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RETINAL DISORDERS

The fluid mechanics of scleral buckling surgery for the repair of retinal detachment

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Abstract

Background Scleral buckling is a common surgical technique used to treat retinal detachments that involves suturing a radial or circumferential silicone element on the sclera. Although this procedure has been performed since the 1960s, and there is a reasonable experimental model of retinal detachment, there is still debate as to how this surgery facilitates the re-attachment of the retina.

Methods Finite element calculations using the COMSOL Multiphysics® system are utilized to explain the influence of the scleral buckle on the flow of sub-retinal fluid in a physical model of retinal detachment.

Results We found that, by coupling fluid mechanics with structural mechanics, laminar fluid flow and the Bernoulli effect are necessary for a physically consistent explanation of retinal reattachment. Improved fluid outflow and retinal reattachment are found with low fluid viscosity and rapid eye movements. A simulation of saccadic eye movements was more effective in removing sub-retinal fluid than slower, reading speed, eye movements in removing sub-retinal fluid.

Conclusions The results of our simulations allow us to explain the physical principles behind scleral buckling surgery and provide insight that can be utilized clinically. In particular, we find that rapid eye movements facilitate more rapid retinal reattachment. This is contradictory to the conventional wisdom of attempting to minimize eye movements.

Keywords Retinal detachment · Fluid mechanics · Scleral buckle · Vitreoretinal surgery

Introduction

The retina is an approximately 300 mm thick layer of neural tissue that lines the back chamber (the vitreous cavity) of the eye. It is firmly attached at its most anterior aspect (the ora serrata) and the optic nerve. If a hole develops in the retina, vitreous fluid can enter the hole and cause the retina to separate from the back of the eye, leading to a retinal detachment. This condition requires prompt treatment to avoid irreversible blindness.

Perhaps the oldest and most established method to re-attach the retina during retinal detachment surgery is scleral buckling surgery, indenting the wall of the eye by suturing a silicone band or buckle on the sclera. Frequently, at the end of the surgery, the hole in the retina (the underlying cause of the retinal detachment) is over the indentation that is caused by the scleral buckle, but the retina in the area of the hole is not against the back of the eye. Thus, the hole is not closed. While

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WJF has full control of all primary data, and all authors agree to allow Graefe's Archive for Clinical and Experimental Ophthalmology to review the data, if requested.

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an incision can, at the time of surgery, be made in the wall of the eye and sub-retinal fluid can be externally drained, this extra procedure rarely results in a complete absence of fluid under the retina. The question that we are asking is: “Why does the retina attach itself against the back of the eye after the placement of a scleral buckle?”

Previously, Clemens et al. [1] developed a simplified experimental model (Fig. 1) of a retinal detachment and scleral buckling that reproduced the essential features of this problem. They utilized a fish tank with a thin cloth membrane attached at the periphery of the tank. The membrane contained a small hole, and a piece of tubing was placed under the membrane to simulate indentation from the scleral buckle. The tank was then manually rocked back and forth, in an oscillating manner, and the cloth “retina” was found to re-attach itself to the bottom of the tank if the silicone “buckle” were placed under the hole in the “retina”. On the other hand, if the “buckle” were placed in an inappropriate position, not under the hole, the retina would remain detached. Our goal is to simulate this model system using finite element analysis, guided by physical reasoning.

There are other mechanisms that can aid in retinal re-attachment, that are not included in these calculations:

1) The retinal pigment epithelium (RPE), the tissue directly under the retina, is known [2] to pump sub-retinal fluid out of the eye. Despite this, the pump cannot keep up with the influx of fluid caused by the hole in the retina. This will be discussed later in this paper.
2) In addition, by indenting the wall of the eye in the area of the retinal hole, the vitreous gel cannot apply as much traction to the edge of the hole, and the hole may naturally close.
3) The osmotic pressure of the existing vitreous might be hypothesized to aid in re-attachment of the retina. This is known to not be the primary mechanism by which the retina is re-approximated to the back of the eye, given that the results of scleral buckling surgery do not depend upon whether the patient previously underwent a vitrectomy [3] (i.e., removal of the vitreous gel).

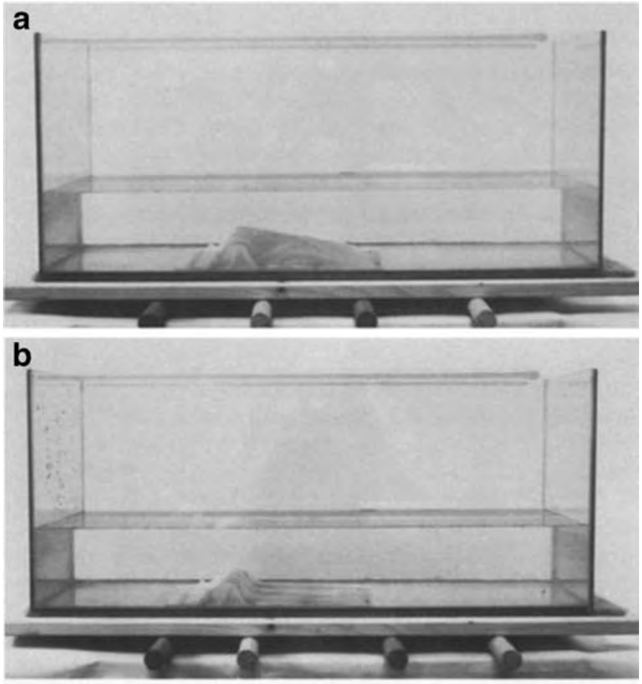


Fig. 1 Experimental model of a scleral buckle, as implemented by Clemens et al. Note the piece of cloth, attached at the lower edge of the tank, with a small central hole in the cloth. A piece of tubing under the cloth serves as the indentation or buckle. Reprinted with permission from Graefes Arch Exp Ophthalmol 225:16–18 (1987)

Materials and methods

In this paper, we utilize a simplified model of the eye, previously described experimentally in the paper by Clemens et al. [1]. The system consists of a solid floor with a membrane suspended above it. A single hole is present in the membrane and an elevation, simulating a scleral buckle, can be placed in various positions under the membrane (Figs. 3 and 4).

The model was implemented using COMSOL Multiphysics®, version 3.4 with the MEMS module to facilitate coupled fluid and structural equations. Unless stated otherwise, the separation between the retina and the back of the eye was initially 5 mm, and the density and dynamic viscosity of the fluid were taken to be that of water at 37.5°C. The retina, which is composed of neural tissue, is simulated as an isotropic membrane, 300 μm thick, with a Young’s modulus of 1000 Pa. For comparison, simulations were also performed with the retina modeled as a 300 mm thick rigid membrane.

Reynolds number of the system

A saccadic eye movement, or saccade is the fastest movement of an exernal part of the body. It is possible to create saccades in which the eye moves with a velocity of 400 degrees/second [4]. Assuming a saccadic velocity of 400 degrees/second and a diameter of the eye of 0.04 meters, this movement results in a linear velocity at the retina of (0.04/2)*400 degrees/sec*pi/180=0.14 m/sec. If the spacing between the back of the eye and the detached retina is 0.5 cm, the Reynolds number for this system is (0.14 m/s) * (0.005 m)/($0.658\times10^{-6}\text{m}^2/\text{s}$)=1,060.

Assuming a reading speed for the eye of 15 degrees/ second and a diameter of the eye of 0.04 mm, reading results in a linear velocity at the retina of (0.04/2)*15

Fig. 2 A simplified model of a retinal detachment

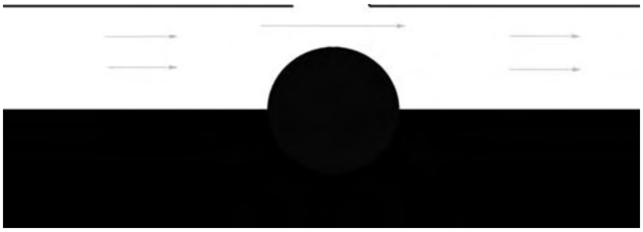


Fig. 4 Changes in fluid velocity, with resulting changes in pressure, in the simplified model

degrees/sec*pi/180=0.00524 m/sec and a Reynolds number of 40. We thus must simulate a system that possesses primarily laminar flow (i.e., Reynolds number<1200), but not at a low Reynolds number.

Fluid flow

Figure 2 illustrates a simplified model of a retinal detachment, where the model retina has a hole in it and is separated from the back of the eye. The length of the arrows illustrates the velocity of fluid flow with eye movement. Figures 3 and 4 illustrate a retinal hole with a scleral buckle in place and, again, the length of the arrows illustrates the velocity of fluid flow. Figures 3 and 4 illustrate two possible routes that fluid can flow in the buckle system, and we propose that the actual fluid flow will be a combination of the two diagrams.

Note that, in Fig. 4, the fluid must flow much faster in the area of the "buckle". Also, the Bernoulli principle states that pressure is inversely related to fluid velocity. Thus, the pressure over the buckle, in areas of higher fluid velocity, will be lower than in the rest of the eye (see Fig. 6). This induced pressure gradient can be utilized as a crude pump, if we consider that the fluid velocity varies with time.

Figure 5 illustrates the hypothesized combined result of the flow of fluid in the system. Note that the trailing retina is pulled downward, toward the back of the eye by the decreased sub-retinal pressure induced by the Bernoulli principle.

Results

An illustration of a typical simulation is given in Fig. 6. Fluid flow is illustrated using arrows, while pressure is displayed using color. Integrated fluid flow through the retinal hole was simultaneously calculated during each step of the simulation and plotted.

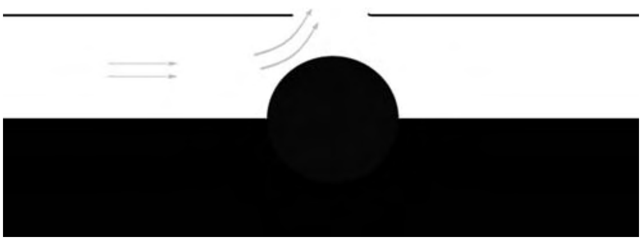


Fig. 3 Deflection of fluid in the simplified model

When the retina is held rigid and an artificially long (1-second) saccade is simulated (Fig. 6), fluid outflow through the hole is paradoxically increased with increased fluid viscosity (Fig. 7). When retinal elasticity is included in the model (Fig. 8), we find that more viscous fluids have diminished outflow, as is known to take place clinically. Given this finding, a flexible retina was utilized throughout all subsequent simulations to provide a more realistic simulation.

The eye moving at reading velocity (Fig. 9) and undergoing rapid-eye movement (REM) sleep-like movement (Fig. 10) were then simulated at varying fluid viscosities (noted to the right in all of the figures, where 1=the viscosity of water at body temperature, 2=twice that viscosity).

A comparison of fluid outflow for the different simulated eye movements (Fig. 11) demonstrates that REM-like movements promote fluid outflow more efficiently than slow reading movements or even single, large saccades.

Comparison with previously hypothesized models

A common textbook in vitreoretinal surgery [2] suggests additional explanations as to how scleral buckling works. The displacement of subretinal fluid away from the location of the retinal break and scleral buckle, as well as the inward displacement of the retinal break so that it is occluded by contact with the adjacent vitreous gel, have both been proposed. These explanations depend upon an assumption that the retina will remain relatively stationary. For most

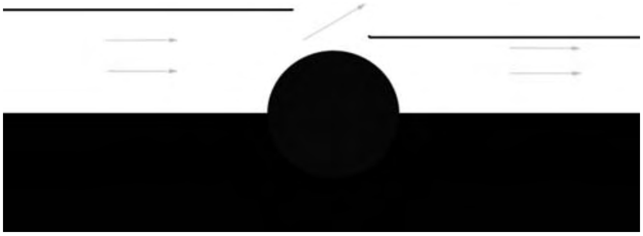


Fig. 5 Resulting displacement of the retina with increased fluid outflow in the simplified system

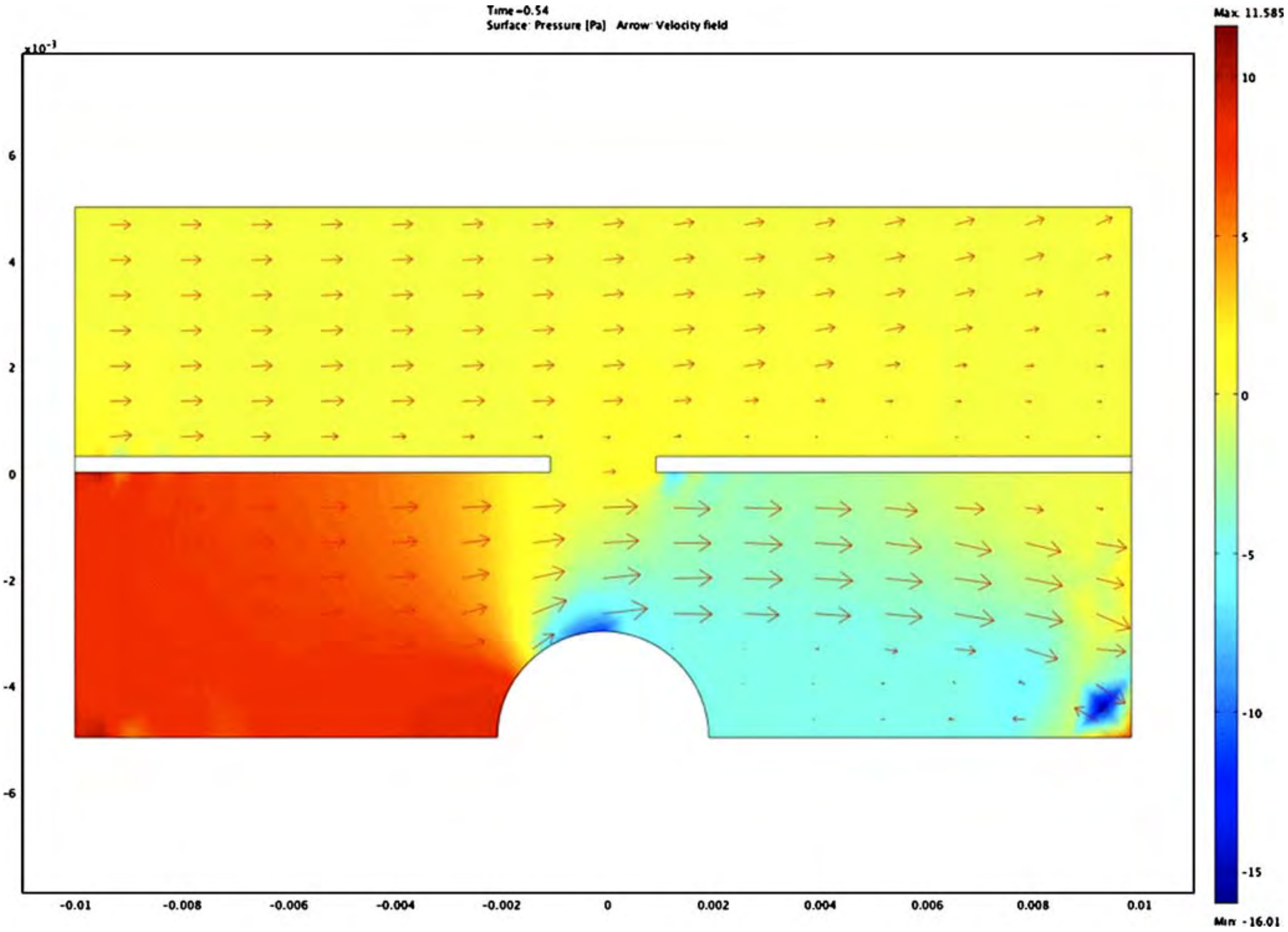


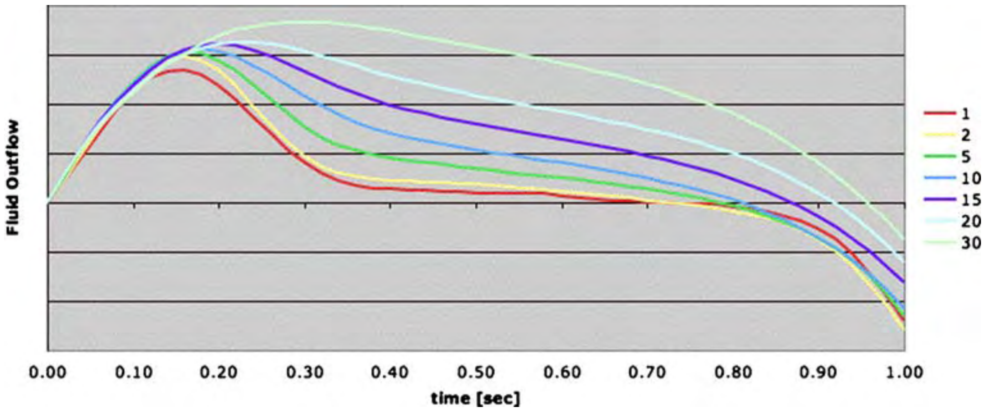
Fig. 6 Simulated fluid flow from left to right. Note the elevated pressure to the left of the buckle indentation and the decreased pressure (signified by the *blue color*) to the right of the indentation

clinical scenarios, the low elastic modulus (~1000 Pa) of the retina results in the retina freely moving, regardless of the position of the eye wall.

Other authors [5] have hypothesized that, in the case of a stationary retina, fluid flow from the vitreous cavity through the hole TOWARD the sub-retinal space can create a force for retinal re-attachment. The calculations in this model of retinal re-attachment can be compared to our computations.

It was previously found that $\Delta P = \frac{3\mu CA}{4\pi h^3}\log\left(\frac{r}{r_0}\right)$, where μ = viscosity, C = choroidal reabsorption rate per unit area, A = area of the choroid exposed by the detached retina, h= 1/2 the height of the retina above the buckle, r = radius of the buckle, and r_0=radius of the retinal hole.

Fig. 7 Fluid flow with rapid eye movements and a rigid retina. On the right of the figure is the simulated viscosity, compared with water. Note that, unphysically, water is less efficiently removed from under the retina than fluid that possesses 30 times the viscosity of water



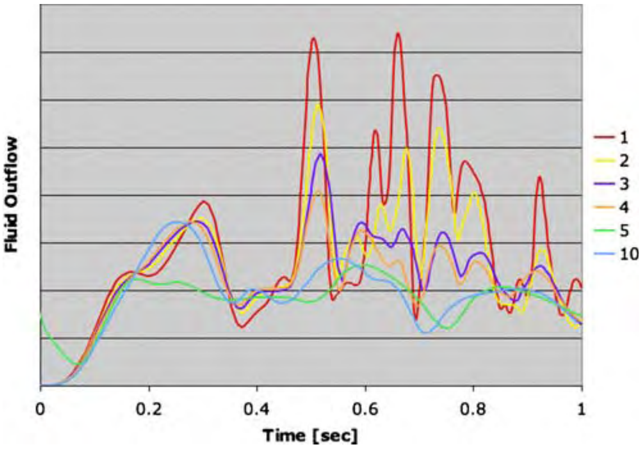


Fig. 8 Fluid flow with rapid eye movements and a flexible retina. On the right of the figure is the simulated viscosity, compared with water. The peaks in fluid outflow correspond to points in time at which the retina was positioned as illustrated in Fig. 5. This was a consistent finding, despite the non-periodic nature of the data

If we assume a retinal detachment of 5 mm, and that the sub-retinal fluid has the physical properties of water at 37.5°C, we compute a trans-retinal pressure gradient, re-attaching the retina of 4×10^{-4}mmHg. This is orders of magnitude lower than the pressures generated by the Bernoulli principle, which are on the order of 5 mmHg. In addition, this previously hypothesized model assumes that the retina is immobile, an improbable condition, given the flexibility of the retina and the involuntary nature of many eye movements, including REM sleep.

Discussion

We have evaluated a numerical model for scleral buckling surgery with sub-retinal fluid of varying viscosity that is based upon a previously described experimental model. Our results allow us to provide insight as to how a scleral buckle serves to re-attach the retina. In particular, laminar fluid flow and the Bernoulli effect both play an important role in this process. Based upon our calculations, rapid eye movements are expected to facilitate improved outflow of subretinal fluid. These computational results are consistent with the clinical findings of Lincoff and Kreissig [6–8] that external drainage of subretinal fluid is not necessary for successful scleral buckling surgery.

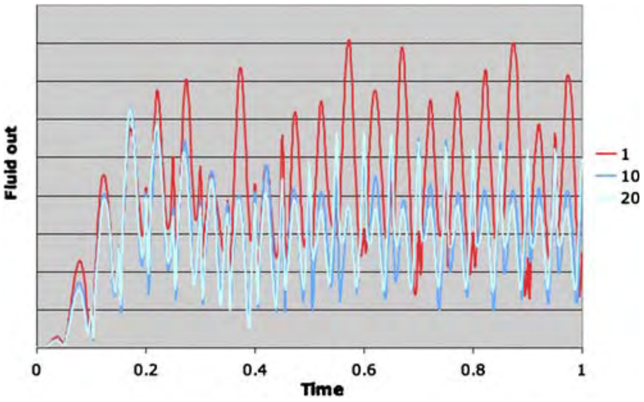


Fig. 10 Fluid flow in simulated REM sleep (rapid, short saccades). On the right of the figure is the simulated viscosity, compared with water. The peaks in fluid outflow correspond to points in time at which the retina was positioned as illustrated in Fig. 5. This was a consistent finding, despite the non-periodic nature of the data

Although patients will naturally have their eyes undergo rapid saccades (during REM sleep and while reading, for example), allowing patients to move their eyes rapidly may facilitate more rapid retinal re-attachment and visual rehabilitation. The concepts described here could be tested in a prospective clinical trial of primary rhegmatogenous retinal detachments repaired with scleral buckling. For example, the treated group might be required to read a given number of lines of text while the control group would be forbidden from reading, while both groups are closely followed during the post-operative period.

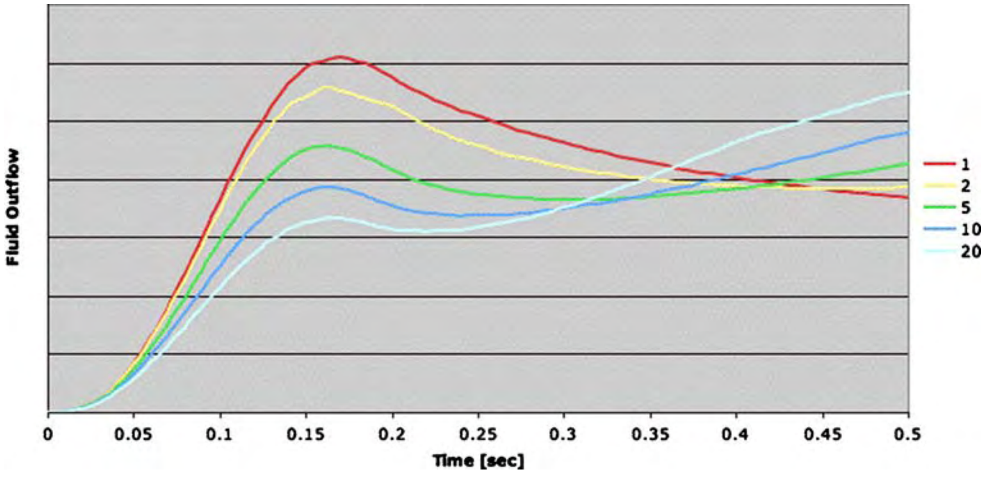


Fig. 9 Fluid flow with slow, steady eye movement. On the right of the figure is the simulated viscosity, compared with water. Again, the peaks in fluid outflow correspond to points in time at which the retina was positioned as illustrated in Fig. 5

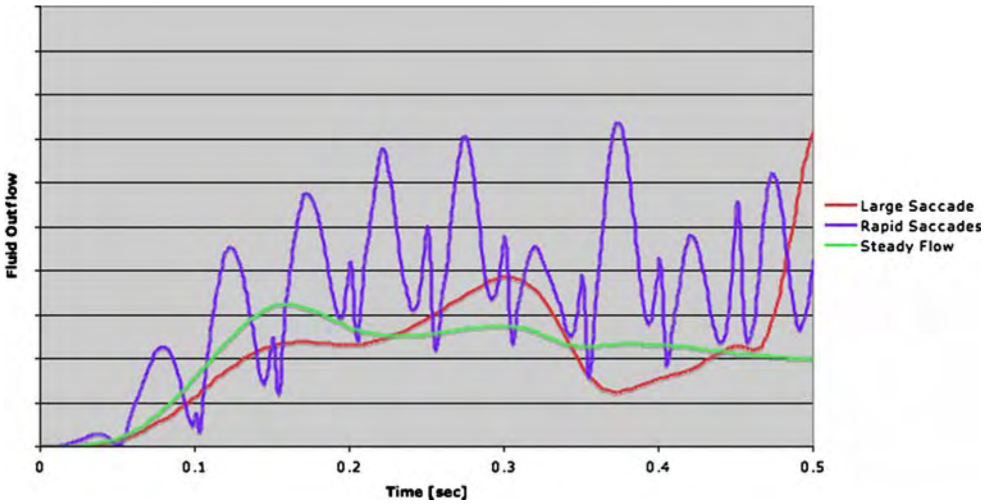


Fig. 11 A comparison of subretinal fluid outflow with different eye movements. The simulated viscosity is that of water at 37.5°C. Note that the area under the curve representing rapid saccades, is consistently the largest

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