Relationship Between Tear Volume and Tear Meniscus Curvature

Norihiko Yokoi, MD, PhD; Anthony J. Bron, FRCOphth; John M. Tiffany, PhD; Kunio Maruyama, BS; Aoi Komuro, MD, PhD; Shigeru Kinoshita, MD, PhD

Objective: To investigate the relationship between tear volume and tear meniscus curvature by means of the video meniscometer.

Methods: Eleven eyes of 11 patients with severe dry eye were studied (all female; mean±SD age, 66.2±7.7 years; 7 left eyes and 4 right eyes), each of whose puncta had been therapeutically occluded. Four instillations of balanced salt solution were given at intervals of 1 minute in each studied eye, with the concentration increasing in 5-µL steps from 5 to 20 µL. Before and after the instillation of balanced salt solution, tear meniscus changes were recorded by video meniscometer and radius of the meniscus was calculated from the printed images by means of the concave mirror formula.

Results: The mean radius of the meniscus increased linearly with increased drop volume ($r^2=0.65, P<.001$), with mean±SD radius values of 0.24±0.08 mm at baseline and 0.48±0.13, 0.62±0.13, 0.84±0.26, and 1.00±0.32 mm after separate instillations of 5, 10, 15, and 20 µL of balanced salt solution, respectively. For each subject, a significantly different slope defining the relationship between instilled volume and meniscus radius was seen (0.016-0.063 mm/µL; mean±SD, 0.039±0.015 mm/µL), which was thought to depend on the difference in capacity of the fluid reservoir over the ocular surface.

Conclusions: This study confirmed that the volume of instilled eyedrops is linearly related to the resulting radius of the tear meniscus, suggesting that this radius is a useful measure in monitoring the tear volume. This is likely to have implications both for dry eye diagnosis and for confirming the efficacy of punctal occlusion in this condition.

Arch Ophthalmol. 2004;122:1265-1269

In human eyes, the total tear volume is distributed among 3 continuous compartments: the culs-de-sac, menisci, and precorneal film. The menisci act as a reservoir supplying fluid from which the precorneal film is re-formed at each blink. They also accommodate the excess tears that accumulate with reflex tearing, from lacrimal drainage obstruction, or after drop instillation. The meniscus and tear film are held in place by interfacial forces. Tear volume is positively correlated with lacrimal secretory rate, and meniscus volume is reduced in tear-deficient dry eye. Hence, knowledge of meniscus volume may be useful in the diagnosis of dry eye. Also, in dry eye, meniscus radius can be informative about the efficacy of punctal occlusion, either directly or by demonstrating impaired clearance of an instilled drop.

Reflective meniscometry is a noninvasive technique for the measurement of tear meniscus curvature. The method, which uses a specular reflection technique, projects a target onto the concave, mirrorlike surface of the meniscus, and the size of the reflected image is used to calculate its radius of curvature. With certain assumptions as to the sagittal profile of the meniscus, radius of curvature can be used to estimate meniscus volume.

Recently, a video-based system (the video meniscometer) has been developed and used to demonstrate a significant relationship between the meniscus radius and height. Both measures have been used in the diagnosis of dry eye. The present study aims to assess the relationship between radius of tear meniscus and total tear volume.

METHODS

SUBJECTS

In this study, 11 women with severe dry eyes were enrolled (mean±SD age, 66.2±7.7 years;
range, 58-85 years). For each patient, one eye was randomly selected for study (7 left eyes and 4 right eyes). The 11 patients included 8 with Sjögren syndrome, diagnosed on the basis of the Fox criteria, and 3 patients with non-Sjögren tear-deficient dry eye. All patients either had had upper and lower punctal plugs successfully inserted (8 eyes; Ready-Set M-size Punctum Plug; FCI Ophthalmics, Issy-les-Moulineaux, France), or had undergone upper and lower surgical punctal occlusion by cautery or suture closure (3 eyes). All eyes showed the severest form of dry eye, with a diminished Schirmer I test value (mean ± SD, 1.5 ± 2.5 mm in 5 minutes) and, before occlusion, severe corneal fluorescein staining scores (A3D3 in 8 eyes, A3D2 in 2 eyes, and A2D3 in 1 eye, where A represents area and D, density, scored from 0 to 3 depending on the severity) and a total rose bengal staining score (mean ± SD) of 7.1 ± 2.2 for the cornea and nasal and temporal bulbar conjunctiva. Before punctal occlusion, the patients had been treated with a combination of preservative-free artificial tears containing 0.1% potassium chloride and 0.4% sodium chloride (Softsantear; Santen Pharmaceutical Co, Ltd, Osaka, Japan) and hyaluronate sodium ophthalmic solution (Hyalein-Mini 0.1; Santen Pharmaceutical Co, Ltd) with little improvement.

METHODS

In this study, we used video meniscometry as a noninvasive method to observe and quantify tear meniscus curvature at the center of the lower eyelid margin. The system comprises an illuminated target, CCD camera, video recorder, and video printer. The horizontally striped target is projected onto the center of the lower meniscus, which behaves like a cylindrical, concave mirror. The line separation in the reflected image is used to calculate meniscus curvature by means of the concave mirror formula.

The target consists of a series of black metal bars, 4 mm wide and 4 mm apart, set in front of the objective lens and illuminated from behind. A half-silvered mirror, introduced into the optical pathway, permits coaxial viewing and image capture as well as back illumination of the target. The reflected image appears as a series of black and white stripes. For the purpose of calculating the radius of the tear meniscus, selected meniscus images were printed (print magnification, ×70). In normal subjects, in the absence of drop instillation and with the subject blinking spontaneously, the reflective images of the target are highly stable over time.

To evaluate the relationship between radius of tear meniscus and instilled fluid volume, 4 instillations of balanced salt solution (BSS) were given at intervals of 1 minute into the selected eye of each subject in 5-µL steps, increasing from 5 to 20 µL (ie, 5, 10, 15, and 20 µL). After each instillation, patients were allowed to blink spontaneously for 30 seconds, after which tear meniscus behavior was recorded with the video meniscometer. After the meniscus appearance was recorded, the radius was calculated from the video printed images. The procedure for monitoring tear meniscus behavior at the center of the lower eyelid margin in a typical subject's eye is shown schematically in Figure 1.

The results were expressed as mean ± SD. Regression analysis was used to estimate the straight-line relationship between the radius of tear meniscus and the accumulated volume of instilled eyedrops in each patient. Differences in slopes of the regression line between patients were analyzed by analysis of covariance with volume of eyedrops as a covariate. P ≤ .05 was considered to be significant.

RESULTS

Before drop instillation, the mean baseline meniscus radius was 0.24 ± 0.08 mm. After the cumulative instillation of 5, 10, 15, and 20 µL of BSS, the mean meniscus radius was calculated to be 0.48 ± 0.13, 0.62 ± 0.13, 0.84 ± 0.26, and 1.00 ± 0.32 mm, respectively. A representative example of the change in meniscus image after successive instillation of BSS is shown in Figure 2.

The mean radius increased linearly with total volume instilled (r² = 0.65, P < .001; y = 0.038x + 0.256, where y = radius [in millimeters] and x = total volume of instilled BSS [in microliters], Figure 3). The significant regression between radius and total volume instilled was found for each subject individually (0.039 ± 0.015 mm/µL [0.016-0.063 mm/µL], Table 1 and Figure 4). Also, analysis of covariance showed that there was a signifi-
cant interaction between volume of eyedrops and patients \( (F=12.33, P<.001; \text{Table 2}) \), implying that slopes of regression line between patients were significantly different.

**COMMENT**

One view of tear-deficient dry eye is that it is the result of an autoimmune inflammatory process that destroys lacrimal tissue or function and results in reduced tear secretion.\(^{16}\) The autoimmune process can result, directly or indirectly, in inflammatory events at the ocular surface, particularly the conjunctiva, and lead to tear hyperosmolarity due to evaporation from a reduced aqueous pool. Hyperosmolarity itself leads to surface inflammation.\(^{16-19}\) In tear-deficient dry eye, a reduced tear flow leads to a reduced tear volume. It has been suggested that this in turn leads to a thinning of the precorneal tear film\(^{20}\) and that this is the major factor leading to hyperosmolarity.\(^{17-19,21}\) A mathematical relationship between meniscus curvature and tear film thickness has been proposed,\(^{20,22}\) and for this reason alone, we would expect meniscus curvature to be of diagnostic value in dry eye. In this study, we attempted to show in addition that meniscus curvature, which relates to its volume, is an index of total tear volume. This again would support its potential value in diagnosis of dry eye.

For the purposes of discussion, the term *total tear volume* will be used to mean the aggregate volume of tears distributed between the culs-de-sac, menisci, and precorneal tear film.\(^1\) Meniscus volume is chiefly regulated by the balance between lacrimal secretion and tear drainage, with evaporation playing a minor role. Evaporation is, however, of increasing importance in

---

### Table 1. Regression Between Radius of Meniscus and Total Volume of Instilled BSS

<table>
<thead>
<tr>
<th>Patient No./Eye/ Sex/Age, y</th>
<th>Regression Line ( y = ax + b )</th>
<th>( r^2 )</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/L/F/58</td>
<td>( y = 0.063x + 0.224 )</td>
<td>0.93</td>
<td>.008</td>
</tr>
<tr>
<td>2/L/F/67</td>
<td>( y = 0.020x + 0.256 )</td>
<td>0.97</td>
<td>.003</td>
</tr>
<tr>
<td>3/L/F/60</td>
<td>( y = 0.041x + 0.255 )</td>
<td>0.95</td>
<td>.005</td>
</tr>
<tr>
<td>4/R/F/74</td>
<td>( y = 0.036x + 0.166 )</td>
<td>0.98</td>
<td>.001</td>
</tr>
<tr>
<td>5/L/F/85</td>
<td>( y = 0.016x + 0.318 )</td>
<td>0.96</td>
<td>.003</td>
</tr>
<tr>
<td>6/R/F/66</td>
<td>( y = 0.023x + 0.223 )</td>
<td>1.00</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>7/L/F/61</td>
<td>( y = 0.021x + 0.350 )</td>
<td>0.98</td>
<td>.002</td>
</tr>
<tr>
<td>8/L/F/66</td>
<td>( y = 0.057x + 0.398 )</td>
<td>0.99</td>
<td>.001</td>
</tr>
<tr>
<td>9/L/F/66</td>
<td>( y = 0.032x + 0.304 )</td>
<td>0.93</td>
<td>.008</td>
</tr>
<tr>
<td>10/R/F/65</td>
<td>( y = 0.046x + 0.153 )</td>
<td>0.98</td>
<td>.001</td>
</tr>
<tr>
<td>11/R/F/60</td>
<td>( y = 0.033x + 0.172 )</td>
<td>0.96</td>
<td>.003</td>
</tr>
</tbody>
</table>

Abbreviations: BSS, balanced saline solution; \( x \), total volume of instilled BSS; \( y \), radius of meniscus.
dry eye and becomes the dominant feature of evaporative dry eye.23-26

   The present study aimed to assess the relationship between tear meniscus radius and total tear volume under conditions in which total tear volume could be increased incrementally. This was achieved by studying a group of aqueous-deficient patients with severe dry eye, whose tear secretion was minimal (as indicated by the Schirmer I values before the punctal occlusion), and lacrimal drainage was completely obstructed by punctal occlusion. In this situation it was reasonably assumed that the total volume of fluid bathing the ocular surface was determined chiefly by the experimental instillation of BSS. Evaporation was assumed to have a negligible effect on tear volume during the short time course of the study. Relative to the total volume of BSS instilled, the evaporative loss during the course of the study, calculated according to a previous study27 for a dry eye population, would be about 0.23 µL per eye, which would be unlikely to have a major effect on the outcome of the study.

   As mentioned in the “Results” section, a linear relationship was shown between the radius of the lower central tear meniscus and the cumulative volume of instilled fluid, both in the total group (Figure 3) and in individual subjects (Figure 4, Table 1), indicating that the radius of curvature of the meniscus reflects the total volume of tears distributed between the tear compartments at any one time. These findings allow the general conclusion to be drawn that meniscus radius values derived from measurements over a small region of the lower central tear meniscus are probably generalizable to the whole meniscus reservoir, and that the radius is not significantly influenced by any change in surface active properties of the tear fluid28 due to dilution.

   Extrapolation of the group mean regression line to the x-axis in Figure 3, where the radius is notionally zero, may be interpreted to reflect the baseline total volume of tear fluid distributed in sac and film. This value was 6.7 µL for the group. If we take the reported average radius value in normal subjects to be 0.365 mm, using the same video meniscometric technique, then the relationship plotted for the group in Figure 3 shows that this radius would correspond to an additional volume of 2.9 µL above the baseline value for the dry eye group. If the baseline total dry eye volume (6.7 µL) is added to this additional volume (2.9 µL), the sum (9.6 µL) is close to the value reported previously1 for the tear volume in the normal eye. We recognize that this is a crude estimate, but we submit it here to show how such a calculation could be used in the future with more refined techniques.

   Figure 4 demonstrates important individual differences between the patients with dry eye in this study. It should be noted that radius values differed between subjects and that for some subjects these values fell within the reference range. This raises the possibility that these subjects did not comply with instructions not to instill or artificial tear substitutes on the day of study or that artificial tear preparation instilled before the day of the experiment remained on the eye because of the complete occlusion of the puncta. Also, not only do basal radius values differ between patients, but the slopes of the regression lines also significantly differ (0.039±0.015 mm/µL [0.016-0.063 mm/µL], Table 2), implying that the instilled volumes of BSS were accommodated into compartments of differing properties. The most likely factor that might influence these slopes would be cul-de-sac size and physical properties, with surface tension and tear viscosity also playing a small role. Since the tear sacs are not rigid compartments, it might be assumed that elastic factors would influence the response to added volume and that this might be modified by disease.

   The differences in individual slopes of the radius-volume curves draw attention to the likelihood that the same meniscus radii in 2 different individuals may not imply the same total tear volume, probably reflecting differences in sac capacity. On the other hand, in a given individual, changes in radius will directly relate to changes in total tear volume. This is of importance in relation to studies of tear clearance or in clinical trials, particularly of lacrimal secretagogues.

   In summary, the present study indicates that meniscus curvature is an index of total tear volume, while mathematical considerations suggest that it predicts tear film thickness.21,22 These observations support the theoretical value of meniscus curvature measurement and of video meniscometry in the diagnosis of dry eye. We will show elsewhere that the same technology can be used to confirm the efficacy of punctal occlusion in this condition.

Submitted for publication July 17, 2003; final revision received November 17, 2003; accepted April 6, 2004.

This study was supported in part by grants-in-aid for scientific research from the Japanese Ministry of Health, Labor, and Welfare and the Japanese Ministry of Education, Culture, Sports, Science, and Technology (Tokyo) and by research grants from the Kyoto Foundation for the Promotion of Medical Science, the Intramural Research Fund of Kyoto Prefectural University of Medicine (Kyoto, Japan).

This study was presented in part at the annual meeting of the Association for Research in Vision and Ophthalmology, April 30, 2000; Ft Lauderdale, Fla.

We thank Tatsuo Terashima and Kousei Terasaki (Biostatistics Department, Santen Pharmaceutical Co Ltd, Osaka, Japan) for statistical assistance.

Table 2. Analysis of Covariance

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sum of Squares</th>
<th>Variance</th>
<th>F Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients*</td>
<td>10</td>
<td>1.34</td>
<td>0.13</td>
</tr>
<tr>
<td>Volume of eyedrops*</td>
<td>1</td>
<td>3.94</td>
<td>3.94</td>
</tr>
<tr>
<td>Volume of eyedrops × patients*</td>
<td>10</td>
<td>0.61</td>
<td>0.06</td>
</tr>
<tr>
<td>Error</td>
<td>33</td>
<td>0.16</td>
<td>0.01</td>
</tr>
<tr>
<td>Total</td>
<td>54</td>
<td>6.06</td>
<td></td>
</tr>
</tbody>
</table>

Indicates factor was significant by analysis of covariance (P<.001).
REFERENCES