Does the tear film remove higher order wavefront corrections?

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The role of tear film on the refractive state of the eye

- The strongest refracting surface of the eye is the air/tear film interface.

- However, if the tear film has a constant thickness it may be considered to be a zero power element.
The role of tear film on the refractive state of the eye

- If the tear film is constant thickness, i.e. a zero power element, the corneal surface may be considered as the first refracting element.

- In refractive surgery it is the corneal surface that is changed and this is the effect that is usually considered - the tear film is neglected.
The role of tear film on the refractive state of the eye

- But suppose the tear film is not constant thickness and so the air/tear surface does not replicate the corneal surface.
- Now the tear film is no longer a zero power element and must be considered.
- When can this happen? How will it effect refractive corrections?
Effect of a tear film of non-constant thickness

- If a tear film initially of constant thickness covering a local correction in form a local depression
- Flows and fills in that depression, much the corrective effect is removed
The flow of thin fluid films

- Will the tear film flow to partially erase local refractive corrections ablated into the corneal surface in the time between blinks?

- To answer this question we need to consider how and why thin fluid films flow
The flow of thin fluid films

- Parameters effecting flow
  - Surface tension ($\sigma$)
  - Mean surface curvature gradient ($\bar{M}$)
  - Viscosity ($\mu$)
  - Film thickness ($h$)
The flow of thin fluid films - surface tension (Ⅰ)

- The surface tension at a gas/fluid interface - such as the air/tear film surface - acts to minimize surface area.

- Surface area is minimized when the local mean surface curvature, $M$, is constant over the interface surface.

- Surface tension in a curved interface causes a pressure difference, $P$, between the gas and the fluid to be exist.

\[ P = 2\sqrt{\gamma M} \]  
(Young-Laplace formula)
The flow of thin fluid films - mean surface curvature gradient ($\nabla M$)

- A gradient in the mean surface curvature, $\nabla M$, creates a pressure gradient, $\nabla P$, in the fluid film.
- The pressure gradient causes fluid to flow from areas of higher curvature to areas of lower curvature until mean curvature, and hence the pressure, is equalized.
The flow of thin fluid films - viscosity (□)

- In a flowing fluid film in contact with air on one side and solid on the other
  - the fluid in contact with the solid surface moves at exactly the same speed as that surface
  - the fluid at the air interface flows with highest velocity with respect to the solid surface
The flow of thin fluid films - viscosity (\(\square\))

- We may think of the thin flowing film as being made of thin layers sliding with respect to one another.
- Viscosity may be thought of as a ‘friction’ between the layer that slows flow by inhibiting movement between layers.
- The flow restricting force due to viscosity is proportional to the velocity gradient, \(F=\square \partial V/\partial h\)
The flow of thin fluid films - film thickness ($h$)

- For a given surface velocity, the thinner the film, the higher the velocity gradient must be and the greater the viscosity will resist flow.

- Film flow rate is found to be proportional to $h^3$ - as the film gets thinner the flow rate quickly slows.
Tear film dynamics – initial conditions – change with time

- The initial film after a blink – can the tear film be modeled as initially having a constant thickness?
- How does the thickness change with time?
Can we assume the tear film starts life with a constant thickness?

- To answer this question, we turn to *coating flow* theory, the theory of creating thin film via a wiper or dipping action widely used industrially for
  - Flow of paint
  - Creation of thin emulsion films
  - Coating surfaces - such as spectacle lenses
- For the eye, the wiper is the upper eye lid moving over the corneal surface
Creation of a thin film by a moving wiper-coating flow

For *coating flow* the shape of the underlying surface does not effect film thickness
Thin film flow dynamics – change in thickness with time

- Equation giving the time rate of change of the surface air/fluid surface height

\[
\frac{\partial h(x, y)}{\partial t} = \frac{1}{3} \left[ \frac{\partial}{\partial x} \left( \frac{\partial M(x, y)}{\partial x} \right) \right] (h(x, y)^3) + \frac{\partial}{\partial y} \left( \frac{\partial M(x, y)}{\partial y} \right) (h(x, y)^3)
\]

- This equation allows the change in surface height over short periods of time to be directly calculated
Simulation of tear film flow

- Assume an initial constant tear thickness (~ 6 μm)
- Assume the tear film surface assumes the initial shape and local curvature of the corrected wavefront error
- Calculate the local curvature values from the surface elevation values
  - NOTE – second order surfaces have constant mean curvature i.e. $\nabla^2 M = 0$
- Using the differential thickness change equation calculate the rate of thickness change for a short period of time ~ 10 ms
- Find the new surface shape and curvature values
- Iterate the process for a length of time representative of the time between blinks

$$\frac{\partial h(x,y)}{\partial t} = \frac{\partial}{\partial x} \left( h(x,y) \right) \frac{\partial M(x,y)}{\partial x} + \frac{\partial}{\partial y} \left( h(x,y) \right) \frac{\partial M(x,y)}{\partial y}$$
Simulation for an eye with an above average amount of higher order aberrations.

The change in tear film thickness from the initial condition of constant thickness
Simulation for an eye with an above average amount of higher order aberrations.

- The change in tear film thickness from the initial condition of constant thickness

RMS error change = 0.009 micron $\div 1/61$
Experiment observation of tear film flow via live corneal topography video

- Simulation is fine but can these effects be physically measured?
- Flow effects can be observed by recording **live corneal topography video** and observing surface curvature changes as the corneal topographer mires change shape.
Tear film relaxation following blink in a 4 day post op PRK corneal surface
Motion just after a blink -4 days post-op PRK
Untreated cornea having a 50 year old scar at about 165° that induces higher order aberrations
Conclusions

- Tear film flow following initial film formation by a blink can be demonstrated by computer simulation and observed with live corneal topography video.
- For surface variations of the size expected from wavefront corrections the change in the tear film surface is too small to cause noticeable changes in visual image quality.
- Tear film dynamics will not erase the effects of ablative corrections for higher order aberrations.