuli of 47°C and 51°C, which had an interval of 100 seconds, to avoid heat-induced sensitization. The rates of temperature changes depended on the magnitudes of the temperature changes and ranged from 1°C/s to 2.7°C/s for 4°C step cooling and to 2°C/s to 5°C/s for 4°C step heating.

### Drugs

Menthol (Sigma-Aldrich, St. Louis, MO) was dissolved in 40% ethanol to make a 10-mM stock solution. The stock solution was then diluted to the required concentrations with ATs on the day of the experiment. The solutions of NaCl and sucrose (Sigma-Aldrich) were prepared by dissolving in 0.9% saline (vehicle), and their osmolarities were measured with an osmometer (Osmomat 030; Gonotec GmbH, Berlin, Germany). The control solution for menthol was 0.4% ethanol, which was the equivalent concentration contained in the highest menthol dose (100 μM) and was made by diluting 40% of each solution with ATs. The composition of ATs was 106.5 mM NaCl, 26.1 mM NaHCO₃, 18.7 mM KCl, 1.0 mM MgCl₂, 0.5 mM NaH₂PO₄, 1.1 mM CaCl₂, 10 mM HEPES, pH 7.45.

## Statistical Analysis

Because the chemical stimuli (menthol, sucrose, NaCl) were kept at room temperature (21°C–24°C), which was colder than the average corneal temperature of the rats (31°C–33°C), responses during the first 4 seconds after the stimulus application were considered to be due to cold stimulation of the ocular surface. See Figure 5a for a depiction of these initial bursts of activities (arrow) that were constant in magnitude and duration across all doses of menthol and vehicle (0.4% ETOH). In contrast, the chemical stimulus-induced responses were slower to develop, sustained for at least 30 seconds, and dose dependent. Thus, the evoked responses to chemical stimuli in this study (response magnitude [Rmag]) were defined as the total number of spikes for 5 to 35 seconds after the stimulus application after subtracting the background activity (mean ± 2 SD based on the 30-second period preceding the stimulus). Steady state activity to 2°C cooling or warming (see Fig. 5c) was calculated based on the last 30 seconds of each of the 1-minute temperature stimuli. The dynamic responses to 4°C step cooling and noxious heating of the cornea (see Fig. 5c) were defined as the total discharges that exceeded the background activity during the 20-second stimulus periods (i.e., Rmags based on the 20-second period before stimulus). Discharge rates during dry and wet corneal conditions were, respectively, based on the averages of the last 30 seconds of a 1-minute dry corneal period and the 30 seconds immediately preceding the dry period. Statistical analyses for the effects of ocular stimulation on neural discharges were performed with ANOVA (PPC 6.5.1 [GB-STAT, Silver Spring, MD]; 12.0 [SPSS, Chicago, IL]) with or without repeated measures. Post hoc analyses were conducted with Newman-Keuls tests for individual comparisons.17

## Results

### Receptive Fields of Corneal Afferents

The cold-sensitive RFs of the TG neurons on the cornea were identified and found to be restricted to the cornea (Fig. 1). Although the locations of the RFs were widely distributed over the corneal surface, clusters of RFs were also observed at several loci (striped oval). Excluding the units on the equatorial line (n = 9), twice as many cold-sensitive neurons were found on the inferior cornea (n = 26) as on the superior cornea (n = 13). However, RFs on the temporal side of the cornea (n = 20) were approximately equal in number to those on the nasal side (n = 21).

### Response to Drying and Wetting of the Cornea

Discharges of all 48 cold-sensitive TG neurons were increased by drying of the cornea and depressed by wetting of the cornea with AT. Figures 2a and 2b illustrate the activity profiles of two units during dry and wet corneal surface conditions. After the removal of the ATs (upward arrows), the discharge rates gradually increased over the next 20 to 25 seconds to more stable levels. Overall, the difference between the average discharge rates during the dry (15.8 ± 0.9 spikes/s) and the wet (6.0 ± 0.7 spikes/s) conditions for all neurons was highly significant (Fig. 2c; P < 0.01). When, based on CV, units were grouped into Aβ and C fibers, the rates of activity for the Aβ fibers during the dry corneal conditions were greater than those for the C fiber afferents (17.7 ± 1.4 spikes/s vs. 13.8 ± 1.1 spikes/s; P <
however, activity during the wet cornea condition for these two types of afferents was not significantly different (5.1 ± 1.1 spikes/s and 6.4 ± 0.7 spikes/s for Aδ and C fibers, respectively; P = 0.65). Additionally, we examined two mechanically sensitive but cold-insensitive units on the cornea and three cold-sensitive neurons with RFS on the conjunctiva for responses to drying. None of these five units exhibited differential discharge rates to dry and wet ocular conditions (data not shown).

Response to Thermal Stimulation

Forty-two cold-sensitive TG neurons were tested with quantitative thermal stimulation of the corneal surface. Figure 3a shows the typical responses to temperature changes, which were seen in 37 of the 42 units. These units displayed dynamic increases in activity in response to cooling, followed by stable rates of activity that depended on the steady state (SS) temperature (dynamic + static units). All units that exhibited dynamic increases in discharge to cooling rapidly adapted during the SS temperature within 10 seconds. In three units, one of which is shown in Figure 3b, SS temperatures were not encoded by changes in neuronal activity, though their dynamic responses to temperature changes were still present (dynamic-only units). In another two units, the dynamic components were missing, but SS activities were present (static-only units; not shown). The average SS responses to consecutive 2°C step temperatures between 35°C and 15°C were bell-shaped curves with maximum discharge occurring between 25°C and 27°C (Fig. 3c). The overall SS discharge rates were significantly higher in the cool-
Direction than in the warming direction (two-way ANOVA; \( P < 0.001 \)). This fact, which has been termed hysteresis, has been observed previously for innocuous cold trigeminal afferents in monkeys. Furthermore, the SS discharge rates at 33°C to 15°C during the cooling series and at 17°C to 29°C during the warming series were significantly greater than activity at the adapting temperature of 35°C (one-way ANOVA; \( P < 0.05 \) and \( P < 0.01 \)).

During the dynamic 4°C step temperature stimulus series (Fig. 4a), dynamic activity and SS neuronal activity were similar to those observed during 2°C cooling temperatures (Fig. 3a). In addition, increases in evoked activity were observed at 47°C and 51°C (Fig. 4a at arrows; so-called paradoxical discharges to noxious heat in innocuous cold neurons\(^{19}\)). These paradoxical discharges were observed in 30 of 40 cold-sensitive units tested with 51°C. Average responses to 4°C step ramp cooling and heating stimuli for 30 cold-sensitive units are shown in Figure 4b. The responses to 27°C or colder temperatures were significantly higher than activity at the adapting temperature (35°C), whereas only the evoked responses to 51°C were significantly different compared with activity during the adapting temperature. The Rmag to the 51°C stimulus was approximately four times greater than for the 4°C stimulus.

Threshold temperature for dynamic activation of cold-sensitive neurons tested with a 4°C cooling stimulus from the 35°C adapting temperature was \( 1°C \) (e.g., Fig. 4c). The overall average threshold among the 26 units tested for dynamic responses to 4°C cooling was \( 34.3°C \pm 0.2°C \).

**Response to Menthol**

Of the 36 cold-sensitive TG neurons tested with application of menthol to the cornea, 32 showed significant increases in activity above background (total Rmag >10 spikes) by either the 50- or 100-μM concentration (Fig. 5). Four units were not excited by the highest concentration of menthol used in this study (100 μM) and were considered menthol insensitive. Average Rmags to increasing concentrations of menthol were dose dependent, and higher concentrations of menthol produced progressively shorter laten-
Responses to Hyperosmolar Solutions

In one cold-sensitive afferent, we observed that the high ambient temperature and low humidity in the experimental room produced the discharge profiles shown in Figure 6. Low spontaneous activity, seen immediately after the ATs were dropped on the cornea (arrow), gradually increased over a 5- to 15-minute period until the cornea was again wet with ATs (star). The dramatic increase in discharge over this period appears to be the result of evaporation of the ATs from the ocular surface, which would have increased the osmolarity of the tears. If this were the case, the cold-sensitive afferents would also be excited by hyperosmolar solutions applied to the ocular surface. Figure 7 demonstrates that hyperosmolar solutions of both NaCl and sucrose caused significant increases in neuronal activity in a concentration-dependent manner (one-way ANOVA; \( P < 0.01 \)). The average stimulus-response (S-R) relationship of Figure 7b could be best fit by a logarithmic function, regardless of whether the two highest osmolarity values were included [dotted curve, \( y = 151 \ln x - 832; R^2 = 0.957 \)]. The S-R function for osmolarities up to 611 mOsm may be also described by a linear function (not shown; \( y = 0.45 x - 117; R^2 = 0.9692 \)). Furthermore, two additional neurons were tested with osmotic solutions using a nonpermeant substance, mannitol; again, the increases in osmolarity were associated with increases in afferent activity.

**DISCUSSION**

This is the first study to comprehensively characterize the response properties of the specific type of corneal afferents to ocular stimuli that regulate tearing. Two principal types of tears have generally been recognized: basic tears and reflex tears. Basic tears are considered to arise from subtle stimulation of the anterior eye such as cooling and drying caused by evaporation.\(^{20}\) Reflex tearing, on the other hand, is thought to be produced by stronger, noxious stimulation of the ocular\(^{13}\) and extraocular tissues such as the nasal mucosa.\(^{21}\) Strong cooling stimuli (-4.5°C), but not subtle cooling stimuli (-1°C), applied to the cornea significantly increased reflex tear secretion above and beyond basic tears,\(^{12}\) indicating that high-intensity temperature stimulation of the ocular surface produces reflex tears and, conversely, that low-intensity stimuli are important to basic tears. Furthermore, instillation of hyperosmolar solutions to the eyes (~450 mOsm and higher) was reported to evoke ocular discomfort and pain in humans,\(^{22}\) which should provide a strong and necessary stimulus for tear production. These observations are consistent with the conclusion that the corneal afferents reported here play a key role in activating the afferent limb of the lacrimation reflex important in basic tear production. In addition, the negative feedback model of a nervous system reflex predicts that the opposite stimulations (i.e., warming and wetting of the cornea and the isomolar tears) should lessen or even silence the activation of these neurons. Our results are consistent with this prediction. However, the possibility that they may also play a role in the eye blink reflex cannot be excluded because some stimuli that activate these afferents, such as a decrease in ocular temperature, also evoke blinking.\(^{23,24}\) Furthermore, the involvement of other ocular afferents innervating the cornea and conjunctiva, such as polymodal nociceptors\(^{6,25}\) in the tearing reflex, remains to be elucidated.

The corneal afferents in the present study were identified as innocuous cold thermoreceptors because they exhibited temperature response characteristics similar to those observed for previously described innocuous cold thermoreceptors on the skin\(^{26,27}\) and thermosensitive units innervating the orofacial tissues.\(^{5,28-30}\) Consistent with the properties of cold corneal afferents, these afferents produced complete cessation of activity.
afferent reported by Gallar et al., the cold afferents recorded in the present study displayed spontaneous activity, were exquisitely sensitive to dynamic changes in temperature, and responded to hyperosmotic stimuli. In contrast, however, our afferents in rats were able to encode the corneal SS temperatures (Fig. 3c) though cold afferents in the cat failed to do so.

Our corneal afferents appeared to resemble the corneal cold sensitive fibers that were reported to detect cooling of −1°C and to respond to 200 μM menthol. However, the detailed responses of these units to thermal stimuli or corneal drying were not described. Finally, innocuous cold thermoreceptors reported in the present study were clearly different from the polymodal nociceptors because our afferents responded to small temperature decreases (−1°C) and showed substantial spontaneous activity yet failed to respond to CO2 applied to the cornea (n = 5; data not shown).

We acknowledge the technical limitations in our studies. The ocular stimuli used to activate these corneal thermoreceptors are not mutually exclusive: drying of the cornea leads to cooling of the ocular surface and increases the osmolarity of the tear film. We propose that the dry response in innocuous cold thermoreceptors on the cornea is based on two distinct mechanisms: temperature and osmotic changes. To determine which stimulus is more relevant in producing the dry response would require a direct measurement of the changes in temperature and osmolarity that occur during corneal drying. However, we were unable to perform such measurements. Nonetheless, it is interesting to note that the maximum level of discharge attained by the optimum cornea temperature (25°C–27°C; Fig. 3) is only part of the activity achieved by drying of the cornea (Fig. 2), indicating that the excitation of these afferents in response to drying of the cornea involves more than simply the change in temperature. Our preliminary data showed that the dry response of the cornea afferents was partially blocked by the antagonist of the membrane receptor, TRPM8 [N-(4-t-Butylphenyl)-4-(3-Chloropyridin-2-yl)tetrahydropyrazine-1(2H)-carboxamide], suggesting that these membrane channels are important in detecting the dryness of the cornea and in activating the lacrimation reflex. The existence of TRPM8 on the nerve terminals of the cold thermoreceptors on the cornea is consistent with our present findings that these afferents responded to stimulation by menthol and cool temperatures. Other TRP channels, such as TRPV1, may also be involved in sensing osmotic stress during cornea drying.
The importance of the corneal afferents in contributing to the vicious circle that perpetuates DED has been known for some time but has recently been rediscovered. De-nervation of the sensory afferents (destruction of the ophthalmic division of the TG) produces severe consequences on the ocular surface system: it alters protein synthesis and single-unit activity in cats evoked by polymodal stimulation of the cornea. Finally, the central nervous system integration of external and internal inputs important to tear production may provide clues to the pathogenetic mechanisms underlying DED. Hirata et al. found complex interplays of inputs from the periorbital, nasal, and ocular tissues impinging on the central neurons involved in modulation of the lacrimation reflex. From this, we hypothesize that dysfunction of central nervous system integration plays a critical role in an alteration of the lacrimation reflex and ultimately may contribute to some forms of DED.

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References

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Figure 7. Sensitivity of cold-sensitive afferents to the hyperosmolar solutions. (a) Action potential discharges from a single neuron in response to vehicle and two different hyperosmolar solutions applied to the cornea (arrows above action potential traces). Numbers in parentheses are osmolalities of the solutions used to activate the neuron. (b) Average concentration-response functions of neurons to ocular application of NaCl and sucrose solutions.


