Phospholipase A₂ Activity in Normal and Staphylococcus aureus–Infected Rabbit Eyes

Dalia O. Girgis,¹ Joseph J. Dajcs,¹ and Richard J. O’Callaghan¹,²

PURPOSE. To quantify phospholipase A₂ (PLA₂) activity in normal rabbit eyes and in eyes with Staphylococcus aureus keratitis.

METHODS. PLA₂ was assayed by the killing of S. aureus at 33°C or by the release of arachidonic acid from S. aureus labeled with radioactive oleic acid. Rabbit corneas were intrastromally injected with 100 log phase colony-forming units (CFU) of S. aureus 8325-4. The activity of myeloperoxidase (MPO) and PLA₂ were quantified in ocular tissues.

RESULTS. The PLA₂-mediated killing of S. aureus by normal rabbit tears decreased by more than 70% as the rabbits aged from 10 to 28 weeks and by nearly 50% from early morning to afternoon. In rabbits with S. aureus keratitis, the activity of PLA₂ and MPO increased proportionally with time from 5 to 25 hours postinfection (PI), as measured in ocular tissues. PLA₂ activity increased fivefold in tears from infected eyes collected at 25 hours PI compared with normal tears (P ≤ 0.0001), whereas a ninefold increase was found in aqueous humor of infected eyes at 25 hours PI (P ≤ 0.0001). Infected eyes demonstrated a significant increase in MPO activity compared with uninfected eyes beginning at 10 hours PI for the aqueous humor (P = 0.05), at 16 hours PI for the tear film (P = 0.0024) and at 22 hours PI for the corneal homogenate (P = 0.0007).

CONCLUSIONS. The decrease in PLA₂ activity in the rabbit eye with age or after sleep and its increase during sleep or with the progression of infection are consistent with its role as an innate host defense factor. (Invest Ophthalmol Vis Sci. 2003;44: 197–202) DOI:10.1167/iovs.02-0548

The ocular tear film contains numerous components that serve as host defense molecules. This innate defense against bacteria has traditionally been attributed to complement, lysozyme, defensins, lactoferrin, and IgA.¹⁻⁷ However, group II phospholipase A₂ (PLA₂) is increasingly being recognized for its antibacterial activity against Gram-positive bacteria⁸⁻¹² and its important role as a defense molecule in the eye.¹³⁻¹⁵ PLA₂ is secreted from a number of cells,¹⁶ including polymorphonuclear leukocytes (PMNs), and is found at high concentrations in inflammatory fluids¹⁷ and human tears.¹³⁻¹⁸ Group II PLA₂ is present in platelets and numerous fluids and tissues, including Paneth cells, synovial fluid, seminal plasma, and prostatic gland cells.¹⁸⁻¹⁹ The mammalian secretory group II PLA₂ (14 kDa) is mobilized at sites of inflammation and exerts potent antibacterial activity against Gram-positive bacteria.²⁰ PLA₂ is also known to play a role in the initiation and propagation of inflammatory processes.²⁰

Numerous studies have been conducted in an attempt to elucidate the role of PLA₂ as a bacterial host defense molecule. Weiner et al.¹² and Dominiecki and Weiss⁹ have reported that PLA₂ from leukocytes can rapidly kill Staphylococcus aureus. Nevalainen et al.²¹ have demonstrated a high concentration of group II PLA₂ in tears (1.451 mg/L) of healthy individuals. In addition, the antibacterial properties of PLA₂, particularly against S. aureus, have been demonstrated in rabbit and human tears by Moreau et al.¹⁴ and Qu and Lehrer,¹⁵ respectively.

S. aureus is frequently associated with bacterial conjunctivitis and keratitis.²² S. aureus is the most common agent of bacterial keratitis in many human populations.²⁵⁻⁻²⁰ both in normal corneas and previously compromised corneas.²²⁻²⁴ S. aureus corneal infections occur primarily in contact lens wearers and patients with defects in their ocular immunity.²²⁻²⁷ Moreover, bacterial keratitis mediated by S. aureus is a serious condition that can result in loss of vision.²⁹⁻³⁰

Although S. aureus is a common corneal pathogen, efforts to achieve a corneal infection by application of these bacteria to scarified corneas have been unsuccessful. Whereas the topical application of Pseudomonas aeruginosa to a scarified rabbit cornea results in keratitis,³¹ S. aureus does not elicit keratitis in scarified rabbit eyes.³² Topical inoculation of large numbers of S. aureus on the scarified rabbit cornea can result in inflammation, but an actual infection with bacterial replication characteristic of keratitis is not produced. Moreau et al.³⁴ have shown that S. aureus is rapidly killed in the tear film and in vitro when incubated with rabbit tears, except when inhibitors of PLA₂ are present. Positively charged molecules, such as spermidine or certain topical anesthetics, can inhibit this bactericidal reaction of PLA₂ by binding to the bacterial surface.¹⁴ Spermidine has been found to protect bacteria in the tear film, allowing them to infect the scarified rabbit cornea.¹⁵

Because PLA₂ functions in such an important manner in protecting the cornea, further analyses of these reactions were undertaken in this study. The results demonstrate that the activity of PLA₂ in normal rabbit tears decreased with age and after periods of sleep, yet increased multifold in ocular tissues on infection with S. aureus.

METHODS

Bacterial Strains and Growth

S. aureus strain 8325-4 was used in this study and has previously been used in the rabbit intrastromal injection model of keratitis.³⁵⁻⁻³⁷ Bacteria were grown overnight in tryptic soy broth (TSB; Difco Laboratories, Detroit, MI) at 37°C and then subcultured to log phase (OD₆₅₀ = 0.3) under the same conditions.

Rabbits

New Zealand White rabbits used in these studies were maintained in accordance with the ARVO Statement for the Use of Animals in Oph-

From the ¹Department of Microbiology, Immunology, and Parasitology, Louisiana State University Health Sciences Center, New Orleans, Louisiana; and the ²Department of Ophthalmology, LSU Eye Center, New Orleans, Louisiana.

Supported by a National Eye Institute Grant R01 EY10974 with additional support from a Core Grant EY02377.

Accepted August 9, 2002.

Disclosure: D.O. Girgis, None; J.J. Dajcs, None; R.J. O’Callaghan, None.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked “advertisement” in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Richard J. O’Callaghan, Department of Microbiology, Immunology and Parasitology, LSU Health Sciences Center, 1901 Perdido Street, New Orleans, LA 70112; rcallagh@lsuhsc.edu.
Collection of Rabbit Tears
Microliter capillary pipettes were placed into the cul de sac of rabbit eyes and allowed to fill by capillary action. Volumes of 5 to 10 μL were collected from each eye at any one time point. Unless otherwise stated, tears were collected in the midmorning. Tears were not collected from any rabbit on two consecutive days.

To determine the effects of age on PLA₂ activity, tears were collected from both eyes of 10-week-old rabbits and subsequently collected every 4 weeks thereafter, for a total of 32 weeks. Tears collected from rabbits were pooled at each monthly interval and stored at −70°C until assayed.

To determine the effects of collection time on PLA₂ activity, tears were collected at one time point per day, with 2 days between before collecting tears from rabbits for the next time point. Tears were collected individually from both eyes of each rabbit and stored at −70°C until assayed.

Aqueous Humor Collection
A 26-gauge needle on a 1-mL syringe was inserted through the cornea into the anterior chamber of anesthetized rabbits and 0.1 mL of aqueous humor was removed.

Keratitis Model
S. aureus (100 CFU in 10 μL) was intrastromally injected into both eyes of rabbits that had been systemically anesthetized with ketamine and xylazine and topically anesthetized with proparacaine, as previously described. The inocula were plated onto tryptic soy agar (TSA; Difco) plates to confirm the number of colony-forming units injected. At various times post-infection (PI; 5, 10, 16, 22, and 25 hours), tears were collected by intravenous injection with a pentobarbital sodium solution (100 mg/mL; The Butler Co., Columbus, OH). Corneas were aseptically removed and homogenized as previously described. Briefly, corneal homogenates were serially diluted in sterile phosphate-buffered solution (PBS), aliquots (0.1 mL) were inoculated onto TSA plates and the plates incubated at 37°C for 24 hours. Colonies were counted, and colony-forming units per cornea were expressed as log values.

Myeloperoxidase Activity Assay
The amount of myeloperoxidase (MPO) activity was quantified in samples of ocular swabs, aqueous humor, and corneal homogenates, as described previously. Briefly, dilutions of samples of aqueous humor or tears (in triplicate) were added to wells containing BCA working buffer (Sigma). A set of protein standards of bovine serum albumin (BSA; Sigma) was prepared and added to wells containing buffer. After incubation at 37°C for 1 hour, the plate was cooled to room temperature before the absorbance was measured at 560 nm on a microtiter plate reader. A standard curve was prepared by plotting the average blank-corrected absorbance reading for each BSA standard versus its concentration in micromgs per milliliter. Using the standard curve, the protein concentration of aqueous humor or tear samples was determined.

Radioactive Labeling of S. aureus
S. aureus strain 8325-4 was radioactively labeled as previously described. Briefly, bacteria were grown overnight in M9 synthetic medium with amino acids, subcultured to log phase with 0.5 μCi/mL of 14C-labeled oleic acid, and then incubated at 37°C for 2.5 hours. After incubation, the bacteria were centrifuged, the supernatant removed, the bacterial pellet resuspended in TSB, and incubated for 30 minutes at 37°C. The bacteria were then washed in PBS with 1% BSA, resuspended in PBS, and stored at −70°C.

Determination of Phospholipase A₂ Activity
PLA₂ activity in tears and aqueous humor was determined using radioactively labeled S. aureus, as previously described. Briefly, radiolabeled bacteria were incubated with either tears or aqueous humor (or 1:5 dilution thereof in Tris-HCl buffer, pH 7.5), with 2 mM CaCl₂ added. The mixtures were incubated for 50 minutes at 37°C. Reactions were terminated with the addition of ice-cold BSA, and samples were centrifuged to pellet the bacteria. An aliquot of supernatant was used to quantify, by liquid scintillation counting, the products of hydrolysis as counts per minute (cpm). All assays were performed in triplicate.

The PLA₂ content of rabbit tears was also determined with a bacterial assay in which log phase 8325-4 grown in a modified M9 synthetic medium was used, as previously described. Bacteria (100–200 CFU in 15 μL) were mixed with rabbit tears (1–40 μL), and the mixtures were incubated at 35°C for 4 hours. After incubation, aliquots were cultured on TSA in triplicate. Controls included bacteria in M9 medium, PBS, or heat-inactivated tears (heated at 80°C for 5 minutes). The number of colony-forming units was determined from the colony count after 24 hours of incubation. All assays were performed in triplicate.

Statistical Analysis
The mean and the SEM for PLA₂ assays (colony-forming units per cornea, units of MPO, and protein concentration) were determined. Using the standard curve, the protein concentration of aqueous humor or tear samples was determined.

RESULTS

Effect of Age on PLA₂ Activity of Rabbit Tears
To analyze the role of PLA₂ in the bactericidal action of normal rabbit tears, tears were collected from rabbits (n = 4) at regular monthly intervals, and the survival of S. aureus mixed with these tears was determined. The bactericidal activity of the tears remained essentially equivalent from 10 to 18 weeks, declined significantly at week 24 (P ≤ 0.0001), and was undetectable in tears collected at week 28 (40 μL of tears; Fig. 1A).

PLA₂ activity in these tears was also determined by measuring the release of arachidonic acid from radioactively labeled S. aureus. Pooled tears collected from young rabbits (n = 4, 10 weeks old) demonstrated relatively large amounts of PLA₂ activity, as demonstrated by the counts per minute liberated. However, a significant decline in the amount of PLA₂ activity in tears was observed by 28 weeks (Fig. 1B, P = 0.0005), compared with those tears collected at 10 weeks of age and declined even further by 32 weeks of age (Fig. 1B, P ≤ 0.0001).
**Effect of Time of Day on PLA₂ Activity in Rabbit Tears**

To further explore aspects of PLA₂ activity, tears were collected from rabbits (n = 6) at six times during the day and night (3:30 AM, 7:30 AM, 11:30 AM, 3:30 PM, 7:30 PM, and 11:30 PM). The activity of rabbit tears in release of labeled arachidonic acid from bacterial membranes was tested using 14C-labeled *Staphylococcus aureus*, as previously described. Those tears collected early in the morning (3:30 AM) demonstrated significantly more release of radiolabeled arachidonic acid from bacterial membranes than did tears collected at 7:30 AM (P = 0.01), 11:30 AM (P = 0.01), 3:30 PM (P = 0.0075), 7:30 PM (P = 0.0003), and 11:30 PM (P = 0.01; Fig. 2).

**Effects of Keratitis on PLA₂ Activity, MPO Activity, and Protein Content**

The replication of *Staphylococcus* in rabbit corneas (n = 6 rabbits/group) reached 3 log CFU/cornea by 5 hours PI, nearly 7 log CFU/cornea by 16 hours PI, and maintained just over 7 log CFU/cornea up to 25 hours PI (Fig. 3A). The PLA₂ activity of tears or aqueous humor collected from infected rabbits (n = 6 rabbits/group) in cleaving arachidonic...

---

**Figure 1.** Effect of age on bactericidal and enzymatic PLA₂ activity in rabbit tears. (A) Tears (10, 20, or 40 µL) collected from rabbits (n = 4) at monthly intervals were incubated with log phase *Staphylococcus* for 4 hours, and the mixture was cultured to determine remaining colony-forming units. Controls for bacterial viability included bacteria incubated in M9 medium or PBS. The number of colony-forming units of bacteria remaining after incubation with inactivated tears (heated at 80°C for 5 minutes) was used to determine the maximum colony-forming units achievable without killing per volume of tears. Data are expressed as the mean ± SEM. (B) *Staphylococcus* labeled with 14C-oleic acid was incubated with rabbit tears at 33°C for 30 minutes. Reactions were terminated with the addition of BSA and then centrifuged to pellet bacteria. An aliquot of each supernatant was removed and radioactivity quantified by liquid scintillation counting as counts per minute. Data are expressed as the mean ± SEM.

**Figure 2.** Effect of the sleep cycle on PLA₂ activity in rabbit tears. The counts per minute released when 14C-labeled *Staphylococcus* was incubated with tears collected from rabbits (n = 6) at six different times during the day or night. Data are expressed as the mean ± SEM.
Acid from bacterial membranes was analyzed at 5, 10, 16, 22, and 25 hours PI. PLA2 activity in the tears of infected rabbit eyes, as measured by counts per minute, increased significantly by 22 hours PI compared with tears of normal rabbits (P = 0.0229), and demonstrated a fivefold increase in activity by 25 hours PI (P = 0.0001; Fig. 3B). PLA2 activity of infected aqueous humor increased significantly by 22 hours PI (P = 0.0027) and demonstrated a ninefold increase in activity by 25 hours PI (P = 0.0001; Fig. 3B).

Total protein concentration in tears and aqueous humor of S. aureus-infected rabbits (n = 6 rabbits/group) collected at 5, 10, 16, 22, and 25 hours PI was determined. Both tears and aqueous humor collected from infected rabbit eyes demonstrated an increase in total protein with progression of infection (Fig. 3C), correlating with the increased PLA2 activity in these two fluids.

The MPO activity of aqueous humor, ocular swabs, and corneal homogenates collected from each rabbit (n = 6 rabbits/group) at 5, 10, 16, 22, and 25 hours PI was assayed. The MPO activity in aqueous humor, ocular swabs, and corneal homogenates of infected eyes increased from 10 to 25 hours PI. Infected eyes demonstrated a significant increase in MPO activity compared with uninfected eyes beginning at 10 hours PI in the aqueous humor (P = 0.05), at 16 hours PI in the ocular tear film swabs (P = 0.0024), and at 22 hours in the corneal homogenates (P = 0.0007; Fig. 3D).

**DISCUSSION**

This study demonstrates the important role of PLA2 in killing S. aureus in the rabbit tear film and shows that this activity significantly declines with age, increases during sleep, and subsequently declines after periods of sleep. Furthermore, the results show that the PLA2 activity in the tears and aqueous humor increases in parallel with PMN concentrations (MPO activity) and protein increases in the tissue during S. aureus keratitis.

Previous findings by Morneau et al. demonstrated the ability of PLA2 in rabbit tears to kill S. aureus. The data presented herein show the bactericidal role of this enzyme in the tear film and also indicate that the bactericidal activity of this enzyme decreases with the age of the rabbit. The highest bactericidal activity was clearly observed in those tears collected from young rabbits, whereas the bactericidal activity declined significantly in those tears collected from aged rabbits. The results of the bactericidal assay correlated with those results obtained from the radioactive assay specific for PLA2, so that enzyme
activity declined significantly with age. Saari et al. demonstrated similar findings with tears collected from human subjects, demonstrating a decrease in PLA$_2$ concentration that occurred with an increase in age. These findings suggest that loss of this important ocular host defense could render the corneas of aged individuals more susceptible to S. aureus infection than the corneas of younger individuals.

The effects of the sleep cycle on the activity of PLA$_2$ in rabbit tears were also determined. Peaks in PLA$_2$ activity were noted in tears collected from rabbits in deep sleep, with a steady decline in activity noted as the day progressed, when rabbits were awake and active. These findings correlate with studies that suggest that the composition of the tear film varies between open-eye tears and closed-eye tears. The normal composition of tears that are collected from open eyes is primarily lysozyme, lactoferrin, lipocalin, and secretory IgA (sIgA). However, during sleep, there is a decrease in tear flow, and the concentration of total tear protein increases. The composition of the tear film is altered, so that sIgA concentrations increase, serum proteins (tear albumin, fibrinectin, and complement) increase, and there is a large recruitment of PMNs to the tear film. Because neutrophils are an established source of PLA$_2$, their influx into the tear film could serve as an important source of PLA$_2$ during sleep.

The role of PLA$_2$ was also analyzed during the progression of S. aureus keratitis. Activity of PLA$_2$ increased substantially, as measured in the aqueous humor and tear film collected from rabbits as the infection progressed. Increased PLA$_2$ activity also correlated with an increase in total protein concentration in these two fluids, although some of the increases in total protein could be due to increased colony-forming units at the later time points. Inflammation that is characteristic of keratitis in the rabbit model includes chemosis, injection, and accumulation of pus on the corneal surface. Soluble bacterial products, such as toxins, mediate tissue damage and induce host chemotactic agents, such as complement and cytokines, that are known mediators of ocular inflammation. In addition, inflammation may be due in part to the release of arachidonic acid after digestion of the bacterial inoculum by PLA$_2$.

The increase in PLA$_2$ activity in infected rabbit eyes probably reflects a common host response to changes in the ocular environment. Song et al. have demonstrated increased PLA$_2$ activity in the eyes of patients with chronic blepharitis. Tears collected from patients with blepharitis contained twice the PLA$_2$ activity of those of normal individuals. In addition, Aho et al. found a similar two-fold increase in PLA$_2$ activity in the eyes of patients with keratoconjunctivitis sicca.

The parallel increase in MPO and PLA$_2$ activity during infection suggests that PMNs are an important source of PLA$_2$ in the tear film, particularly in response to S. aureus keratitis. Sloop et al. have demonstrated that neutrophils in the tear film are derived in part from the eyelid, and that the eyelid-derived PMNs far exceed those that migrate into the cornea from the limbus during Staphylococcus keratitis. The present study confirms this point, in that the MPO activity of the tear film was several times higher than that of the corresponding corneal homogenate. These results are also supported by other studies that have demonstrated that neutrophils from the tear film are involved in inflammation of the cornea. In addition, one mechanism proposed by Song et al. for the increased PLA$_2$ activity observed in patients with chronic blepharitis suggests that PMNs responding to bacterial inflammatory factors migrate into the tear film and then release quantities of PLA$_2$.

In summary, this study has demonstrated factors that affect the host defense of the ocular tear film by altering the activity of phospholipase A$_2$. Factors that affect host defense include age and the sleep cycle, as well as the progression of keratitis mediated by S. aureus.

**Phospholipase A$_2$ and Staphylococcus aureus**

**Acknowledgments**

The authors thank Julian Reed and Quentin Booker for technical assistance with the research.

**References**

30. Alexandrakis G, Alfonso EC, Miller D. Shifting trends in bacterial
29. Ghabrial R, Climent A, Cevallos VE, Ostler BH. Laboratory results
27. Kerr N, Stern GA. Bacterial keratitis associated with vernal kerato-