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Topical antibiotics reduce CD11c+ cell numbers in the healthy murine cornea and modulate their response to contact lens wear

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Previously we reported contact lens-induced CD11c+ cell responses in healthy mouse corneas, a phenomenon that also occurs in humans. To test involvement of ocular-associated bacteria, the impact of topical antibiotics on corneal CD11c+ cell populations during 24 h of lens wear was examined. Corneas were treated with gentamicin and ofloxacin (0.3%) or gentamicin alone, some also treated prior to lens wear (24 h). Contralateral PBS-treated eyes served as controls. CD11c-YFP (Yellow Fluorescent Protein) mice allowed CD11c+ cell visualization. Viable bacteria, on the ocular surface or contact lens, were labeled using FISH (16S rRNA-targeted probe) or click-chemistry (alkDala). Antibiotic treatment reduced baseline CD11c+ cell numbers without lens wear and suppressed CD11c+ cell responses to lens wear if corneas were both pretreated and treated during wear. Few bacteria colonized corneas or lenses under any circumstances. Conjunctival commensals were significantly reduced by antibiotics with or without lens wear, but minimally impacted by lens wear alone. Deliberate inoculation with conjunctival commensals triggered CD11c+ cell responses irrespective of antibiotic pretreatment. These results suggest that while lens wear does not necessarily increase quantifiable numbers of conjunctival commensals, those neutralized by antibiotics play a role in lens-associated CD11c+ cell responses and maintaining baseline CD11c+ cell populations.

The healthy cornea of the eye is remarkably resistant to bacterial infection but can be rendered susceptible by injury or contact lens wear. Research by us and others has shown that this resistance depends on a constitutive defensive combination of tear fluid, epithelial and basal lamina barrier function, and the ability of resident immune cells to detect and respond to injury, microbes or their ligands¹. In this regard, the cornea contains a small resident population of bone-marrow derived dendritic cells and macrophages in the stroma and epithelium^{2,3}, with centrally-located stromal dendritic cells being primarily immature precursors that can mature and acquire MHC Class II expression during inflammatory events^{2,3}. Dendritic cells are professional antigen presenting cells that help link innate and adaptive immunity^{4,5} and represent a major contributor to defending the cornea against infection and other threats^{2,6,7}. Expression of CD11c, a transmembrane protein that functions as a complement receptor, is considered a reliable marker for this cell type⁸.

The mechanisms by which contact lens wear predisposes to corneal infection by *P. aeruginosa* and other bacteria are yet to be resolved. Recently, we reported the development of a murine model of contact lens-associated *P. aeruginosa* keratitis in which lens wear was associated with a corneal para-inflammatory response involving CD11c+ (dendritic cell) infiltration/activation by 24 h and Ly6G+ cell (neutrophil) infiltration after 5–6 days⁹, despite corneas remaining free of visible pathology. Importantly, contact lens-associated corneal para-inflammatory responses involving Langerhans cells have also been reported in humans^{10–12}.

Previously, we showed that CD11c+ cells in murine corneas respond to *P. aeruginosa* challenge in vivo, contributing to IL-1R-dependent epithelial barrier function against bacterial adhesion after superficial injury¹³. Here, we sought to determine the role of bacteria in triggering corneal CD11c+ responses to contact lens wear. While healthy corneas do not host resident viable bacteria¹⁴, adjacent tissues are colonized with a microbiome. For example, the conjunctiva hosts numerous resident bacteria including *Staphylococcus* spp., and *Corynebacterium* spp.^{15,16}, the latter shown to be important for corneal immune responses during active infectious disease¹⁷.

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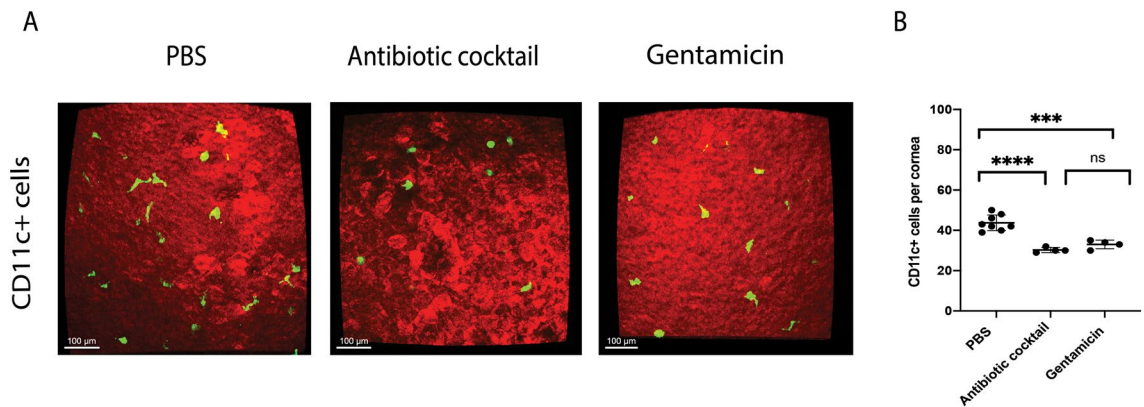


Figure 1. Antibiotic-treated corneas of CD11c-YFP mice show a decrease in baseline CD11c+ cells. **(A)** Maximum intensity z-projection of the YFP signal from CD11c+ cells (yellow) in the central cornea of healthy mouse eyes treated with antibiotic cocktail or gentamicin (see “Methods”) show reduced numbers of CD11c+ cells versus contralateral PBS treated controls at 24 h. Scale bar = 100 μm. **(B)** Quantification of CD11c+ cells in antibiotic-treated eyes versus PBS controls after 24 h (*** $P=0.001$, **** $P<0.0001$, ns = not significant; One-way ANOVA with Tukey’s multiple comparisons test).

Contact lens wear can potentially alter bacterial colonization in the conjunctiva¹⁸, and cornea¹⁹, including via lens binding^{20,21}. Indeed, in the murine lens-wear model, and in humans, worn lenses were found colonized by bacteria typical of those found on the skin and conjunctiva^{9,20,22}. To explore the involvement of bacteria in corneal CD11c+ responses to lens wear, CD11c-YFP mice were treated with topical antibiotics with and without contact lens wear, and imaging used to quantify CD11c+ responses in addition to conjunctival and lens colonization by viable bacteria.

Results

Topical antibiotic application decreases CD11c+ cell numbers in the healthy murine cornea. Prior to exploring topical antibiotic effects on contact lens-associated CD11c+ responses, a control experiment was performed to determine if antibiotics affected baseline numbers of resident corneal CD11c+ cells. CD11c-YFP mice were treated topically with a cocktail of gentamicin and ofloxacin (0.3% of each in solution), or gentamicin alone, from 0 to 6 h and corneal CD11c+ cell numbers imaged and quantified at 24 h (“Methods” “Procedure 1”). Figure 1 shows that both antibiotic treatments caused a reduction of corneal CD11c+ cell numbers versus PBS-treated contralateral controls. PBS (44 ± 4 cells) versus antibiotic cocktail (28 ± 3 cells, 36% decrease) or gentamicin (33 ± 2 cells, 25% decrease) ($P < 0.0001$ One-Way ANOVA Tukey’s multiple comparisons test, Fig. 1A,B). There was no significant difference between antibiotic cocktail and gentamicin alone. FISH labeling confirmed an absence of viable bacteria on antibiotic-treated corneas as for healthy murine corneas (Supplemental Fig. S1).

Topical gentamicin application modulates contact lens-associated CD11c+ cell responses. Having shown that gentamicin alone was not significantly different from its combination with ofloxacin, gentamicin was used to explore the role of bacteria in contact lens-associated CD11c+ cell responses (increase in number) in the central murine cornea after 24 h of lens wear⁹. It was tested if topical gentamicin treatment could abrogate that response. Mice were divided into PBS or gentamicin treated groups and fitted with a contact lens on one eye for 24 h (“Methods” “Procedure 2”). Contralateral eyes served as no lens wear controls. Figure 2 shows that 24 h of contact lens wear was associated with a significant increase in CD11c+ cell numbers in both the PBS control group (~44% increase) and the gentamicin-treated group (~36% increase) (Fig. 2A,B). However, no significant change in CD11c+ cell morphology (circularity) was observed under any condition (Fig. 2C). Thus, despite a reduction in baseline CD11c+ cells with gentamicin treatment, contact lens-induced CD11c+ cell responses after 24 h remained intact.

Since potential antibiotic effects may require extended exposure time, the experiment shown in Fig. 2 was repeated but eyes were first pretreated with either PBS or gentamicin (“Methods” “Procedure 3”). Under these conditions, topical gentamicin blocked the 24 h contact lens-associated corneal CD11c+ cell response (Fig. 3A,B). If only gentamicin pretreatment was applied, the 24 h contact lens-associated CD11c+ cell response remained intact. This experiment also showed that the reduction in corneal CD11c+ cells induced by topical gentamicin was maintained for 24 h after antibiotic removal. As above, no significant change in CD11c+ cell morphology (circularity) was observed under any condition (Fig. 3C).

Antibiotic treatment reduced the number of viable conjunctival bacteria detected by alkDala labeling with and without contact lens wear. In both of the above experiments (Figs. 2, 3), FISH or alkDala labeling of bacteria on the cornea revealed very few bacteria under all conditions with no significant differences between PBS or gentamicin treated groups and with or without contact lens wear for 24 h (Supplemental Fig. S2), a finding consistent with our previous work^{9,14,23}. Also consistent with our previous work, FISH

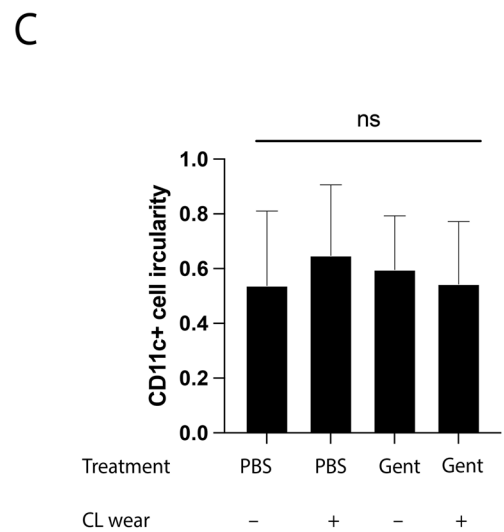
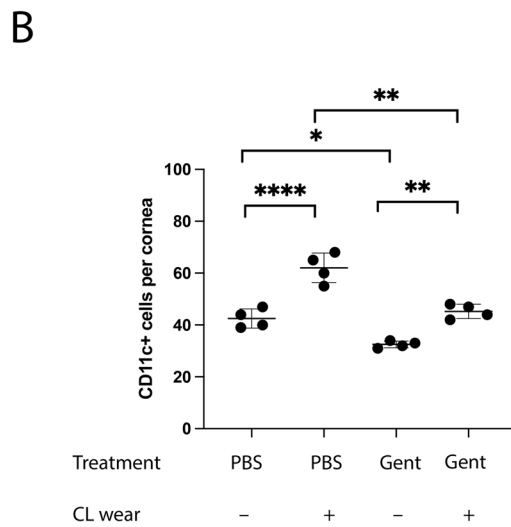
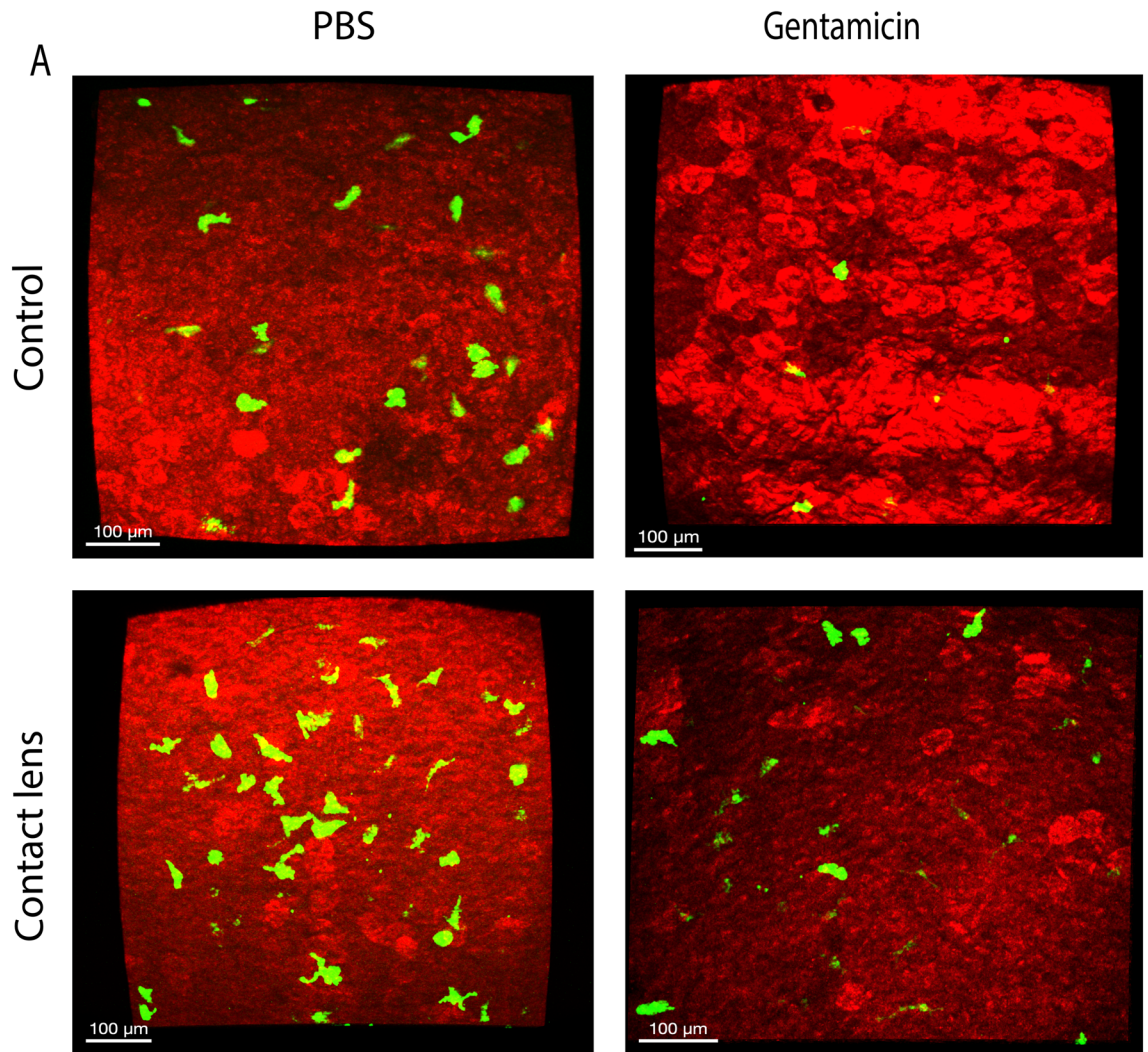


Figure 2. Gentamicin treatment did not prevent the 24 h CD11c+ cell response to contact lens wear. (A) Maximum intensity z-projection of the YFP signal from CD11c+ cells in the central cornea after 24 h of contact lens (CL) wear versus non-lens wearing contralateral controls with PBS or gentamicin treatment. (B) Quantification of the CD11c+ cell responses after 24 h. Lens-associated CD11c+ cell responses were evident in each instance. Scale bar = 100 μm (* $P < 0.05$, ** $P = 0.002$, **** $P < 0.0001$; One-way ANOVA with Tukey’s multiple comparisons test). (C) Quantification of morphological parameters (circularity) of CD11c+ cells from the same experiment. There was no significant difference between groups (*ns* not significant; One-way ANOVA with Tukey’s multiple comparisons test).

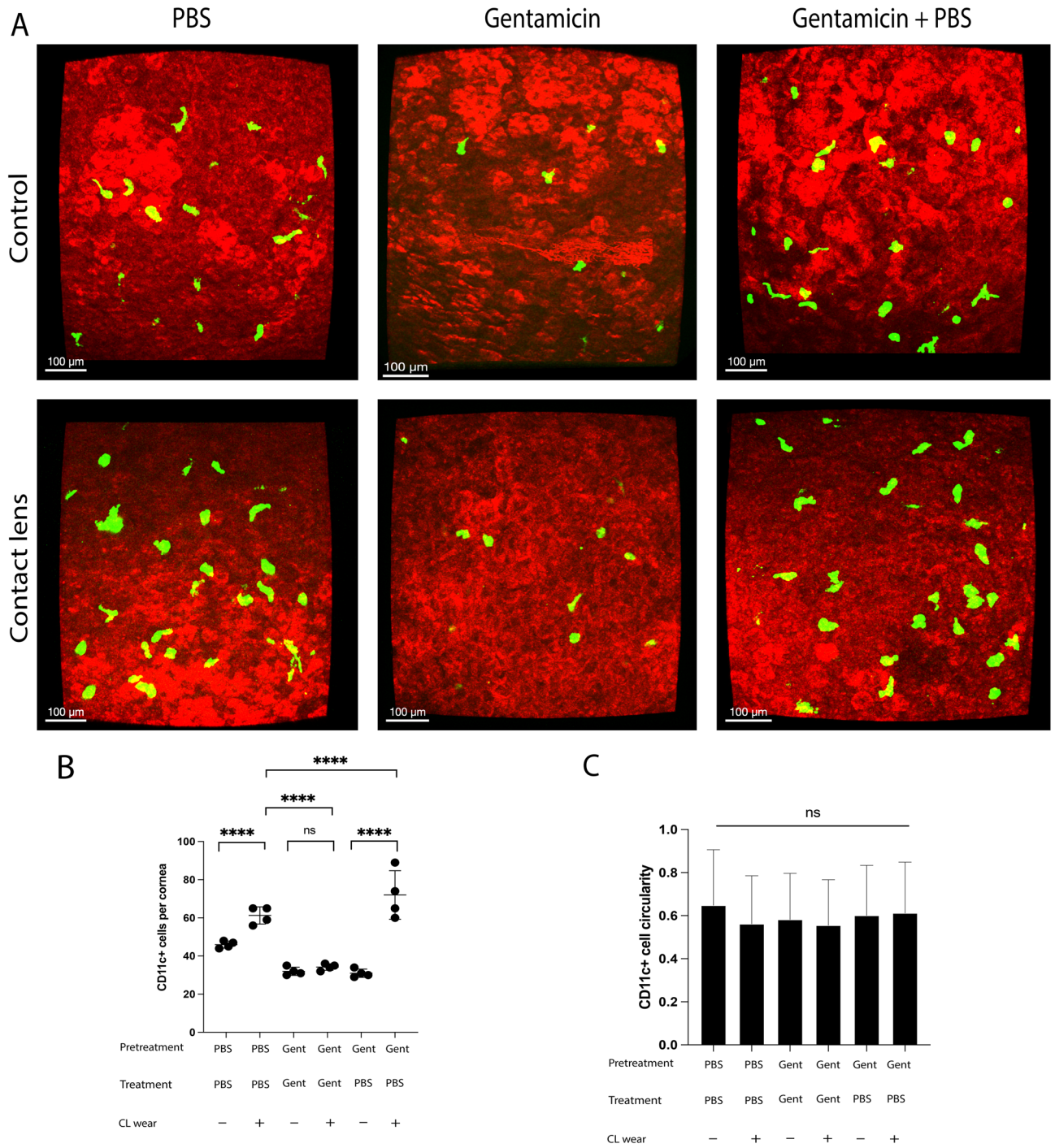


Figure 3. Contact lens-associated CD11c+ cell responses at 24 h are prevented by gentamicin pretreatment combined with continued gentamicin during lens wear. (A) Maximum intensity z-projection of the YFP signal from CD11c+ cells in the central cornea under different conditions of PBS or gentamicin pretreatment and treatment with or without contact lens (CL) wear. Lens-associated CD11c+ responses were prevented only if eyes were gentamicin pretreated combined with treatment during CL wear. Scale bar = 100 μ m. (B) Quantification of corneal CD11c+ cells under the above conditions (**** $P < 0.0001$, *ns* not significant; One-way ANOVA with Tukey’s multiple comparisons test). (C) Quantification of morphological parameters (circularity) of CD11c+ cells from the same experiment. There was no significant difference between groups (*ns* not significant; One-way ANOVA with Tukey’s multiple comparisons test).

labeling of worn lenses revealed bacterial binding to worn lenses but without a difference between groups (Supplemental Fig. S2). Thus, increases in corneal CD11c+ cell numbers associated with 24 h of contact lens wear (Figs. 2, 3) and their suppression by antibiotic treatment (Fig. 3) were not associated with any changes in the number of viable bacteria detected by FISH on the cornea or worn lenses.

Thus, the adjacent conjunctiva was examined using the same experimental conditions. AlkDala labeling alone was used given its distinctive (bacteria-specific) labeling of the filamentous conjunctival bacteria in mouse eyes observed in our previous studies^{14,23}, and because FISH labeling can be to be problematic for the conjunctiva¹⁴. The filamentous nature of the conjunctival bacterial population required quantifying area of alkDala fluorescence per field of view rather than individual bacterial cells. As shown in Fig. 4, there was a significant decrease in bacterial fluorescence in gentamicin-treated eyes versus PBS controls with and without contact lens wear, showing a reduction in the population detectable. These results suggested a potential relationship between the conjunctival population of commensals and the corneal CD11c+ cell responses during gentamicin treatment with and without lens wear (comparing Fig. 4A and B with Figs. 2B and 3B, respectively). Results of gentamicin removal following pretreatment also supported a relationship between conjunctival commensals and corneal CD11c+ cell responses to lens wear since eyes pretreated with gentamicin that were then PBS-treated showed a significant increase in bacterial fluorescence with lens wear versus their no lens control (Fig. 4B) that correlated with recovery of CD11c+ cell responses to lens wear (Fig. 3B). Interestingly, gentamicin-pretreatment followed by PBS treatment without lens wear showed a significant increase in baseline bacterial fluorescence similar to that of PBS-only treated eyes without a corresponding increase in corneal CD11c+ cells (compare Fig. 4B with Fig. 3B).

Addition of commensal conjunctival bacteria restores CD11c+ cell numbers in antibiotic treated murine corneas.

Having found that changes in corneal CD11c+ cells associated with gentamicin treatment and contact lens wear correlated with the detection of viable conjunctival bacteria using alkDala labeling, it was next explored if the CD11c+ response could be complemented using a conjunctival commensal inoculation. Thus, post-gentamicin treated eyes (healthy corneas) were inoculated in vivo with Gram-positive commensals (mouse-derived *C. mastitidis*, and human-derived coagulase-negative staphylococci). The opportunistic pathogen *P. aeruginosa* was also used since it can induce CD11c+ cell responses in mouse corneas¹³. After 4 h exposure to $\sim 10^{11}$ CFU/ml bacteria, corneal CD11c+ cell numbers were quantified ex vivo. Figure 5 shows that the exposure of previously gentamicin-treated eyes to Gram-positive commensal bacteria restored corneal CD11c+ numbers to the same level as control non-antibiotic treated eyes after bacterial challenge, i.e. showing that the reduction in CD11c+ cells induced by prior antibiotic treatment could be complemented by the addition of conjunctival commensals (Fig. 5). While *P. aeruginosa* also increased corneal CD11c+ cell numbers, levels in gentamicin treated eyes, remained below those of control untreated eyes suggesting a commensal is needed to complement the CD11c+ cell response after antibiotic treatment.

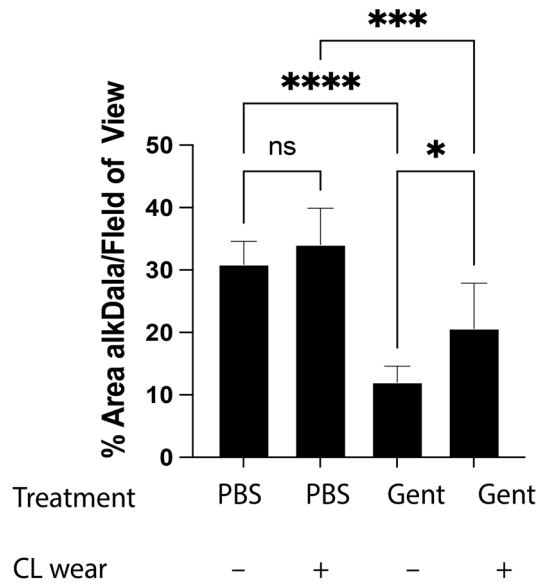
Discussion

Previously, we reported the development of a murine model of contact lens wear which showed lens-associated corneal parainflammation after 5–6 days of wear, that was preceded by infiltration of corneal CD11c+ (dendritic) cells after 24 h⁹. The latter response mimicked those observed for Langerhans cells during human lens wear^{12,24}. Here, the potential role of microbial triggers in contact lens-induced CD11c+ responses in the murine model was investigated. Using topical application of broad-spectrum antibiotics to target bacteria on the ocular surface and surrounding tissues (e.g. eyelids) with and without lens wear, results showed that antibiotic exposure reduced baseline CD11c+ cell levels in healthy corneas after 24 h and suppressed corneal CD11c+ cell responses to 24 h of contact lens wear but only if corneas were pretreated with antibiotic and treatment continued during lens wear. In both cases, this correlated with reduced numbers of viable conjunctival-associated bacteria. Adding commensal bacteria to antibiotic-treated eyes restored corneal CD11c+ cell numbers: not the case with addition of the potential pathogen *P. aeruginosa*. Together these findings suggest a role for ocular-associated commensal flora in maintaining CD11c+ cell homeostasis and in enabling contact lens-induced parainflammation. They also appear to be important for the induction of the CD11c+ response to *P. aeruginosa* challenge which contributes to resisting *P. aeruginosa* colonization if the cornea is superficially-injured¹³.

How might topical antibiotics mediate the CD11c+ phenotypes observed in this study? While a combination of ofloxacin and gentamicin was used initially, gentamicin alone was found effective. This is an aminoglycoside antibiotic, with bactericidal activity against many Gram-negative bacteria and some medically-important Gram-positive bacteria²⁵. Since there are very few viable bacteria on the murine cornea¹⁴ (confirmed in the present study), or on contact lenses, the most likely mechanism is that the antibiotic interfered with conjunctival commensals, either directly reducing their viability and/or interfering with their growth or metabolism. Indeed, there was a significant decrease in conjunctival alkDala (peptidoglycan cell wall) labeling after gentamicin treatment closely correlating with changes in baseline levels of CD11c+ cells and their responses to contact lens wear.

Involvement of conjunctival-associated commensals in the observed CD11c+ phenotypes would not be surprising as others have shown conjunctival-associated bacteria (*C. mastitidis*) to be important for corneal immune responses against *P. aeruginosa* infection via effects on gamma-delta T cells¹⁷. However, the CD11c+ cell response as a result of lens wear, a completely different phenotype occurring in healthy rather than diseased corneas, could involve different mechanisms. Indeed, other possibilities include that topical gentamicin affects commensal bacteria beyond the eye. The nasolacrimal drainage system exits the eye and drains tear fluid into the back of the nose and throat so topically added gentamicin solution at this very high concentration (3 mg/ml) could influence microbiota of the nasopharynx or intestinal tract, the latter well known to influence immune responses at distant mucosal sites including the conjunctiva^{26–28}. Another potential explanation is that topical gentamicin influenced corneal CD11c+ cell numbers and responses to lens wear independently of effects on

A



B

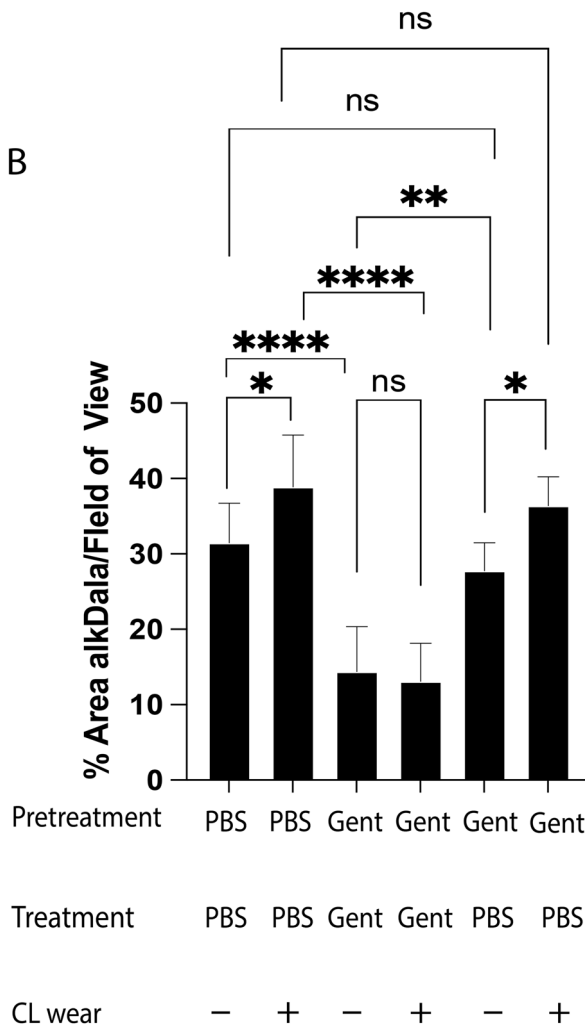


Figure 4. AlkDala labeling of viable conjunctival-associated bacteria. Quantification of alkDala (bacterial) fluorescence on the conjunctiva with (A) PBS or gentamicin treatment with contact lens (CL) wear for 24 h or (B) PBS or gentamicin pretreatment followed by the same treatments with or without CL wear. Gentamicin treatment/pretreatment was associated with decreased bacterial fluorescence on the conjunctiva with or without CL wear and these changes correlated with corneal CD11c+ changes under most respective conditions (* $P < 0.05$, **** $P < 0.0001$, *ns* not significant; Two-way ANOVA with Tukey’s multiple comparisons test).

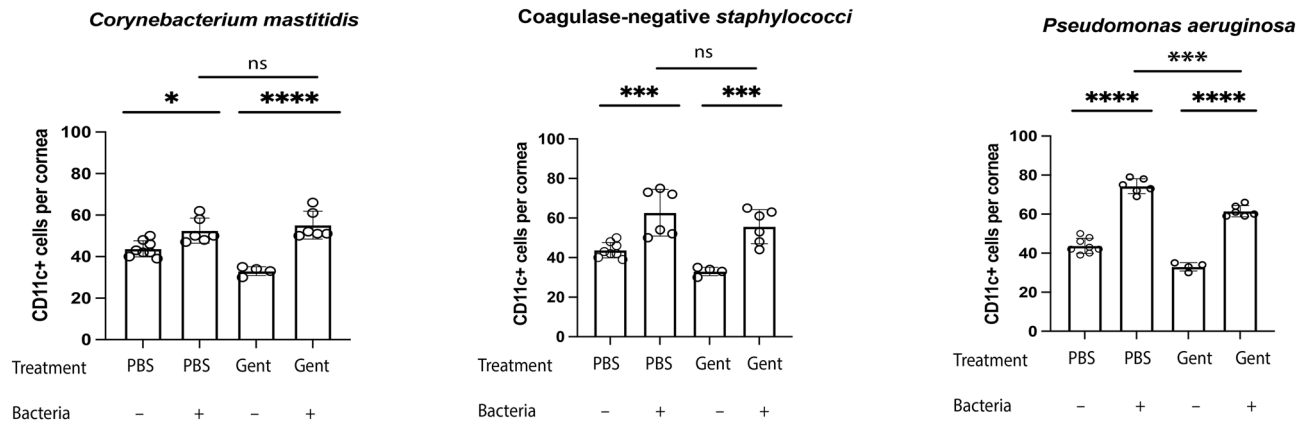


Figure 5. Quantification of corneal CD11c+ cells after inoculation with (A) *Corynebacterium mastitidis*, (B) Coagulase-negative *Staphylococci* or (C) *Pseudomonas aeruginosa* ($\sim 10^{11}$ CFU/ml) for 4 h beginning at 24 h after PBS or gentamicin treatment. Addition of Gram-positive commensal bacteria (A,B) increased CD11c+ numbers in antibiotic-treated corneas to levels similar to controls (* $P < 0.05$, *** $P < 0.001$, **** $P < 0.0001$, ns not significant; One-way ANOVA with Tukey's multiple comparisons test).

bacteria. Indeed, aminoglycosides and other antibiotics are known to have a multitude of direct impacts on immune cell function^{29–32}. Further studies will be needed to delineate the respective roles of bacteria, conjunctival or other, versus other potential mechanisms, in mediating the CD11c+ phenotypes observed.

Even if topical ocular gentamicin does mediate the CD11c+ phenotypes observed in our study via an impact on microbes, it cannot be assumed that bactericidal effects are exclusively involved. In this study, the presence of numerous filamentous forms of murine conjunctival bacteria¹⁴ necessitated the quantification of total alkDala (peptidoglycan cell wall) fluorescence rather than distinguishing individual bacterial cells. Thus, it remains possible that changes in alkDala fluorescence with gentamicin exposure resulted from reduced cell wall synthesis while bacteria remained viable. Another possibility is that gentamicin inhibited bacterial protein synthesis (part of its established mechanism of action²⁵) interfering with the expression of bacterial ligands, metabolites, or other secreted factors that mediate the CD11c+ responses. In this regard, the rapid return of CD11c+ responses to contact lens wear after gentamicin removal (Fig. 3B) is interesting and may reflect a rapid resumption of bacterial ligand/metabolite/secreted factor expression by conjunctival commensals. Consistent with this hypothesis, gentamicin removal was associated with a significant increase in alkDala fluorescence in lens wearing eyes versus controls (Fig. 4B). It is also interesting that baseline levels of CD11c+ cell numbers did not recover in the same time frame after gentamicin removal (Fig. 3B), despite a recovery of baseline alkDala fluorescence (Fig. 4B), suggesting the possibility that distinct mechanisms mediate these CD11c+ cell phenotypes. It is also possible that CD11c+ cell responses to lens wear reflect the presence of responsible bacterial factors trapped under or bound to the contact lens. Related to that possibility, some contact lens-associated CD11c+ responses (Figs. 2B, 3B) occurred with little or no observable increase in alkDala fluorescence of conjunctival commensals (Fig. 4A,B) suggesting that commensal bacteria involvement might not be via direct triggering of contact lens-associated CD11c+ cell responses. In other words, some other trigger associated with contact lens wear might instead stimulate already existing conjunctival commensals to drive lens-associated CD11c+ responses independently of peptidoglycan cell wall synthesis, e.g. expression of ligands, metabolites etc. Given how dramatically a contact lens can alter the ocular surface environment, conjunctival (or other) commensals may play an even more complex role being only one part of a system regulating responsiveness and homeostasis of corneal CD11c+ cells. Our results showing that gentamicin exposure reduced corneal CD11c+ responses to *P. aeruginosa* but not to known commensals (Fig. 5) would be consistent with a more complex mechanism.

In our original report showing contact lens induced corneal parainflammation in the lens wearing murine model, morphological observations and shape measurements of Lyz2+ immune cells in situ were helpful to infer differences in corneal cell sub-type(s) after 7 days of wear⁹. In the present study, CD11c+ cell circularity was measured after 24 h of lens wear since changes in morphology of these cells can indicate differences in activation and maturation state^{33–35}. No significant differences in CD11c+ cell circularity were observed between groups with or without 24 h of lens wear (or different protocols of antibiotic treatment) despite significant changes in cell numbers. However, this finding does not preclude differences in CD11c+ corneal phenotypes occurring under these conditions given the diversity of CD11c+ cells, and other antigen presenting cells, present in a healthy murine cornea, their ability to respond to numerous external signals, and a need to define cellular subsets using additional markers such as MHC Class II, B7 (CD80/CD86) and CD40^{2,3,36}.

A number of prior studies have investigated changes in corneal and conjunctival dendritic cells, or Langerhans cells (a subset of dendritic cells), during normal and symptomatic contact lens wear in humans^{10,11,37–39}. Subclinical increases in Langerhans cell density in the lens-wearing human cornea occur during the first few hours of lens wear, have led in part to the concept of contact lens associated corneal parainflammation¹², an asymptomatic state of heightened immune and inflammatory readiness that may be protective but also portend symptomatic and more serious adverse events. Results from this study, derived from a lens-wearing murine model of corneal parainflammation, show that topical antibiotic application modulates corneal CD11c+ cells influencing their

constitutive (baseline) levels and ability to respond to contact lens wear or *P. aeruginosa* challenge. While the results implicate commensal conjunctival bacteria in these CD11c+ phenotypes, further studies will be needed to determine the nature of their contribution which the data suggest might be complex. This study helps advance our understanding of CD11c+ cell homeostasis in the murine cornea and contact lens induced corneal parainflammation. Future studies using this model will also be of value in understanding the mechanisms, and predicting the consequences of, contact lens induced corneal parainflammation during different modes of lens wear in humans.

Methods

Mice. Transgenic wild-type C57BL/6 female mice (6–8 weeks old) were used that express both a CD11c-YFP reporter (CD11c-positive cells, e.g. dendritic cells, yellow) and *mT/mG* knock in (cell membranes, red)^{9,13}. At the end of each experiment, or if mice presented with excessive weight loss, distress, signs of keratitis, euthanasia was performed using isoflurane inhalation (5%) for 10 min, or combined administration (intra-peritoneal injection) of ketamine (80–100 mg/kg) and xylazine (5–10 mg/kg), either method followed by cervical dislocation. Eyes were enucleated for fixation and imaging. All procedures involving animals were carried out in accordance with the standards established by the Association for the Research in Vision and Ophthalmology, under a protocol AUP-2019-06-12322 approved by the Animal Care and Use Committee, University of California Berkeley. This protocol adheres to PHS policy on the humane care and use of laboratory animals, and the guide for the care and use of laboratory animals. This study is reported in accordance with the ARRIVE guidelines (Animals in Research: Reporting In-Vivo Experiments).

Topical antibiotic treatment. One or both eyes of each mouse were treated topically with a 5 µl drop of antibiotic solution: a combination (cocktail) of gentamicin and ofloxacin (Falcon Pharmaceuticals, Fort Worth, TX, USA) in solution (0.3% of each), or gentamicin alone in solution (0.3%) for 3 applications during time 0–6 h. Control eyes were treated with PBS. Eyes were examined for various phenotypes at 24 h. In some experiments, eyes were pretreated with antibiotic solution or PBS using the same timing prior to the above treatment.

Contact lens fitting. In some experiments, mice were fitted with custom-manufactured silicone hydrogel contact lens as previously described⁹. Contact lenses were fitted only onto the right eye and the contralateral eye used as a non-lens wearing control. Before fitting, contact lenses were removed from their packaging solution and soaked for 1 h in sterile phosphate buffered saline (PBS). After lens insertion under isoflurane anesthesia, mice were single-housed without enrichment to prevent lens removal. Pure-oCel paper bedding (The Andersons Inc., Maumee OH) was used to reduce dust level. For overnight lens wear mice were returned to the animal care facility. Mice were monitored daily for lens retention, and evidence of pathology, e.g. discharge or corneal opacity. Any mouse that lost its contact lens was excluded from further experimentation.

Fluorescein in-situ hybridization (FISH). FISH-labeling was performed as previously described using universal 16S rRNA-targeted gene [Alexa488]-GCTGCCTCCCGTAGGAGT-[Alexa488] (Eurofins Genomics)¹⁴. Contact lenses or enucleated eyes were fixed in paraformaldehyde (2%) for 24 h then stored in PBS at 4 °C until processed for FISH. Samples were washed in 80% EtOH, 95% EtOH then PBS for 10 min each with rotation, placed in hybridization buffer [NaCl (0.9 M), Tris-HCl (20 mM, pH 7.2) and SDS (0.01%)] for incubation (55 °C, 30 min), then incubated overnight at 55 °C with the 16S rRNA probe (100 nM). Samples were transferred to wash buffer solution [NaCl (0.9 M) and Tris-HCl (20 mM, PH 7.2)], then washed three times for 10 min each with rotation. For imaging, contact lenses were flat-mounted with Prolong Gold™ and eyes were whole-mounted in a 47 mm Petri dish filled with PBS to cover the eyeball completely. Bacteria were imaged and quantified using ImageJ with maximum intensity projections.

AlkDala (alkyne-functionalized D-alanine) labeling. Viable bacteria on the murine ocular surface were also labeled using an alkyne functionalized D-alanine (alkDala) biorthogonal probe as previously described^{14,40,41}. Freshly enucleated eyes were incubated in a solution of alkDala (10 mM) in Dulbecco's Modified Eagle Medium (DMEM) at 37 °C for 2 h then transferred to pre-chilled 70% EtOH then fixed for 20 min at –20 °C. After a thorough rinse in PBS, eyes were permeabilized in PBS with Triton-X100 (0.5%) for 10 min with shaking at room temperature and washed 3 times for 5 min each in PBS with Triton-X100 (0.1%) and BSA (3%) with shaking. Eyes were transferred to click-labeling cocktail [in PBS, TBTA (100 µM), CuSO₄ (1 mM), sodium ascorbate (2 mM), a 488 nm azide-fluorophore (10 µM), and BSA (0.1 mg/ml)] for 1 h with shaking at room temperature. Eyes were imaged as described below.

Imaging. Confocal imaging of the mouse cornea (whole eyes ex vivo), or worn contact lenses, was performed using a 20×/1.00 NA water-dipping objective with an upright Olympus Fluoview FV1000 microscope. Whole mounted eyes were imaged using a 512 nm laser for detection of CD11c+YFP cells (Yellow Fluorescence Protein) and a 559 nm laser for detecting red fluorescent cell membranes. A 488 nm laser was used to detect bacteria labeled with FISH or alkDala. For Z stacks at 1.00 µm steps, images were collected from 4 or more random fields per sample. 3-D image reconstruction (reducing a 3-D image into 2-D) was achieved by projecting the maximum intensity of each pixel in a specific channel to the z plane. Image-J (MorpholibJ tools collection) and Imapis (Bitplane) were used for image processing and analysis. To measure changes in the circularity of CD11c+ cells, one indicator of activation and maturation^{34–36}, morphological image analysis was performed using 3-D segmentation in ImageJ and parameters related to z-projections used (circularity) to exclude artifacts due to lower z resolution.

Bacteria. Three bacterial species were used in this study. *Corynebacterium mastitidis*¹⁷ (kindly provided by Dr. Anthony St. Leger, University of Pittsburgh, PA, USA), a clinical isolate of coagulase-negative *Staphylococcus* spp. and *Pseudomonas aeruginosa* strain PAO1F. Bacteria were grown on tryptic soy agar plates at 37 °C for ~16 h. A bacterial inoculum was prepared by suspension in PBS to a concentration of ~10¹¹ CFU/ml that was confirmed by viable counts. To inoculate mouse eyes, mice were anesthetized using ketamine (80–100 mg/kg) and dexmedetomidine (0.25–0.5 mg/kg) and the cornea of one eye was inoculated with 5 µl of bacterial suspension. An additional 5 µl of bacterial suspension was re-inoculated onto the corneas each hour up to 4 h (4 inoculations per eye in total). Mice remained anesthetized and covered under a heat lamp for the entire 4 h period. Subsequently, mice were subject to euthanasia and eyes examined by quantitative imaging.

Experimental procedures. *Procedure 1.* Mice were divided into experimental groups containing 3–4 mice. One group was treated with antibiotic solution (cocktail), another with gentamicin alone, in one eye as described above. Contralateral eyes were treated with PBS as a control. After 24 h, eyes were imaged ex vivo to measure corneal CD11c+ cell numbers or subject to FISH labeling to determine if viable bacteria were present.

Procedure 2. Two groups of 3–4 mice were used. One group was treated with gentamicin solution (timing as above) in both eyes, the other group similarly treated in both eyes with PBS as a control. For the antibiotic treated group, after the first application of antibiotic, contact lens fitting was performed on one eye followed by remaining antibiotic applications. Contralateral eyes served as non-lens wearing antibiotic-treated controls. The PBS control group was treated similarly. One eye fitted with a contact lens followed by remaining PBS applications; contralateral eyes served as non-lens wearing PBS-treated controls.

Procedure 3. Similar to Procedure 2 with two groups of 3–4 mice: antibiotic treated group versus PBS control group. However, prior to each experiment, each group was pretreated with either antibiotic or PBS with the same timing as used for the primary experiment. In some experiments, however, antibiotic pretreatment was followed by contact lens application with PBS or PBS alone.

Statistical analysis. Data analysis was performed using Prism 9.0 for Mac, Microsoft Excel 2010, and the Statistical Package for Social Science for Mac version 27.0 (SPSS, Inc, Chicago, IL, USA). The distribution of data was assessed by the normality test (Shapiro–Wilk test and Kolmogorov–Smirnov test), and since most data was normally distributed, it was expressed as the mean with standard deviation. One-way or Two-way ANOVA with Tukey's multiple comparisons test for post-hoc analysis. P values less than 0.05 were considered significant.

Data availability

All data generated or analyzed in this study are included in this published article and its Supplementary Information files.

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Author contributions

A.D., J.L., and T.T. performed the experiments. A.D., D.E. and S.F. analyzed the data. A.D., D.E. and S.F. wrote the manuscript. D.E. and S.F. designed the study and supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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