

The Watery Eye

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Abstract The surface of the eye needs to be wet constantly to ensure its integrity in maintaining ocular comfort, clear vision, and ocular health. This article presents new findings in the tear dynamics of the human eye, with an emphasis on the tear meniscus and tear film through the day and in response to punctual occlusion and wearing of contact lenses. Recent advances in imaging technique are briefly discussed.

Keywords Tear film · Tear meniscus · Ocular surface · Dry eye · Tearing · Ocular comfort · Contact lens · Punctual occlusion · Optical coherence tomography · Diurnal variation · Post-lens tear film

Introduction

The tear system of the human eye involves tear secretion, distribution, evaporation, and drainage [1, 2]. The system apparently has some degree of autoregulation, which limits

the volume of tears on the ocular surface—not too much and not too little—to maintain the integrity of the ocular surface [1, 3•]. Being wet all the time throughout the day is essential for ocular health, ocular comfort, and sharp vision [3•, 4]. Nutrition for the ocular surface, especially for the cornea, is transferred by the tears, and debris is also removed through the tear system [3•, 5].

Three components hold the tears on the ocular surface: upper and lower tear menisci and tear film on the ocular surface (Fig. 1). These components are linked during blinking and may be separated during the eye-opening period. Some evidence has shown the linkage between upper and lower tear menisci through the canaliculi all the time [1, 3•, 5, 6]. Eye blinking redistributes the tears from the tear meniscus to form the tear film [5, 6]. An abnormal tear dynamic system resulting from the lack of tears and/or excessive tear loss due to hyper-evaporation may result in symptoms of dry eye [5, 7].

Regulation of the Tear System

Eye blinking makes the tear system highly dynamic with each cycle of tear secretion: mixing, distribution, and drainage [1, 2]. Tears from the upper and lower tear menisci are redistributed to form the pre-corneal tear film (PCTF) on the ocular surface during each blink [1, 8–10] and thus protect the ocular surface [11]. Periodic renewal of the PCTF on the ocular surface relies on an adequate supply of tears and on the blinking pattern [12]. In dry eyes, decreases in tear quantity and quality result in tear volume insufficiency [13] and tear film instability [13–15], which can potentially result in damage to the ocular surface [13, 14]. Patients with aqueous tear deficiency (ATD) also have reduced tear meniscus dynamics [16]. However, not much

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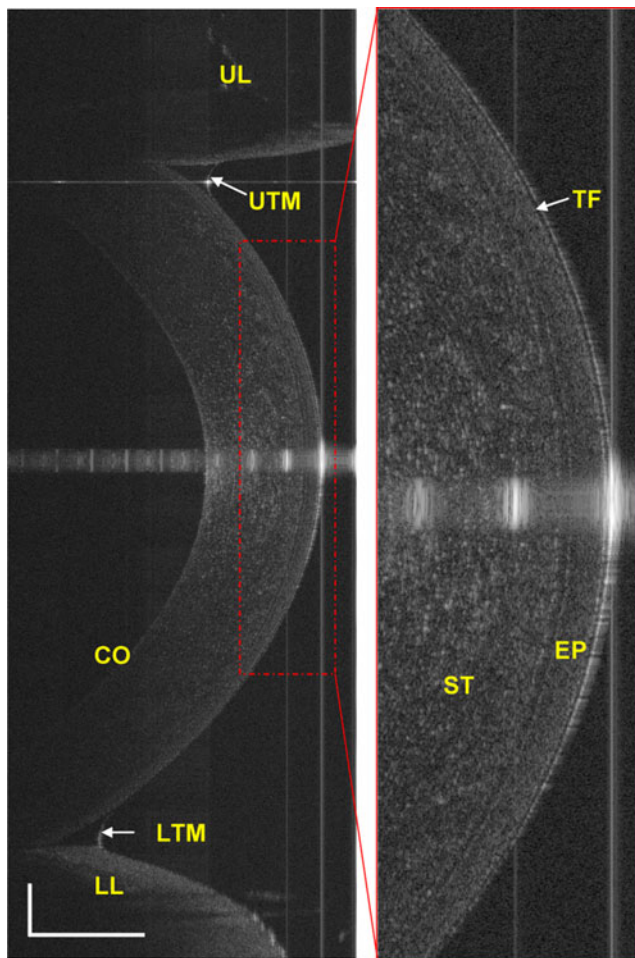


Fig 1 Tears on the ocular surface. A healthy human eye was imaged with ultra-high resolution optical coherence tomography on the vertical meridian. The upper (UL) and lower (LL) lids, cornea (CO), upper tear meniscus (UTM), and lower tear meniscus (LTM) were clearly visualized. The enlarged sectional image shows the pre-corneal tear film (TF), epithelium (EP), and stroma (ST) (bars=500 μm)

is known about PCTF thickness in dry eye patients. This lack of information is mainly due to the instability and irregularity of the tear film itself and the inability to evaluate this micrometer-thin tear film layer in cases of dry eye.

Imaging Methods of the Tear Film and Tear Meniscus

As a noninvasive and noncontact method, optical coherence tomography (OCT) has been used to diagnose dry eye [7] and assess the tear meniscus dynamics in healthy and dry eye patients [16]. Ultra-high resolution OCT (UHR-OCT) has made it possible to visualize the PCTF (Fig. 1), tear films on contact lenses, and further details of the ocular surface [17•, 18, 19•]. Other methods for estimating the tear film include interferometry [20•] and reflectance

spectra [21]. Tearscope was also used to quantitatively estimate the thickness of the tear lipid layer [22].

A new technique for evaluating the tear film on contact lenses has been demonstrated using optical reflectometry technique [23]. We have configured an optical reflectometer to evaluate the thickness of water film on the contact lens and its thinning process. With white light illuminating on the water and contact surfaces, the multiple air–water and water–contact lens surface reflection and transmission results in a spectral-dependent reflectance. The evaluation of such spectral-dependent reflectance via an optical spectrometer and the reflectometer software that performs curve fitting using known water (or tear) and contact lens complex refractive indices can reveal the water (or tear) film thickness. The thickness variation as a function of time results in the water film thinning process that can reveal the tear dynamics of a contact lens wearer. The thickness measurement resolution of the optical reflectometer is on the order of nanometers to tens of nanometers, which is much more accurate than all conventional OCT techniques.

Dry Eye and Tear Film

Dry eye is ocular surface disease resulting from the lack of tear volume due to low tear secretion or excessive tear loss caused by evaporation [24]. Ocular discomfort and irritation are common. With aqueous tear deficiency (ATD), patients normally have lower tear volume on the ocular surface, mainly on both upper and lower tear menisci around the upper and lower eyelids [7]. Patients also have slow tear dynamics as detected with OCT [16].

The PCTF plays a critical role in maintaining the integrity of the ocular surface. It ensures the sharpest vision [11], protects the ocular surface against infection [11], and provides for lubrication to minimize or avoid the damage from shear forces between the eyelids and the corneal epithelium incurred during eye blinking [5, 25]. Evaluating the quality and quantity of the PCTF helps us to estimate the health of the ocular surface, especially in dry eye disease [26]. Many measurements have been used to determine the thickness of the PCTF [21, 27–30]. Using invasive methods, the PCTF has been reported to be between 4 [27, 28] and 8 μm [29]. Compared with the limitation of the invasive procedures, noninvasive methods may provide a better assessment of the PCTF. King-Smith et al. [21] investigated the PCTF using interferometric methods and reported that the normal tear film thickness is approximately 3 μm . As another noninvasive method to evaluate the PCTF, Chen et al. [17•] used UHR-OCT to measure the dynamic changes of tear film on contact lenses. UHR-OCT was considered a promising tool for measuring the PCTF in dry eye patients.

The PCTF thickness of dry eye patients during normal blinking was thinner than that in healthy eyes, as reported by Palakuru et al. [12] and others [20•]. In dry eye patients, reduced tear secretion is strongly evident [24, 31–33]. Smaller tear menisci variables were found by Yuan et al. [16] in dry eye patients compared with healthy individuals. Thus, the deficient tear volume may form a thinner PCTF in dry eyes [20•]. Wang et al. [8, 34] reported that the average thickness of the PCTF was 3.3 μm in healthy eyes. Due to reflex tearing, the balance of tear secretion and drainage in healthy eyes is altered during delayed blinking [9]. Also, during delayed blinking, the increased rate of secretion is accompanied by a reduced rate of drainage [9, 10]. Consequently, the tear menisci are increased significantly during delayed blinking [12, 16]. In healthy eyes, Palakuru et al. [12] found no significant difference in PCTF thickness between normal and delayed blinks. However, the resolution of the time domain OCT that they used was insufficient to detect the small changes. In dry eye patients, the average PCTF thickness determined by UHR-OCT was 5.7 μm immediately after delayed blinking, which was higher than after normal blinking. The increase in thickness during delayed blinking may be associated with increases in the tear menisci. Although the increase in tear menisci was smaller than in healthy individuals during delayed blinking [16], the same results were reported by Farris and associates [35], who found that dry eye patients were deficient in basal and reflex tears.

During the interblink period, tear fluid secreted by reflex appears in the upper tear meniscus, and then flows to the lower tear meniscus via the lid junctions [1]. During this period, there is no flow or transfer of fluid from the marginal tears in the menisci to the corneal surface. This indicates that the thickness of the PCTF depends on the amount of tears in the menisci at the moment that the blink starts. Due to the micrometer-thin PCTF itself, a small increase in tears may give rise to a visible increase in the PCTF, although under conditions of reduced tear secretion in dry eye patients.

Tears with Blinking

Blinking plays a role in tear dynamics whether it is normal or delayed [1, 3•, 6, 16]. During normal blinking, the upper meniscus is smaller than the lower meniscus. Both upper tear meniscus volume (UTMV) and lower tear meniscus volume (LTMV) in healthy individuals decreased after blinking compared with before blinking, and increased during the open eye period. However, the UTMV showed no significant changes in relation to blinking in healthy or dry eyes, whereas blink outcome and open eye outcomes of the lower tear meniscus were significantly smaller in dry eyes compared with healthy eyes.

Reflex tearing occurs during delayed blinking, and significant changes occur in the tear volume of the lower tear meniscus, whereas few changes occur in the upper tear meniscus. The inability of the upper tear meniscus to hold much fluid may be due to its structure and the aid of gravity, as the upper tear meniscus remained relatively unchanged when limited tears were added. During delayed blinking, the open eye outcomes of the UTMV and LTMV were also significantly increased in healthy individuals and greater than those of dry eye patients.

Blinking facilitates removal of excessive tears [3•, 6]. When a large amount of tears was added (eg, the instillation of a drop of artificial tears), the upper and lower tear menisci increased in volume, with most of the changes in the lower tear meniscus [3•]. After the instillation, a blinking-induced decrease in the LTMV caused tear loss in total tear volume. However, the blink outcome of the upper tear meniscus remained virtually unchanged. At the end of the eye-opening period, LTMV increased significantly, with no significant changes in total tear volume. Immediately after the instillation, net loss was evident in LTMV and total tear volume during the blink cycle, which was defined as the period beginning with the action of blinking and after the open eye period up to the next blink. In short, the tear menisci appear to respond differently to blinking when a large amount of tears is added as compared with the addition of limited tears.

Diurnal Variation of the Tear System

The tear system is subject to diurnal variation [4]. Tear film is essential to the maintenance of the eye's health, comfort, and optical quality. The tear film must be renewed with each blink. Structural failure of the tear film results in symptoms of "dry eye syndrome," such as ocular discomfort and visual distortion.

In healthy individuals, the tear system is highly dynamic, and alterations in the tear menisci occur during blinking. In the Shen et al. [4] study, both upper and lower tear menisci increased at eye opening after overnight sleep compared with the baseline before sleep and kept increasing up to 10 min, which indicated that there is a diurnal change in the upper and lower tear menisci in healthy individuals.

The deficient tear volume may change the tear dynamics in dry eye patients and make them different from those of healthy individuals. Shen et al. [7] measured the upper tear meniscus in dry eye patients for the first time using real time OCT. In their study, both upper and lower tear menisci were found to be decreased in ATD patients compared with healthy individuals. They also found that lower tear meniscus variables were more sensitive and specific than the upper ones in the diagnosis of ATD patients.

Using a similar device, Yuan et al. [16] investigated the tear meniscus dynamics during the blink cycle in ATD patients. They also reported that tear meniscus volume decreased in ATD patients during the normal blink cycle. In addition, ATD patients had a smaller increase in tear volume than healthy individuals during delayed blinking. These results may suggest that lower tear secretion and the possible reduction or shutting down of the tear drainage system in ATD or other types of dry eye may be induced by the reduction of tear meniscus dynamics.

Tear Dynamics After Punctal Occlusion

Chen et al. [36] investigated the tear meniscus volume in dry eye after punctal occlusion using real time OCT. They occluded both upper and lower puncta with collagen plugs on 1 eye each in 20 dry eye patients and 20 healthy individuals. Both UTMV and LTMV increased in dry eye patients after punctal occlusion; however, short-term punctal occlusion (10-day period) had no effect on tear volume in healthy individuals. These results may suggest that an autoregulatory mechanism exists in the tear system. This mechanism leads to reduced tear secretion after punctal occlusion and prevents flooding of the eye with tears. Chen et al. [37] also compared the effectiveness of upper punctal occlusion and lower punctal occlusion in dry eye treatment. They occluded with collagen plugs on one eye's upper punctum and the contralateral eye's lower punctum in 20 dry eye patients and 20 healthy individuals. They found that subjective symptoms were relieved and objective signs were improved in dry eye patients after mono-occlusion of the upper or lower punctum. The effectiveness of upper and lower punctal occlusion is similar. Very recently, Hosaka et al. [20] investigated the tear film thickness in ATD patients using tear interferometry and compared it with that of healthy individuals, finding that ATD patients had thinner tear film thickness. After punctal occlusion surgery, tear film thickness increased in the ATD patients.

Tear Dynamics in Contact Lens Wearers

Wearing contact lenses alters the tear system [17, 18, 19, 38, 39]. Chen et al. [38, 39] investigated the tear meniscus volumes in soft contact lens wearers with dryness symptoms. They recruited three groups: SCL wearers with self-reported dryness, asymptomatic wearers, and asymptomatic non-lens wearers. In a short time study (30 min of lens wear), they found lower volumes of tear menisci in contact lens wearers with dry eye symptoms. The lower tear menisci may have contributed to the dryness in contact lens wearers. In the daily lens wear study (10 h), they found

that tear meniscus volume decreased gradually during lens wear in both symptomatic and asymptomatic wearers. The comfort rating also decreased after 10-hour lens wear. These results also suggest that the reduction of tears may contribute to the discomfort in contact lens wearers.

Wang et al. [18] demonstrated the visualization of post-lens tear film in vivo using UHR-OCT. A very recent report from Gonzalez-Mejome et al. [19] also showed that high-resolution OCT is a promising tool for visualizing the relationship among the contact lens, tear film, and ocular surface. Chen et al. [17] determined the dynamic pre- and post-lens tear film thicknesses using UHR-OCT. They reported that the thickness of the PCTF was about 2 μm . They also showed that artificial tears did not increase the post-lens tear film.

Conclusions

This article has highlighted the watery eye with an emphasis on new findings on tear dynamics in healthy individuals and dry eye patients. It appears that the tear system is regulated with fine tuning to maintain the minimal tear volume for wetting the ocular surface through the formation of the PCTF. The relationship and interaction between the tear meniscus and tear film facilitated by blinking play roles in the health of the ocular surface. The distorted tear dynamics due to both tear deficiency and excessive tear evaporation may cause dry eye symptoms. Intervention with artificial tears, punctal occlusion, and contact lens wear may further alter the tear system with apparent differences in responses between healthy individuals and dry eye patients.

Disclosure No potential conflicts of interest relevant to this article were reported.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
- Of major importance

1. Doane MG. Blinking and the mechanics of the lacrimal drainage system. *Ophthalmology*. 1981;88:844–51.
2. Tsubota K, Nakamori K. Effects of ocular surface area and blink rate on tear dynamics. *Arch Ophthalmol*. 1995;113:155–8.
3. Palakuru JR, Wang J, Aquavella JV. Effect of blinking on tear volume after instillation of midviscosity artificial tears. *Am J Ophthalmol*. 2008;146:920–4. *This article describes for the first*

- time the effect of blinking on tear volume after instillation of artificial tears.
4. Shen M, Wang J, Tao A, et al. Diurnal variation of upper and lower tear menisci. *Am J Ophthalmol*. 2008;145:801–6.
 5. Lemp MA. Advances in understanding and managing dry eye disease. *Am J Ophthalmol*. 2008;146:350–6.
 6. Palakuru JR, Wang J, Aquavella JV. Effect of blinking on tear dynamics. *Invest Ophthalmol Vis Sci*. 2007;48:3032–7.
 7. Shen M, Li J, Wang J, et al. Upper and lower tear menisci in the diagnosis of dry eye. *Invest Ophthalmol Vis Sci*. 2009;50:2722–6.
 8. Wang J, Aquavella J, Palakuru J, et al. Relationships between central tear film thickness and tear menisci of the upper and lower eyelids. *Invest Ophthalmol Vis Sci*. 2006;47:4349–55.
 9. Sahlin S, Laurell CG, Chen E, Philipson B. Lacrimal drainage capacity, age and blink rate. *Orbit*. 1998;17:155–9.
 10. Sahlin S, Chen E. Gravity, blink rate, and lacrimal drainage capacity. *Am J Ophthalmol*. 1997;124:758–64.
 11. Rolando M, Zierhut M. The ocular surface and tear film and their dysfunction in dry eye disease. *Surv Ophthalmol*. 2001;45 Suppl 2:S203–10.
 12. Palakuru JR, Wang J, Aquavella JV. Effect of blinking on tear dynamics. *Invest Ophthalmol Vis Sci*. 2007;48:3032–7.
 13. Methodologies to diagnose and monitor dry eye disease: report of the Diagnostic Methodology Subcommittee of the International Dry Eye Workshop (2007). *Ocul Surf*. 2007;5:108–52.
 14. Bron Anthony J. Diagnosis of dry eye. *Surv Ophthalmol*. 2001;45 Suppl 2:s221–6.
 15. Pflugfelder SC, Tseng SC, Sanabria O, et al. Evaluation of subjective assessments and objective diagnostic tests for diagnosing tear-film disorders known to cause ocular irritation. *Cornea*. 1998;17:38–56.
 16. Yuan Y, Wang J, Chen Q, et al. Reduced tear meniscus dynamics in dry eye patients with aqueous tear deficiency. *Am J Ophthalmol*. 2010;149:932–8.
 17. •• Chen Q, Wang J, Tao A, et al. Ultrahigh-resolution measurement by optical coherence tomography of dynamic tear film changes on contact lenses. *Invest Ophthalmol Vis Sci*. 2010;51:1988–93. *This article reports for the first time on visualized post-lens tear film and its alternation over time.*
 18. Wang J, Jiao S, Ruggeri M, et al. In situ visualization of tears on contact lens using ultra high resolution optical coherence tomography. *Eye Contact Lens*. 2009;35:44–9.
 19. • Gonzalez-Mejome JM, Cervino A, Carracedo G, et al. High-resolution spectral domain optical coherence tomography technology for the visualization of contact lens to cornea relationships. *Cornea*. 2010;29:1359–67. *This article reports on the use of UHR-OCT for imaging the post-lens tear film and its relationship to ocular surface.*
 20. • Hosaka E, Kawamori T, Ogasawara Y, et al. Interferometry in the evaluation of precorneal tear film thickness in dry eye. *Am J Ophthalmol*. 2011;151:18–23. *This is the first report on the evidence of thinned tear film in dry eye.*
 21. King-Smith PE, Fink BA, Fogt N, et al. The thickness of the human precorneal tear film: evidence from reflection spectra. *Invest Ophthalmol Vis Sci*. 2000;41:3348–59.
 22. Nichols JJ, Nichols KK, Puent B, et al. Evaluation of tear film interference patterns and measures of tear break-up time. *Optom Vis Sci*. 2002;79:363–9.
 23. Leveque G, Villachon-Renard Y. Determination of optical constants of thin film from reflectance spectra. *Appl Opt*. 1990;29:3207–12.
 24. Lemp MA. Report of the National Eye Institute/Industry workshop on Clinical Trials in Dry Eyes. *CLAO J*. 1995;21:221–32.
 25. Doane MG. Interactions of eyelids and tears in corneal wetting and the dynamics of the normal human eyeblink. *Am J Ophthalmol*. 1980;89:507–16.
 26. Murube J. Tear osmolarity. *Ocul Surf*. 2006;4:62–73.
 27. Mishima S. Some physiological aspects of the precorneal tear film. *Arch Ophthalmol*. 1965;73:233–41.
 28. Benedetto DA, Shah DO, Kaufman HE. The instilled fluid dynamics and surface chemistry of polymers in the precorneal tear film. *Invest Ophthalmol*. 1975;14:887–902.
 29. Ehlers N. The thickness of the precorneal tear film. *Arch Ophthalmol*. 1965;81:92–100.
 30. Prydal JI, Artal P, Woon H, Campbell FW. Study of human precorneal tear film thickness and structure using laser interferometry. *Invest Ophthalmol Vis Sci*. 1992;33:2006–11.
 31. Oguz H, Yokoi N, Kinoshita S. The height and radius of the tear meniscus and methods for examining these parameters. *Cornea*. 2000;19:497–500.
 32. Uchida A, Uchino M, Goto E, et al. Noninvasive interference tear meniscometry in dry eye patients with Sjogren syndrome. *Am J Ophthalmol*. 2007;144:232–7.
 33. Mainstone JC, Bruce AS, Golding TR. Tear meniscus measurement in the diagnosis of dry eye. *Curr Eye Res*. 1996;15:653–61.
 34. Wang J, Fonn D, Simpson TL, Jones L. Precorneal and pre- and postlens tear film thickness measured indirectly with optical coherence tomography. *Invest Ophthalmol Vis Sci*. 2003;44:2524–8.
 35. Farris RL, Stuchell RN, Mandel ID. Basal and reflex human tear analysis. I. Physical measurements: osmolarity, basal volumes, and reflex flow rate. *Ophthalmology*. 1981;88:852–7.
 36. Chen F, Shen M, Chen W, et al. Tear meniscus volume in dry eye after punctal occlusion. *Invest Ophthalmol Vis Sci*. 2010;51:1965–9.
 37. • Chen F, Wang J, Chen W, et al. Upper punctal occlusion versus lower punctal occlusion in dry eye. *Invest Ophthalmol Vis Sci*. 2010;51:5571–7. *This article reports on the dynamic changes in tear meniscus volume after punctal occlusion.*
 38. Chen Q, Wang J, Shen M, et al. Lower volumes of tear menisci in contact lens wearers with dry eye symptoms. *Invest Ophthalmol Vis Sci*. 2009;50:3159–63.
 39. Chen Q, Wang J, Shen M, et al. Tear menisci and ocular discomfort during daily contact lens wear in symptomatic wearers. *Invest Ophthalmol Vis Sci*. 2010.