The Diurnal Variation of Matrix Metalloproteinase-9 and Its Associated Factors in Human Tears

Maria Markoulli,1,2 Eric Papas,1,2,3 Nerida Cole,1,2,3 and Brien A. Holden1,2,3

PURPOSE. Matrix metalloproteinases (MMPs) are degrading enzymes which maintain and remodel tissue architecture. Upregulation of MMP-9 has been associated with corneal erosions and ulceration. As these conditions are often exacerbated on waking, suggesting that degrading activity is upregulated overnight, this study set out to determine the diurnal variation of MMP-9, Tissue Inhibitor of Metalloproteinase (TIMP)-1, and Neutrophil Gelatinase-Associated Lipocalin (NGAL).

METHODS. Tear samples were collected from 46 healthy, non-contact lens wearers at midday, before sleep, and immediately on waking. Total protein content (TPC) was measured using the bicinchoninic acid method, and MMP-9, TIMP-1, and NGAL concentrations were measured using sandwich enzyme-linked immunosassay. Statistical analysis was performed using repeated measures analysis of variance.

RESULTS. TPC was 3.4 ± 1.5 mg/mL, 5.0 ± 3.7 mg/mL, and 15.5 ± 8.4 mg/mL for midday, before sleep, and on waking respectively, the latter being significantly greater than the other two (P < 0.001). MMP-9 concentrations at the corresponding time points were 9.8 ± 14.3 ng/mL, 8.5 ± 11.7 ng/mL, and 2000.7 ± 1950.7 ng/mL. Again, the value on waking was significantly greater than the previous two visits (P < 0.001). TIMP-1 concentrations exceeded those of MMP-9 at midday but the ratio of the two reversed on awakening.

CONCLUSIONS. Concentrations of MMP-9 are negligible during the day and completely inhibited by TIMP-1. On awakening, MMP-9 increases 200-fold, an increase that is not completely inhibited by TIMP-1. This diurnal change, along with the presence of NGAL which protects MMP-9 from degradation, suggest that the closed eye is an environment conducive to extracellular matrix remodeling. (Invest Ophthalmol Vis Sci. 2012;53:1479–1484) DOI:10.1167/iovs.11-8365

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Matrix metalloproteinases (MMPs), also called matrixins, are a family of degrading enzymes whose function is to maintain and remodel the tissue architecture by their ability to degrade the structural proteins of the extracellular matrix (Blanco A, et al. IOVS 2008;49:ARVO E-Abstract 3404).1,2 They have been implicated in diverse physiological processes including embryonic development, tissue morphogenesis, and wound repair, as well as pathologic processes such as inflammatory diseases, epidermolysis bullosa,2 rheumatoid arthritis,2,3 and the progression of cancer due to the breakdown of the structural barriers.2

There are at least 23 MMPs and these can be grouped into subfamilies: collagenases,1–5 gelatinases,1 stromelysins,1 matrixins,4 and membrane-types.1 In the cornea, MMP-9, also known as gelatinase B, is the primary matrix-degrading enzyme produced by basal corneal epithelial cells6 and neutrophils7 and is known to degrade the major components of the epithelial basement membrane such as collagen type VIIb and impede re-epithelialization of the cornea.9 As the fibrils responsible for anchoring the basement membrane to the stroma are composed of type VII collagen, an upregulation in MMP-9 may result in a weakening of these attachments, contributing to the cascade of events resulting in corneal erosion.10,11 An upregulation of MMP-9 has been associated with the epithelial defect in corneal ulceration6,12 as well as in corneas with ocular rosacea,9 keratoconus,13 and pterygia.14

MMP-9 can be inhibited, and hence regulated, by binding to tissue Inhibitor of metalloproteinase (TIMP)-1.15 The MMP/TIMP ratio is an indicator of the regulation of matrix degradation and an imbalance in this ratio toward excess MMP-9 may result in collagen degrading effects.16 Neutrophil Gelatinase-Associated Lipocalin (NGAL) which has a number of possible roles in the tear film17–19 can also bind to MMP-9 when released from neutrophils. Its role however is thought to be protective of MMP-9 degradation, thereby increasing its activity.18

Conditions such as recurrent corneal erosions and corneal infections, as well as contact lens-related adverse events, are exacerbated on waking, suggesting that degrading activity is upregulated overnight. Thus it is essential to understand how MMP-9 and its associated factors, vary as a function of the diurnal cycle in healthy individuals and what levels are tolerated by the ocular surface. This study therefore set out to establish the diurnal variation of MMP-9, TIMP-1, and NGAL, in the healthy ocular surface.

MATERIALS AND METHODS

Study Participants

This study was approved by the Institutional Ethics Committee of the University of New South Wales (UNSW) for the first 37 participants (Approval numbers: 08/H055 and 08/H056) and the Vision CRC and Institute for Eye Research Ethics Committee (VIHEC) Human Ethics Committee with ratification from UNSW for the last nine participants (Approval number 10/09 and Human Research Ethics Committee...
Tears were collected by instilling a 60–cein evaluation and lid eversion were conducted after flush tear collection while fluorescein were conducted before flush tear collection. As such, visual acuity and evaluation of the cornea and conjunctiva without impact on the ocular surface before flush tear collection. As such, assessed on awakening. The order of tests was such to minimize the impact on the ocular surface before flush tear collection. As such, visual acuity and evaluation of the cornea and conjunctiva without fluorescein were conducted before flush tear collection while fluorescein evaluation and lid eversion were conducted after flush tear collection.

Flush Tear Collection. Flush tears as described previously were collected from both eyes of nine participants at midday and on awakening, on two separate days so that day-to-day repeatability could be assessed.

Clinical Techniques

Visual acuity using computer letter charts and slit lamp biomicroscopy (Zeiss SL-120, Carl Zeiss Meditec, Jena, Germany) was performed at midday to exclude any pre-existing conditions. Bulbar and limbal redness as well as palpebral redness and roughness were assessed with white light and corneal and conjunctival staining in conjunction with fluorescein (Fluorets ophthalmic strips, 1 mg, Chauvin Pharmaceuticals, Essex, England) and a filter (Wratten #12; Bausch & Lomb, Rochester, NY). The Brien Holden Vision Institute Grading scales were used. Bulbar and limbal redness were also assessed on awakening. The order of tests was such to minimize the impact on the ocular surface before flush tear collection. As such, visual acuity and evaluation of the cornea and conjunctiva without fluorescein were conducted before flush tear collection while fluorescein evaluation and lid eversion were conducted after flush tear collection.

Sample Treatment

After collection, samples were centrifuged at 1145 g force for 20 minutes at 4°C to remove cellular debris. The supernatants were collected and stored in siliconized polypropylene microcentrifuge tubes (Sigma-Aldrich) at −80°C in four aliquots, one for each analysis.

Total Protein Content

Total protein content (TPC) was determined using the bichinchoninic acid (BCA) method and using reagents (Pierce; Thermo Fisher Scientific) and flat-bottom 96-well microplates (Nunc-F Maxisorp; Thermo Fisher Scientific). Serial dilutions of bovine serum albumin (BSA) were used as standard. This was loaded in triplicate starting at 2 mg/mL down to 0.1 mg/mL in ultrapure laboratory grade water (MilliQ; Millipore, Billerica, MA) and 0.1 µL was added to each well. Tear samples were loaded at a 1:10 dilution. Tears were analyzed in duplicate and a 10 µL volume was added to each well. Solution A (BCA Protein Assay Reagent A; Pierce, Thermo Fisher Scientific) and solution B (BCA Protein Assay Reagent B; Pierce, Thermo Fisher Scientific) were combined in respective volumes of 20 mL and 0.4 mL. This mixture was then added at a volume of 200 µL per well. The optical density was read with a microplate reader (Spectra Fluor Plus, Tecan Multifunction Microplate reader using the X-Fluor 4 software; Tecan, Männedorf, Switzerland) at 595 nm after 30 minutes and a standard linear curve generated using the BSA as a reference.

MMP-9, TIMP-1, and NGAL Analysis

Total MMP-9 concentration (92 kDa pro- and 82 kDa active forms), TIMP-1 and NGAL concentration were each determined using sandwich enzyme-linked immunosorbent assay (ELISA) with an ELISA development kit (Duoset kit; R&D Systems, Inc., Minneapolis, MN). These were performed according to the manufacturer’s directions.

Gelatin Zymography

Gelatinolytic activity of MMP-9 was determined using gelatin zymography. Ten micrograms of each tear sample was added to 5 µL of sodium dodecyl sulfate (SDS) sample buffer (2× Novex Tris-Glycine; Invitrogen, Carlsbad, CA) and the volume was made up to 12 µL with ultrapure laboratory grade water (MilliQ, Millipore). A concentration of 50 mg/mL of MMP-9 standard (R&D Systems) was activated by incubating with 1 mM 4-aminophenylmercuric acetate (APMA; Sigma-Alrich, Steinheim, Germany) and stored in siliconized polypropylene microcentrifuge tube of 0.65 mL capacity (Sigma-Aldrich, Steinheim, Germany) and placed on ice until processing. A limit of 1 minute was imposed to avoid reflex tearing. All three visits were conducted consecutively. For on awakening, participants slept overnight in the clinic. In the evening before this visit, participants were informed that they would be woken up at an allocated time as agreed by both the Optometrist (MM) doing the tear collection and the participant. They were also advised that should they wake, not to open their eyes unless instructed to do so by the Optometrist. In the morning, they were awakened and instructed not to open their eyes as they were lead to the clinic chair. On instruction, the participants were asked to open their eyes and flush tear collection would commence immediately under dim lighting. All participants were questioned as to whether they had opened their eyes before instruction. In this case, the results were excluded from the analysis. The order of eyes for flush tear collection was randomized. This technique was previously validated for MMP-9 analysis.

Study Design

Diurnal Study. This was a prospective, bilateral clinical study. A baseline visit (midday) was conducted between 11 AM and 2 PM whereby baseline measurements were taken before flush tear collection from both eyes of 46 participants. Participants were asked to stay overnight in the clinic and tears were collected again before sleep and immediately on awakening. All samples were collected by the same investigator (MM, trained and experienced in the technique for several years at this institute).

Day-To-Day Repeatability Study. Tears were collected from both eyes of nine participants at midday and on awakening, on two separate days so that day-to-day repeatability could be assessed.

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Each sample was resolved using 10% zymogram gelatin gel (Novex; Invitrogen) under denaturing but nonreducing conditions. Gels were electrophoresed at a constant voltage of 120 V for 3.5 hours in running buffer (glycine, Tris base and 1% SDS) at 4°C. As proteolytic activity can be reversibly inhibited by SDS during electrophoresis and recovered by incubating the gel in aqueous Triton X-100, the gels were washed with 2.5% (vol/vol) Triton X-100 (Astral Scientific, Amresco, Solon, OH) for 1 hour. This was then decanted and the gels were equilibrated with developing buffer (Novex zymogram developing buffer; Invitrogen) for 30 minutes. The gels were then transferred to

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Table 1. Flush Tear Collection Rate (Mean ± SD)

<table>
<thead>
<tr>
<th>Visit</th>
<th>Flush Tear Collection Rate (µL/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midday (n = 46)</td>
<td>22.8 ± 10.8</td>
</tr>
<tr>
<td>Before sleep (n = 37)</td>
<td>27.9 ± 17.1</td>
</tr>
<tr>
<td>Upon awakening (n = 46)</td>
<td>22.4 ± 12.6</td>
</tr>
</tbody>
</table>

Before sleep was significantly greater than that at both the midday (P = 0.048) and upon awakening (P = 0.02) visits.

Table 2. The Coefficient of Repeatability for Eyes and Days for Each of the Proteins Measured

<table>
<thead>
<tr>
<th>Visit</th>
<th>Variable</th>
<th>Coefficient of Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eyes (n = 37)</td>
<td>Days (n = 9)</td>
</tr>
<tr>
<td>Midday</td>
<td>TPC (mg/mL)</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>MMP9 (ng/mL)</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>TIMP-1 (ng/mL)</td>
<td>91.9</td>
</tr>
<tr>
<td></td>
<td>NGAL (ng/mL)</td>
<td>—</td>
</tr>
<tr>
<td>Before sleep</td>
<td>TPC (mg/mL)</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>MMP9 (ng/mL)</td>
<td>19.9</td>
</tr>
<tr>
<td>Upon awakening</td>
<td>TPC (mg/mL)</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>MMP9 (ng/mL)</td>
<td>4548.1</td>
</tr>
<tr>
<td></td>
<td>TIMP-1 (ng/mL)</td>
<td>307.6</td>
</tr>
<tr>
<td></td>
<td>NGAL (ng/mL)</td>
<td>—</td>
</tr>
</tbody>
</table>

Repeatability

Coefficients of repeatability were calculated at each time point and for each protein between replicates taken from the two eyes of each subject when randomized (Table 2). There were no significant differences between eyes.

Day-to-day repeatability was determined from the pooled tears of nine participants. Of the proteins measured only NGAL at midday was significantly different (P = 0.03). Table 2 lists the coefficients of repeatability.

As the eyes and days were not significantly different, except for NGAL, these were averaged and repeated measures was performed on this to determine the diurnal variation.

Diurnal Variation

Table 3 lists the concentrations of the proteins measured at each time point. TPC was significantly greater on awakening than at midday and before sleep (P < 0.001) and midday and before sleep were also significantly different from each other (P = 0.03).

The concentration of MMP-9 was significantly greater on awakening compared with both midday and on awakening (P < 0.001) and midday and before sleep were not significantly different (P = 0.6).

TIMP-1 was measured as it is the main inhibitor of MMP-9. Concentrations were significantly greater on awakening compared with midday (P < 0.001). The MMP-9/TIMP-1 ratio provides an indication of the potential for MMP-9 to cause tissue damage. The MMP-9/TIMP-1 ratio was significantly greater on awakening than at midday (P < 0.001). These ratios indicate that at midday, the concentration of TIMP-1 exceeded that of MMP-9, hence completely inhibiting MMP-9. In contrast, on awakening the ratio indicates that this balance is reversed, with an excess of MMP-9 in the tear film, indicating a shift from TIMP-1 dominance during the day to MMP-9 dominance on awakening. NGAL was significantly elevated on awakening compared with midday (P = 0.002). When considered as an MMP-9/TIMP-1 ratio, the concentration of NGAL was significantly greater on awakening than at midday and before sleep (P < 0.001).

Table 3. The Diurnal Variation of Each of the Proteins Measured in the Tear Film

<table>
<thead>
<tr>
<th>Visit</th>
<th>TPC (mg/mL)</th>
<th>MMP9 (ng/mL)</th>
<th>TIMP-1 (ng/mL)</th>
<th>MMP9/TIMP-1 Ratio</th>
<th>NGAL (ng/mL)</th>
<th>MMP9:NGAL Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midday</td>
<td>3.4 ± 1.5</td>
<td>9.8 ± 14.3</td>
<td>74.5 ± 39.7</td>
<td>0.3 ± 0.4</td>
<td>680.8 ± 523.3</td>
<td>0.01 ± 0.04</td>
</tr>
<tr>
<td>Before sleep</td>
<td>5.0 ± 3.7</td>
<td>8.5 ± 11.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Upon awakening</td>
<td>15.5 ± 8.4</td>
<td>2000.7 ± 1950.7</td>
<td>277.8 ± 282.2</td>
<td>13.9 ± 15.8</td>
<td>3620.3 ± 1832.1</td>
<td>0.16 ± 0.14</td>
</tr>
</tbody>
</table>

Data are shown as mean ± SD; n = 46 except for NGAL and MMP9:NGAL ratio, where n = 9, and before sleep where n = 37. Brackets denote statistical significance (P < 0.05). Exact P values are reported in the text.
NGAL ratio, the ratio on awakening was significantly greater than that at midday \( (P = 0.006) \). At both the midday and on awakening visits, NGAL exceeded the concentration of MMP-9 present in the tear film.

Sex was not significantly different for TPC, MMP-9, NGAL or TIMP-1 and its ratio with MMP-9 \( (P = 0.86, 0.13, 0.39, \text{and } 0.23 \) respectively). The ratio of MMP-9 to NGAL showed a significant difference between the sexes, with males having a significantly greater ratio on awakening than the females and the reverse at midday \( (P = 0.048) \).

### Zymography

Figure 1 shows a Coomassie Blue-stained gel of tear samples of two non-contact lens wearing participants at midday and on awakening. The bands against the stained gelatin background are areas of gelatinolytic activity.\(^{27}\) Overnight closure resulted in prominent bands at 92, 135, and \( > 200 \) kDa (Fig. 1, lanes 2 to 5). These bands are consistent with those previously identified by others and correspond to pro-MMP-9, NGAL, or \( \alpha_\text{2} \)-macroglobulin complexes not dissociated by SDS, and a dimer of MMP-9, respectively.\(^{30-33} \) At midday (Fig. 1, lanes 6 to 9), faint bands were detected at 135 kDa and 92 kDa, corresponding to the MMP-9 complex and pro-MMP-9 respectively. The difference between the on awakening lanes and the midday lanes is consistent with the diurnal variation of MMP-9 measured with ELISA.

### Clinical Correlation

Correlation analysis did not show any association between changes in clinical signs and TPC or MMP-9. A significant, though weak, positive correlation was found between TIMP-1 and limbal redness \( (R = 0.44; P = 0.04) \). A significant positive correlation was also found between age and the diurnal change in NGAL \( (R = 0.83; P = 0.01) \).

### DISCUSSION

MMP-9 is a vital but potentially destructive enzyme by virtue of its ability to degrade corneal collagen. Control of this activity is thus critical to maintaining corneal health. When the eyes are open, there is little cause for concern as, in agreement with previous studies,\(^{6,8-10,15} \) these data suggest that MMP-9 concentrations are negligible and significantly exceeded by those of the inhibitor molecule TIMP-1. The potential for proteolytic activity is thus inhibited and hence the corneal epithelium and basement membrane are protected from degradation.

During sleep however, this situation changes dramatically as MMP-9 concentration increases roughly 200-fold, while TIMP-1 barely triples. The shift in the balance from TIMP-1 to MMP-9 dominance, which may be a downstream effect of increased neutrophil activity,\(^{7,24} \) suggests that there may be an increased propensity for basement membrane degradation overnight. This is further supported by the excess NGAL in the tear film compared with MMP-9, both at midday and on awakening, a finding that is in agreement with previous studies.\(^{7} \) While this diurnal variation may be necessary to facilitate increased cell desquamation during sleep, or it may be that this increase in MMP-9 is a byproduct of epithelial cell breakdown during eye closure, it also apparently sets the scene for tissue destruction by virtue of the excess MMP-9 present. In reality however, such tissue damage was not evident among the participants in this study, nor does it typically occur overnight in the general population. Clearly then, our understanding of the regulatory mechanisms of MMP-9 in the tear film is incomplete.

Looking at the zymography results indicates that the MMP-9 in the closed-eye tear film is in thezymogen form rather than the active form (Fig. 1), suggesting that this may be one contributory factor. Additionally, some MMP-9 was detected at molecular weights in excess of 220 kDa indicating it to be in the dimeric state which does not differ in enzymatic activity from the inactive form at 92 kDa.\(^{30} \) It may also be that MMP-9 is being regulated by nonspecific inhibitors such as \( \alpha_\text{2} \)-macroglobulin which traps activated MMP so that the complex can be removed by the receptor.\(^{34} \)

Many conditions such as recurrent corneal erosions and corneal ulcers are known to be exacerbated by eye closure.\(^{35} \) Due to its action on collagen and hence the anchoring complexes of the corneal epithelium, MMP-9 could contribute to the increased incidence of recurrent erosions by virtue of its diurnal variation, particularly when the regulatory mechanisms are not controlled.\(^{11,36} \) The diurnal profile of MMP-9 and its associated factors could also indicate why the epithelium is particularly prone to erosion and infection with overnight contact lens wear,\(^{37,38} \) as well as corneal ulceration\(^{10,12,13,39} \) and corneal desiccation on awakening.

MMP-9 concentration in the tears varies considerably within the population at any given time as demonstrated by the coefficients of repeatability presented in Table 2. This may be...
in part attributable to the variability in the flush tear collection rate as shown in Table 1. The lack of correlation with clinical signs of redness suggests that this ubiquitous sign of ocular distress is not particularly helpful as a marker for raised MMP-9 levels however. It may also be that this presence of elevated levels of the inactive form of MMP-9 does not produce redness because it does not constitute an insult to the ocular surface.

Finally, it may be that these results also have implications for certain topical therapies, in particular the use of prostaglandin analogues. These compounds are used for the treatment of glaucoma and work by increasing the concentration of MMP-9 as a means of degrading ciliary muscle extracellular matrix and increasing uveoscleral outflow. Concurrent increased MMP-9 concentrations have also been found in the tear film, increasing the potential for corneal damage as has been found in both animal and human studies. It may then be advisable to adjust the instillation timing for prostaglandin drops to avoid the periods before sleep and immediately on awakening, particularly for those already prone to corneal erosions.

In conclusion, this study has shown that there is a substantial diurnal variation of MMP-9 and its associated factors. Concentrations of MMP-9 are negligible during the day and completely inhibited by TIMP-1. On awakening MMP-9 increases 200-fold, an increase that is not completely inhibited by TIMP-1. This diurnal change, along with the presence of NGAL, suggests that the closed eye is an environment conducive to extracellular matrix remodeling. The fact that we typically do not see corneal damage on awakening suggests that other regulatory mechanisms are active to prevent excess extracellular matrix degradation.

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References


