Bilateral Patching in Retinal Detachment: Fluid Mechanics and Retinal “Settling”

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PURPOSE. When a patient suffers a retinal detachment and surgery is delayed, it is known clinically that bilaterally patching the patient may allow the retina to partially reattach or “settle.” Although this procedure has been performed since the 1860s, there is still debate as to how such a maneuver facilitates the reattachment of the retina.

METHODS. Finite element calculations using commercially available analysis software are used to elucidate the influence of reduction in eye movement caused by bilateral patching on the flow of subretinal fluid in a physical model of retinal detachment.

RESULTS. It was found that by coupling fluid mechanics with structural mechanics, a physically consistent explanation of increased retinal detachment with eye movements can be found in the case of traction on the retinal hole. Large eye movements increase vitreous traction and detachment forces on the edge of the retinal hole, creating a subretinal vacuum and facilitating increased subretinal fluid. Alternative models, in which intraocular fluid flow is redirected into the subretinal space, are not consistent with these simulations.

CONCLUSIONS. The results of these simulations explain the physical principles behind bilateral patching and provide insight that can be used clinically. In particular, as is known clinically, bilateral patching may facilitate a decrease in the height of a retinal detachment. The results described here provide a description of a physical mechanism underlying this technique. The findings of this study may aid in deciding whether to bilaterally patch patients and in counseling patients on pre- and postoperative care. (*Invest Ophthalmol Vis Sci*. 2010;52:5437-5440) DOI:10.1167/iovs.11-7249

A well known but, perhaps, underused method to decrease the height of a retinal detachment before surgical repair is to bilaterally patch the eyes of the patient.^{1,2} Such patching, which was first proposed in 1861,³ is thought to minimize eye movements and, by an unspecified mechanism, at least partially reattach the retina. Indeed, there are even published reports of the retina becoming completely attached⁴ after such noninvasive treatment, and of the use of this technique to rapidly clear vitreous hemorrhage.^{1,5} Incredibly, further immo-

bilization of both eyes with traction sutures under the inferior and medial recti muscles lead to a reattachment rate of 45%.⁶ My goal is to explain this clinically observed phenomenon using a combination of computational simulations and physical reasoning.

In an elegant series of studies using electro-oculography, bilateral patching has previously been shown in vivo in humans to lead to a decrease in both the frequency and amplitude of eye movement.⁷ Little formal explanation has been provided for why bilateral patching and the resulting decrease in eye movement works to decrease the degree of retinal detachment. An improved understanding of the mechanism of action of bilateral patching may aid surgeons in patient selection for patching before surgery as well as in pre- and postoperative recommendations to patients with retinal detachments.

A basic physical concept that is necessary to understand the results discussed here is the Reynolds number. The Reynolds number is unitless and can be thought of as the ratio of inertial forces or “momentum” to viscous forces or “thickness.” It can be calculated as the product of a characteristic length (say, the height of the retinal detachment) times the characteristic velocity in the system divided by the kinematic viscosity (the “thickness” of the fluid involved), as shown in equation 1.

$$R = \frac{L \times V}{\nu} \quad (1)$$

where L represents the characteristic length, V represents the fluid velocity, and ν represents kinematic viscosity.

For systems with a very low Reynolds number (think of a bacterium swimming), momentum plays no role (i.e., the bacterium cannot build up some speed and then coast). For systems with a high Reynolds number (i.e., a jet airplane), momentum is very important in describing their motion. Viscosity, on the other hand, plays a lesser role in a jet airplane. By varying the Reynolds number in a simulation, one can probe the range of configurations (e.g., height of retinal detachment or viscosity of the fluid).

Tissues are known to have varying stiffnesses,⁸ and the stiffness can be characterized by a quantity known as the Young's modulus. For reference, brain tissue has an average Young's modulus of 1000 Pa, while muscle has an average Young's modulus of 10,000 Pa.

These physical concepts have been used in a computational model of vitreous traction to help explain the role of vitreous traction in retinal detachment.

METHODS

In this article, I used a simplified model of the eye, similar to one previously described experimentally in the paper by Clemens et al.⁹ The system consists of a solid floor with a membrane suspended above it. A single hole is present in the membrane and one or both edges of the retinal hole is attached to a vertical spring in order to simulate vitreous traction on the retinal hole. The equilibrium position of the

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spring was 1 mm above the plane of the retina to provide traction. In a series of experiments, the spring constant was varied from 0 to 100 mN/m in 20-mN/m steps, and 100 mN/m was found to be a point at which the edge of the retinal hole was consistently displaced upward from the plane of the retina under all flow conditions. This force is physically reasonable in that it is of the same order of magnitude as surface tension (~ 72 mN/m) at a water-air interface. The behavior of the system remained consistent throughout the series of experiments.

Unless otherwise stated, 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 (similar to neural tissue⁸).

The model was implemented using commercially available analysis software (COMSOL Multiphysics, version 3.5; COMSOL, Burlington, MA) with the MEMS module to facilitate coupled fluid and structural equations. Finite element calculations are performed by the COMSOL system by simultaneously solving the equations of motion (in this case, the equations describing fluid flow and structural mechanics) on a mesh of points in space, with given boundary conditions (i.e., no-slip conditions at fluid-solid boundaries, fluid cannot flow through solid objects, and the velocity of the fluid was fixed on the entrance side). By iteratively solving the equations, and using the results from one time point to determine the initial conditions for the next set of equations, I was able to simulate physical phenomena. In areas of rapid change (i.e., if the pressure or fluid velocity changes rapidly), the mesh and the time between time points is made extremely fine, with the software aiding in the determination of the coarseness of the mesh and time points. With the rapid advances in computational abilities of modern personal computers and sophisticated programming and image rendering techniques, simulations that would have required a supercomputer 10 years ago now can be performed on an office-based computer system.

A saccadic eye movement, or saccade, is the fastest movement of an external part of the body. It is possible to create saccades in which the eye moves with a velocity of 400° per second.¹⁰ Assuming a saccadic velocity of 400° per second and a radius of the eye of 0.02 meters (rounded from Gullstrand's model¹¹ and a standard reference¹²), this movement results in a linear velocity at the retina of $(0.02) \times 400^\circ$ per second $\times \pi/180 = 0.14$ meters per second. If the spacing between the

FIGURE 1. Simulation of fluid flow into the subretinal space (negative on this scale) with simulated eye movements, as described in the text. The horizontal (time) axis spans 0.2 seconds, while the vertical axis is relative fluid outflow, integrated over the retinal hole. Both slow (reading) and rapid (saccade) eye movements were simulated. With no traction on the retina, there is little or no flow of fluid into the subretinal space. Similar initial fluid flow into the subretinal space is found with traction applied to the upstream edge (upstream) or downstream edge (downstream) of the retinal hole, suggesting that it is the traction itself—and not the position of the traction relative to the intraocular fluid flow—that determines the flow of subretinal fluid.

FIGURE 2. Simulation of fluid flow into the subretinal space (negative on this scale) with no simulated eye movements. The horizontal (time) axis spans 0.2 seconds, while the vertical axis is relative fluid outflow, integrated over the retinal hole. Similar initial fluid flow into the subretinal space is found with traction applied to either edge of the retinal hole, while significantly more subretinal fluid flow is found when traction is applied to both edges of the retinal hole (both), highlighting the important role that vitreous traction plays in promoting subretinal fluid flow.

back of the eye and the detached retina is 0.5 cm, the Reynolds number for this system is $(0.14 \text{ m/s}) \times (0.005 \text{ m}) / (0.658 \times 10^{-6} \text{ m}^2/\text{s}) = 1060$.

Assuming a reading speed for the eye of 15° per second and a radius of the eye of 0.02 mm, reading results in a linear velocity at the retina of $(0.02) \times 15^\circ$ per second $\times \pi/180 = 0.00524$ meters per second and a Reynolds number of 40. Therefore a system must be simulated that possesses primarily laminar flow (which is known to occur for Reynolds numbers <1200), but not at a low Reynolds number.

This work uses mathematical simulations (with assumptions that are inherent to this form of investigation and the ability to study a phenomenon under a wide range of conditions) to explain a phenomenon that has been experimentally studied in previous clinical research. No new experimental testing on humans was performed. Other potential variables may influence the “settling” of the retina, including the influence of patching on the RPE pump, the age of the patient, and any intrinsic structure of the vitreous (i.e., incomplete liquefaction).

RESULTS

Finite-element calculations of coupled fluid and structural mechanics with integration of the fluid flowing into the subretinal space were performed at each time point. In Figures 1 and 2, the horizontal (time) scale spans 0.2 seconds while the vertical axis is relative fluid outflow, normalized to the size of the retinal hole.

Fluid flow into the subretinal space was found to be similar with traction on the upstream and downstream edge of the retinal hole, with minimal dependence on fluid velocity (Fig. 1). Minimal subretinal fluid flow was found when there was no traction on the retina, regardless of fluid flow (Fig. 1). There was an increased initial fluid flow into the subretinal space (Fig. 2) when traction was applied to both edges of the retinal hole.

DISCUSSION

Attachment of the retina depends on a balance between processes that act to attach the retina and those that act to detach the retina. Alternatively, the reader may think of retinal “settling” as a condition where fluid flowing into the subretinal space through the retinal tear is less than the fluid flowing out from the subretinal space via the RPE pump. This delicate balance can be disrupted by a variety of pathologic processes. Here, the clinical scenario of a tear in the retina is discussed.

FIGURE 3. Simulation of traction being applied to both edges of the retinal hole. Note the decreased subretinal pressure (illustrated by blue in the subretinal space) and the resulting fluid flow into the subretinal space (arrows).

Processes that can contribute to attachment of the retina include the RPE pump, osmotic swelling of the vitreous gel (balanced against the less osmotically active subretinal fluid), and fluid flow that is directed out of the subretinal space. Processes that can contribute to retinal detachment include traction on the retina and fluid flow that is directed into the subretinal space.

The presence of a hole or tear in the retina allows the flow of vitreous fluid into the subretinal space and detachment of

the retina. In addition, traction can obviously contribute to detachment. A consideration of intraocular fluid mechanics can aid in understanding conditions under which the retina might be more likely to detach and, in addition, allows us to evaluate the effect of eye movements on retinal detachment.

There are at least two potential models for how vitreous traction can promote the flow of vitreous fluid into the subretinal space: either the traction itself causes lower pressure in the subretinal space, or the traction positions the retinal hole

FIGURE 4. Drawing of fluid flow toward the retinal hole from the side without traction. Note that it might be reasonable to expect that the vitreous traction could further open the retinal hole, leading to increased flow of fluid into the subretinal space. This does not seem to be the case in these simulations.

FIGURE 5. Drawing of fluid flow toward the retinal hole from the side with traction. Note that it might be reasonable to expect that the vitreous traction could deflect fluid away from the retinal hole, leading to decreased flow of fluid into the subretinal space. This does not seem to be the case in these simulations.

so that fluid is better directed into the subretinal space with eye movements.

As shown in Figure 3, traction on the edge of a retinal hole can create an area of decreased pressure in the subretinal space. This is similar to dragging a sea anchor or parachute through water. Asymmetric traction on a retinal tear, when coupled with intraocular fluid flow may facilitate flow of vitreous fluid into the subretinal space. In Figures 4 and 5, a flap tear is illustrated, in which traction is applied to the flap, creating asymmetric traction on the edge of the retinal hole. If fluid flow is directed toward the hole from the side without traction (Fig. 4), the downward force of the fluid will serve to push the proximal edge of the hole downward, opening the hole further and facilitating entry of fluid into the hole. On the other hand, if fluid flow is directed toward the hole from the side with traction (Fig. 5), little fluid is expected to enter the subretinal space. Based on this reasoning, because of asymmetric traction on the edge of the hole, alternating eye movements would provide a pump-like mechanism to detach the retina.

Given the minimal difference in subretinal fluid flow with upstream and downstream traction on the retinal hole, regardless of fluid flow, these results imply that it is the vitreous traction itself—rather than the traction in combination with preexisting intraocular fluid flow—that determines subretinal fluid flow.

If one considers the case of patients undergoing bilateral patching, eye movements should be diminished. Therefore, as has been noted clinically, bilateral patching can be an effective modality to decrease the height of retinal detachment. There are previously described risks of bilateral patching, including the risk of falls and burns as well as “black patch delirium”¹³ that should be taken into account when recommending this treatment.

In summary, these results highlight, in a quantitative fashion, that there is a reasonable physical mechanism whereby bilateral patching can aid in the reattachment of the retina; that eye movement influences retinal detachment indirectly, by inducing vitreous traction on the retina and creating a subretinal vacuum; and that relief of traction on the edge of a retinal

hole, by the creation of an operculated hole or indentation of the eye can, as is known clinically, aid in the prevention of retinal detachment.

References

1. Lincoff H, Stopa M, Kreissig I. Ambulatory binocular occlusion. *Retina*. 2004;24:246–253.
2. Lincoff H, Kreissig I, Uram D. Minor surgery for the repair of retinal detachment emanating from retinoschisis. *Acta Ophthalmol*. 2009;87:281–284.
3. Stellwag CC. *Lehrbuch der praktischen Augenheilkunde*. Vienna, Austria: W Braumüller; 1861.
4. Lincoff H, Kreissig I. The treatment of retinal detachment without drainage of subretinal fluid. (Modifications of the Custodis procedure. VD). *Trans Am Acad Ophthalmol Otolaryngol*. 1972;76:1121–1133.
5. Lincoff H, Kreissig I, Wolkstein M. Acute vitreous haemorrhage: a clinical report. *Br J Ophthalmol*. 1976;60:454–458.
6. Algrere P, Rosengren B. Active immobilization of the eye in the treatment of retinal detachment. *Mod Probl Ophthalmol*. 1977;18:286–291.
7. Adams GL, Yee RD, Hahn PM, Pearlman JT. Effect of binocular and monocular patching on eye movements. *Arch Ophthalmol*. 1973;90:117–120.
8. Engler AJ, Sen S, Sweeney HL, Discher DE. Matrix elasticity directs stem cell lineage specification. *Cell*. 2006;126:677–689.
9. Clemens S, Kroll P, Stein E, Wagner W, Wriggers P. Experimental studies on the disappearance of subretinal fluid after episcleral buckling procedures without drainage. *Graefe's Arch Clin Exp Ophthalmol*. 1987;225:16–18.
10. Stetter M, Sendtner RA, Timberlake GT. A novel method for measuring saccade profiles using the scanning laser ophthalmoscope. *Vision Res*. 1996;36:1987–1994.
11. Emsley HH. *Visual Optics*. 5th ed. London: Hatton Press Ltd; 1952.
12. American Academy of Ophthalmology. *2010–2011 Basic and Clinical Science Course (BCSC) Section 2: Fundamentals and Principles of Ophthalmology*. San Francisco: American Academy of Ophthalmology; 2010.
13. Weisman A, Hackett T. Psychosis after eye surgery: establishment of a specific doctor-patient relation in the prevention and treatment of “black-patch delirium.” *N Engl J Med*. 1958;258:1284–1289.