A Computational Study of the Flow Through a Vitreous Cutter

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Abstract

Background: Vitrectomy is an ophthalmic microsurgical procedure which removes part or all of the vitreous humor from the eye. The procedure uses a vitreous cutter, consisting of a narrow shaft with a small orifice at the end through which the humor is aspirated by an applied suction. An internal guillotine oscillates back and forth across the orifice to alter the local shear response of the humor. In this work, a computational study of the flow in a vitreous cutter is conducted in order to gain better understanding of the vitreous behavior and provide guidelines for new vitreous cutter design.

Method of approach: The flow of a Newtonian surrogate of vitreous in a two-dimensional analog geometry is investigated using a finite difference-based immersed boundary method with algebraically formulated fractional-step method. A series of numerical experiments are performed to evaluate the impact of cutting rate, aspiration pressure and opening/closing transition on the vitreous cutter flow rate and transorifice pressure variation during vitrectomy.

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Results: The mean flow rate is observed to increase approximately linearly with aspiration pressure and also increase nearly linearly with duty cycle. A study of time-varying flow rate, velocity field and vorticity illuminates the flow behavior during each phase of the cutting cycle and shows that opening/closing transition plays a key role in improving the vitreous cutter’s efficacy and minimizing the potential damage to surrounding tissue.

Conclusions: The numerical results show similar trend in flow rate as previous in vitro experiments using water and balanced saline solution, and also demonstrate that high duty cycle and slow opening/closing phases lead to high flow rate and minor disturbance to the eye during vitrectomy, which are the design requirements of an ideal vitreous cutter.

Keywords: Immersed boundary method; Vitreous; Vitreous cutter; Vitrectomy.

Nomenclature

D Inner diameter of the inner shaft
f Boundary force
P Pressure (mmHg or Pa)
V Velocity
n Unit normal vector
s Lagrangian parameter
t Time
u Velocity vector in Cartesian coordinates
ub Boundary velocity vector at Lagrangian points
1 Introduction

Vitreous humor is a transparent, gel-like substance filling the space between the lens and retina in the eye. Various abnormalities of the eye (e.g. vitreous hemorrhage, retina detachment) require an ophthalmic medical procedure to remove vitreous from the eye, and this delicate procedure is called vitrectomy, performed using a microsurgical instrument called a vitreous cutter. The removal of the vitreous gel, which can adhere to the retina, must be performed quickly but the stress applied on the vitreous base and the retina should be controlled to avoid any iatrogenic retinal tears. The vitreous humor is composed of 99% water, 0.9% salt and 0.1% macromolecular components including soluble protein, collagen fibers and hyaluronic acid [1, 2]. The combination of the large molecular elements provides a mechanical protection to the surrounding tissues during eye movement and physical activity, and is subjected to elastic response to an applied stress; with the aqueous part, vitreous
humor exhibits viscoelastic behavior. Due to this viscoelastic characteristic, a cutting mechanism is mandatory to remove the vitreous through the small-diameter port without creating significant traction force to the surrounding tissue or retina. The cutting mechanism, however, might limit the flow rate and cause disturbance in the vicinity of the probe. Since the early 1970s, the standard vitrectomy has utilized 3-port, 20-gauge guillotine action vitreous cutters, comprised of a small probe and an internal shaft (driven by pneumatic or electric mechanism) that oscillates back and forth to provide a cutting mechanism to excise the vitreous through the orifice at the probe end [3, 4]; the availability of 23- and 25-gauge vitreous cutters has recently opened a new era of transconjunctival sutureless vitrectomy. The smaller diameter makes the procedure less invasive, improves patient comfort and also facilitates the postoperative recovery [5, 6]. Nevertheless, these advantages are often mitigated by longer operation time due to the reduction of flow rate caused by its smaller diameter [7] and possibly larger traction to the surrounding tissue from the higher aspiration pressure. From the clinic viewpoint, an ideal vitreous cutter should have a small diameter probe to reduce invasiveness, a proper guillotine motion operating with a moderate vacuum pressure to remove the vitreous and apply minimal traction to the retina, and high flow rate to minimize the operation time (high efficacy). To improve the design and resolve the limitations of the device, it is important to study the fundamental mechanisms of vitreous cutters.

Previous researchers have conducted *in vitro* experiments with various commercially available vitreous cutters in water, egg white, balanced saline solution and porcine vitreous to evaluate the performance and to determine the major parameters contributing to the efficacy. The impacts of duty cycle (the ratio of the time the cutter is open to total cycle time), aspiration pressure and cutting rate (cuts per minute, CPM) on the flow rate
have been heavily addressed in many \textit{in vitro} studies [8, 9, 10, 11, 12]; the importance of cutting phases has just been brought to attention in a recent paper [13]. Though these \textit{in vitro} tests have provided many useful aspects about vitreous cutters, they are constrained by the existing model dimensions and manufacturer’s console setup. The mismatch of the vitrectomy console and vitreous cutter could result in biased results [8], and the fundamental character of the flow is difficult to elucidate. Therefore, a computational study of the vitreous cutter can provide new and unique insights. Numerical experiments can be carried out with physical models to investigate the flow field and individually address the impact of each possible parameter on the vitreous cutter’s performance. The information obtained from the simulation could be used as a guideline in the design of new vitreous cutters and also as an indication for optimal device settings (e.g. cutting rate or vacuum pressure) during surgery.

The purpose of this paper is to investigate the flow field produced by vitrectomy with direct numerical simulation, and to evaluate the impacts of vacuum pressure, duty cycle, cutting rate and cutting phases on the efficacy of the vitreous cutter and its potential damage to the eye. In Section 2, the methodology of the numerical model and problem configuration are presented. In section 3, the numerical results of flow rate and flow field at different cutting rates and applied vacuum pressures are presented and compared; the significance of opening/closing phases is also examined. Section 4 includes further discussion of the numerical results and provides conclusions.
2 Methods

2.1 Numerical Algorithm

The complex moving geometry of a vitreous cutter is challenging to simulate with a conventional conforming mesh. To avoid the complications of adaptive mesh regeneration, the numerical scheme used in this study is a finite difference-based immersed boundary method with algebraically formulated fractional-step method [14, 15]. The merit of the immersed boundary method is that the flow simulation is carried out on a stationary Cartesian mesh, which is not required to conform to the geometry, and sets of Lagrangian points represent the complex geometry and enforce the boundary deformation or movement (Fig. 1). In the immersed boundary framework, the dimensionless governing equations are

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + \int s f(\xi(s,t))\delta(\xi(s,t) - x)ds
\]

\[
\nabla \cdot \mathbf{u} = 0
\]  

\[
\mathbf{u}(\xi(s,t)) = \int_x \mathbf{u}(x)\delta(x - \xi(s,t))dx = \mathbf{u}_B(\xi(s,t)),
\]

where \( x = (x, y) \) are the fixed Cartesian coordinates, \( \xi \) are the Lagrangian points parameterized by \( s \) and moving with velocity \( \mathbf{u}_B \), \( f(\xi(s,t)) \) are boundary forces applied on the Lagrangian points to enforce the no-slip condition, and \( \delta \) is the Dirac delta function. The velocities on the Cartesian grids are interpolated onto the Lagrangian points to enforce the boundary velocity, and the boundary forces on the Lagrangian points are regularized onto the neighboring Cartesian grid points to satisfy the no-slip condition in the flow field. A staggered mesh is adopted for spatial discretization along with the second-order implicit
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Crank-Nicolson method for viscous terms and the second-order explicit Adams-Bashforth method for convective terms.

The objective of this study is to explore trends of the response to changes in parameters, rather than obtain quantitative predictions of flow rate in the actual device. Therefore, for simplicity, the simulations are performed with a two-dimensional analog of the vitreous cutter, and the aspiration fluid is assumed Newtonian. As mentioned before, vitreous humor is a complex viscoelastic fluid, and its nonlinear response to shear will undoubtedly affect the results. To date, there have been very few rheological studies of this material [1, 16, 2]. Therefore, the Newtonian assumption is made in the absence of a reliable model and for obtaining initial understanding.

Figure 1: Sketch of immersed boundary method. —: Cartesian mesh; ■: Lagrangian points representing the boundary of the object. The Navier-Stokes equations are solved on the Cartesian mesh as the no-slip boundary condition on the surface of the object is enforced by applying body force on the Lagrangian points.
2.2 Computational Model

Figure 2 illustrates the computational model setup. The model contains two zones: zone I is the main investigation domain comprising a small portion of the vitreous cutter and part of the vitreous humor; zone II is the extended domain including the remaining length of the inner probe of the vitreous cutter and the draining tube and serving to impose the outflow boundary condition. The dimension of the eye, of which the average diameter is 25.4 mm, is much larger than that of the cutter, of which internal diameter ranges from 227 µm (25-gauge vitreous cutter; ref#8065750220, Alcon Laboratories, Fort Worth, TX, USA) [8] to 510 µm (20-gauge vitreous cutter; ref#2540E, Midlabs, San Leandro, CA, USA) [13]; therefore, the natural domain (whole eye) is truncated to save computational cost and only the vitreous humor in the vicinity of the cutter is taken into consideration in zone I. The draining tube extending from the vitreous cutter is connected to an imposed suction pressure (‘vacuum pressure’) to enable the aspiration, and its length is also truncated for computational purposes.

In zone I, two sets of Lagrangian points are used to represent the outer shaft and the tip part of the inner shaft (Fig. 2(c)). The remaining part of the inner shaft and the connecting draining tube are represented as a straight channel in zone II using directly-enforced boundary conditions via one-sided finite difference stencils; the outer shaft and other parts of the cutter are reasonably neglected.

When the cutter is on, the inner shaft moves back and forth as a guillotine, and the cutting cycle can be divided into four phases: opening, opened, closing and closed (Fig 3). The speed of the guillotine is assumed to be constant during the opening and closing
phases in the simulation and is determined by the cutter’s distance of travel and the time duration measured by high-speed movies of the actual device; it is zero during the opened and closed phases. In this study, a 20-gauge pneumatic vitreous cutter (ref#8065740253, Alcon Laboratories, Fort Worth, TX, USA; referred to as A20 in the following) is used as the testing model, and the aspiration fluid has the same density and viscosity as egg white [17] (Egg white has similar consistency to the vitreous humor and is also a common surrogate for vitreous humor in the in vitro experiments [8, 18]) but assumed Newtonian. The dimensional and physical parameters used for the simulation are listed in Table 1; the duration of each phase and the corresponding duty cycle for different cutting rates are listed in Table 2.
Figure 3: The cutting cycle can be divided into four phases: (a) opening, the guillotine moving toward the handle and the cutter’s mouth being revealed; (b) opened, the cutter remaining stationary and the mouth (usually) being fully opened; (c) closing, the cutter moving toward the probe’s tip and the mouth reducing in area; (d) closed, the guillotine having no motion and the mouth being fully closed.

2.3 Boundary conditions

In zone I, the no-slip conditions on the fixed outer and moving inner shafts are enforced by the combination of immersed boundary method and one-sided difference stencil. The only boundary condition required is for the computational boundaries to account for domain truncation; for this purpose, traction and free-slip conditions are applied in the normal and tangential directions, respectively [19, 20]. The former condition will allow the fluid to be entrained from the surrounding region due to the pressure difference and the latter simplifies the discretization:

\[-P + 2\mu \frac{\partial u_n}{\partial n} = \sigma_n \text{ (traction condition)} \tag{4}\]

\[\frac{\partial u_\tau}{\partial \tau} = 0 \text{ (free-slip condition).} \tag{5}\]

During the vitrectomy procedure, while the vitreous is removed, fluid (e.g. balanced saline solution) is simultaneously infused into the eye to maintain intraocular pressure, which ranges from 10–21 mmHg (gauge) in normal eyes; the pressure variation caused by the guillotine
Table 1: Fluid and physical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensional</th>
<th>Dimensionless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$)</td>
<td>1038 kg/m$^3$</td>
<td>-</td>
</tr>
<tr>
<td>Dynamic viscosity ($\mu$)</td>
<td>4.5 mPa-sec</td>
<td>-</td>
</tr>
<tr>
<td>Inner diameter of the inner shaft ($D$)</td>
<td>475 $\mu$m</td>
<td>1</td>
</tr>
<tr>
<td>Outer diameter of the shaft</td>
<td>910 $\mu$m</td>
<td>-</td>
</tr>
<tr>
<td>Axial dimension of the orifice</td>
<td>475 $\mu$m</td>
<td>1</td>
</tr>
<tr>
<td>Length if the inner probe</td>
<td>0.075 m</td>
<td>158</td>
</tr>
<tr>
<td>Length of the draining tube$^a$</td>
<td>0.03 m</td>
<td>63.16</td>
</tr>
</tbody>
</table>

$^a$the original length of the draining tube is assumed to be 1.8 m long and is truncated to 0.03 m to save the computational cost.

Table 2: Duty cycle of the probe A20 by HSF camera ($10^4$ frames/sec).

<table>
<thead>
<tr>
<th>Cutting rate (CPM)$^b$</th>
<th>Time duration ($10^{-4}$ sec)</th>
<th>Duty cycle$^a$ (%)</th>
<th>Reynolds number (Re)$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opening</td>
<td>Opened</td>
<td>Closing</td>
</tr>
<tr>
<td>500</td>
<td>6.67</td>
<td>89.8</td>
<td>1.67</td>
</tr>
<tr>
<td>1000</td>
<td>6.9</td>
<td>36.6</td>
<td>1.8</td>
</tr>
<tr>
<td>1500</td>
<td>7.167</td>
<td>15.22</td>
<td>2.72</td>
</tr>
<tr>
<td>2000</td>
<td>7.3</td>
<td>3.6</td>
<td>3.2</td>
</tr>
<tr>
<td>2500</td>
<td>6.2</td>
<td>0.4</td>
<td>2.9</td>
</tr>
</tbody>
</table>

$^a$Duty cycle = \frac{opening+0.5\times(opening+closing)}{total\ cycle\ time}$

$^b$CPM: cutting per minute

$^c$Re=$\frac{\rho DV}{\mu}$. D is the inner diameter of the internal shaft; V is opening velocity of the gate.

motion and aspiration is restricted to the vicinity of the orifice. In this study, the vitreous cutter is operated away from the retina and the computational domain in zone I is sufficiently large to contain the pressure variation caused by the guillotine motion; therefore, the pressure surrounding the cutter tip can be assumed constant. The normal traction on the boundaries is set to zero relative to the intraocular pressure, and the resultant pressure difference will be accounted for at the outlet in zone II.

The same traction and free-slip conditions are applied to the outlet in zone II and the
normal traction accounts for the entire pressure in the system, including the aspiration pressure contributed by the vacuum pump and the pressure difference from zone I,

\[
\sigma_n = -P_{\text{vacuum}} = -(P_{\text{aspiration}} - P_{\text{intraocular}}).
\]

The manufacturer’s recommended aspiration pressure for the 20-gauge vitreous cutter is 250 mmHg (below atmospheric) and the intraocular pressure is assumed to be 15 mmHg (gage). The magnitude of applied ‘vacuum’ pressure is adjusted to account for the truncation of the extended tube and is approximated using Poiseuille’s law and the mean flow rate at zero cutting rate, resulting in 14.869 mmHg (below the intraocular pressure). Portions of the walls in zone II represent the moving guillotine with prescribed velocities; the remaining portions (the draining tube) are assumed to be stationary rigid walls.

For each cutting rate, the simulation was carried out for 3 cycles at 3 different applied vacuum pressures (for simplicity, the negative sign of the vacuum pressure has been omitted in this paper). The resulting volume flow rate drawn through the cutter was computed and compared for different combinations of parameters.

3 Results

3.1 Flow Rate

The mean flow rates (volume flow rate per unit depth) at different cutting rates with various vacuum pressures are depicted in Fig. 4 and also listed in Table 3. An approximately linear change in flow rate with vacuum pressure is observed. With the vacuum pressure held constant, the cutter with lower cutting rate has a higher flow rate and the flow rate decreases.
Table 3: Mean flow rates ($10^{-6} \text{ m}^2/\text{sec}$) for A20 at various cutting rate and with different vacuum pressures.

<table>
<thead>
<tr>
<th>Cutting rate (CPM)</th>
<th>Vacuum Pressure (mmHg)</th>
<th>Duty cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.605 37.145 55.613</td>
<td>100%</td>
</tr>
<tr>
<td>500</td>
<td>15.730 30.610 45.439</td>
<td>84.32%</td>
</tr>
<tr>
<td>1000</td>
<td>12.966 24.405 35.814</td>
<td>68.48%</td>
</tr>
<tr>
<td>1500</td>
<td>9.763 17.497 25.220</td>
<td>50.77%</td>
</tr>
<tr>
<td>2500</td>
<td>3.404 5.567 7.733 21.309</td>
<td>20.29%</td>
</tr>
</tbody>
</table>

Figure 4: Mean flow rates for different cutting rates at different vacuum pressures.

The time-varying flow rates at different cutting rates with various vacuum pressures are shown in Fig. 5. At the opening phase, flow rate increases gradually after the cutter mouth is more than 0% open, which is a result of increasing orifice area, the inner shaft motion and the vacuum pressure; it reaches a peak value when the cutter mouth is 100% opened. The guillotine motion stops immediately when the cutter is fully opened, and this causes the flow...
Figure 5: Time-varying flow rate ($10^{-5}\text{m}^2/\text{sec}$, 2-dimensional) of A20 in one complete cycle at various cutting rates with different vacuumed pressures. (The dotted line indicates the cutter mouth is more than 0% open)
rate to suddenly drop at the beginning of the fully opened phase. During the fully opened phase, the time varying flow rates behave differently with vacuum pressure and cutting rate. At lower vacuum pressure, the flow rate decreases slowly (at 7.434 mmHg) or increases slightly (at 14.869 mmHg), and then reaches a steady value in the cases of cutting rates 500 cpm and 1000 cpm, which have longer fully opened periods. At higher vacuum pressure (22.303 mmHg), the flow rate increases gradually and if the opened phase is sufficiently long, the flow rate reaches a steady value that may be greater than its peak value at the last moment of the opening phase. The time-varying flow rate during the initial portion of the fully opened phase is almost identical across different cutting rates with fixed vacuum pressure. The major effect of cutting rate is to determine whether the opened phase is long enough to reach a steady flow rate. During the closing phase, flow rate declines rapidly, and reaches and remains zero when the cutter mouth is fully closed.

3.2 Flow Pattern

The velocity fields produced by cutting rates of 1500 cpm and 500 cpm are shown in Fig. 6. As the cutter mouth opens, the fluid accelerates through the orifice and then develops into uni-directional flow through the probe. Higher aspiration pressures would result in higher velocities through the orifice and into the probe, but the flow patterns are almost identical (e.g. comparing Fig. 6(a) and 6(b)). The guillotine motion stops when the mouth is 100% opened; the central core of the fluid starts to accelerate and the velocity distribution inside the probe becomes parabolic beyond the entrance. Depending on the duty cycle and the vacuum pressure, a steady, fully-developed flow does not always occur during the opened
Figure 6: Velocity field at different instants during the opening, opened and closing phases of A20 at (a) 1500 cpm and applied vacuum pressure of 14.869 mmHg; (b) 1500 cpm and applied vacuum pressure of 22.303 mmHg; (c) 500 cpm and applied vacuum pressure of 14.869 mmHg.

phase. For instance, at 1500 cpm with both vacuum pressure of 14.869 mmHg and 22.303 mmHg, the centerline velocity is still accelerating slightly and this is also reflected in the increasing mean flow rate at the end of the fully opened phase (Fig. 5). However, at 500 cpm, the flow rate reaches a steady value during the opened phase, also reflected in the constant flow rate (Fig. 5). When the cutter is closing, a recirculating flow region forms just outside the cutter at cutting rates of 500 cpm and 1500 cpm (Fig. 6(a) and Fig. 6(c)) with
vacuum pressure of 14.869 mmHg, but is not seen at higher pressure (Fig. 6(b)).

Fig. 7 depicts the vorticity contours at the same cut rate (1500 cpm) with two different vacuum pressures. During the opening phase, vortices are formed at the edges of the orifice as fluid is rapidly drawn into the probe. When the cutter is just fully opened (T=0.455), the vortices weaken as the guillotine suddenly stops and the velocity in the mouth decreases; this is consistent with the small drop in flow rate exhibited in Fig. 5. At the fully opened phase, the vortices regrow as fluid is entrained into the device. During the closing phase, the guillotine motion creates boundary layers on either side, reflected in vorticity of opposite sign on the inside and outside of the cutter. In particular, the fluid adjacent to the inner wall of the cutter is dragged opposite the direction of the central core of fluid, leading to larger vorticity magnitudes than during the opening phase when fluid is all moving in the same direction toward the vacuum. The vorticity just outside the cutter rotates with opposite sign, and is consistent with the recirculatory region evident in Fig. 6(a) and a small ejection of fluid out of the device just at the end of the closing phase. Because the guillotine motion is opposite the direction of flow induced by suction, the flow rate drops during the closing phase faster than it increases during the opening phase.

During the opening and opened phases, higher aspiration pressure results in stronger vorticity around the edge of the orifice and more fluid entrained into the probe; during the closing phase, the cutter with higher pressure still has strong vorticity rotating clockwise at the edge of the orifice, showing that the fluid is still drawn into the probe. At the lower vacuum pressure, in contrast, the vorticity on the edge of the cutter is positive (counterclockwise) and fluid is ejected from the mouth, consistent with Fig. 6(a) at T = 0.0614. In other words, the increased flow induced in the core of the probe by the higher vacuum
Figure 7: Vorticity contour at different instants during the opening, opened and closing phases of A20 for 1500 cpm at (a) vacuum pressure of 14.869 mmHg; (b) vacuum pressure of 22.303 mmHg.

pressure overcomes the reverse flow generated adjacent to the walls by the closing cutter.

3.3 Opening/Closing Transition

In order to further investigate the opening/closing impact on the vitreous cutter’s efficiency, the same geometry was tested with 5 different cutting cycles with the same duty cycle but different opening or closing speed (Table 4). Cutting cycle 1 is identical to A20 at 1500 cpm, and cycles 2-5 are synthesized cycles. The testing aspiration pressure is 14.869 mmHg throughout. The mean flow rates of cycles 1-3 in Table 4 show that slower opening results in higher mean flow rate (higher cutter efficiency), which is consistent with previous in vitro experimental results [13]. The vorticity distribution of cycle 3 during the opening/opened phases is illustrated in Fig. 8. During opening, cycle 3 has a stronger vortex at the inside
Table 4: Cutting cycles and mean flow rates at 1500 cpm for opening/closing transition test.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Time duration($10^{-3}$ sec)</th>
<th>Duty cycle (%)</th>
<th>Mean Flow Rate ($10^{-6}$m$^2$/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opening</td>
<td>Opened</td>
<td>Closing</td>
</tr>
<tr>
<td>Cycle1</td>
<td>7.167</td>
<td>15.22</td>
<td>2.72</td>
</tr>
<tr>
<td>Cycle2</td>
<td>3.58</td>
<td>17.01</td>
<td>2.72</td>
</tr>
<tr>
<td>Cycle3</td>
<td>14.33</td>
<td>11.64</td>
<td>2.72</td>
</tr>
<tr>
<td>Cycle4</td>
<td>7.167</td>
<td>13.56</td>
<td>5.44</td>
</tr>
<tr>
<td>Cycle5</td>
<td>7.167</td>
<td>15.90</td>
<td>1.36</td>
</tr>
</tbody>
</table>

edge of the orifice than cycle 1 (Fig. 7(a)), which indicates that more fluid is entrained into the probe and passes through the lumen. Though the flow rate increases more slowly in cycle 3, the peak value at the end of opening phase is higher (Fig. 9(a)). When the cutter is fully opened and stopped, the vorticity in cycle 3, with a slower opening speed, does not decline as much as it does in cycle 1. The decline in vorticity is also consistent with the flow rate drop (Fig. 9(a)), which is larger in cycle 1 than in cycle 3.

Unlike the opening speed, the closing speed has less impact on the flow rate. Cycle 5, which has faster closing, produces only a slightly higher flow rate compared to cycle 1, and cycle 4, with a slower closing speed, produces a slightly lower flow rate. However, in both cases, the difference in mean flow rate is not significant. From Fig. 9(b), it can be seen that flow rate change at the closing phase is rapid, and the minor flow rate difference might be attributed to the differences in the duration of the fully opened phase.

In both the opening and closing phases, a pressure wave is formed and creates an immediate change in the motion of the fluid in the vicinity of the device. Strong transorifice pressure variation may induce retina motion and damage if the vitrectomy is operated nearby [21]. Figure 10 depicts the pressure variations across the cutter mouth during the opening and
Figure 8: Vorticity contours of cycle 3 at opening and opened phases.

Figure 9: Time varying mean flow rate for opening/closing transition test. Between the dash-dot lines, it is one complete cycle.
closing phases. During the opening phases (25% and 75% opened), the pressure variation is similar in cycle 1 and cycle 3, and is steepest within 0.5 mm from the cutter at higher vacuum pressure. During the closing phase, strong pressure variation is seen within 0.5 mm from the cutter and gradually diminishes further away; this variation is much stronger in cycle 5 (with faster closing speed) compared with cycle 1. At 25% closed, higher vacuum pressure ($P_3$) resulted in smaller variation in pressure but the variation inclined at 75% closing.

![Figure 10: Transorifice pressure distributions at the opening and closing phases. ($P_2=14.869$ mmHg and $P_3=22.303$ mmHg)](image)

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4 Discussion and Conclusions

The simulations in this paper are two-dimensional and the magnitudes of volume flow rate cannot be compared directly to the experimental results; however, the trends can be. The mean flow rate of A20 at different aspiration rates has a similar trend as the in vitro experiments using water or balanced saline solution [10, 12]: higher cutting rate resulted in a lower mean flow rate and the best flow rate occurred at zero cutting rate (100% duty cycle). The result of zero cutting rate might seem contradictory to prior experimental results of using porcine vitreous, which shows zero flow rate with cutter off [12]. Note that vitreous humor is a gel-like and viscoelastic substance exhibiting both solid-like and fluid-like properties, and its apparent viscosity varies with flow conditions. The purpose of cutting is not to improve flow rate beyond what can be achieved with fully opened condition, but rather, to affect the rheology of the vitreous humor with high shear. Unlike the cutting rate, which associates with the flow rate by changing vitreous’ viscosity, the impact of the duty cycle to flow rate is more straightforward, with higher duty cycle and higher aspiration pressure producing higher flow rate; this should be true even without considering viscoelasticity. The pneumatic vitreous cutter’s opening and closing are controlled by the air pulse shape generated by the console and properties of the spring inside the cutter. For the same cutter model operated with the same console, the opening and closing duration are similar at different cutting rates, and the duty cycle is mainly based on the time during opened and closed phases. Generally, a lower cutting rate has a longer opened phase and, therefore, higher duty cycle. Clinically, higher cutting rate is preferred because of vitreous’ rheological behavior; however, the duty cycle and therefore the flow rate would be compromised. The balance between cutting rate
and duty cycle is a key point in vitreous cutter design and can be better assessed when the viscoelastic model is introduced in a future study.

The comparison of vorticity and time-varying flow rate shows that stronger vorticity is associated with higher flow rate, and the strength of vorticity depends on the opening/closing transition and vacuum pressure. Therefore, in the simulations of probe A20 (Table 2), the time-varying flow rates during the opening/closing phases and the initial portion of the fully opened phase are almost identical at different cutting rates with fixed vacuum pressure since the opening and closing durations are similar. For the same reason, the velocity fields at different cutting rates are also similar across cutting rates with the same vacuum pressure. The mean flow rates of A20 with various vacuum pressures (Table 3) are consistent with the characteristics of incompressible flow in a channel, which is that higher pressure gradient results in higher flow rate.

In this study, the importance and effect on the vitreous cutter performance of opening/closing transition is revealed. The manner in which the opening/closing transition affects the cutter’s efficiency and flow field has been investigated through synthesized cutting cycles with fixed duty cycle, and the results show that slower opening phase allows higher mean flow rate and has a similar transorifice pressure variation as faster opening. As for the closing phase, its impact on flow rate is not significant but faster closing could result in strong traction in the adjacent environment, which should be avoided. Therefore, to satisfy the design needs of an ideal vitreous cutter, namely high efficacy and minor disturbance to the vitreous humor, slow opening/closing is preferable. The results might be different with the rheological effect added to the model, but the opening/closing transition will still play a key role in the vitreous cutter performance.

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In this study, the impacts of cutting rate, duty cycle, aspiration pressure, and opening/closing transition have been addressed using a 2-D numerical model. The Newtonian model is sufficient for a preliminary study, but a non-Newtonian model considering vitreous’ complex viscoelastic behavior is a necessity for further investigation in order to verify the aspect of the cutting mechanism and furthermore optimize the vitreous cutter design suited for clinic operation.

References


A Computational Study of the Flow Through a Vitreous Cutter


Juan 25 June 8, 2010


List of Figure Captions

1. Figure 1: Sketch of immersed boundary method. —: Cartesian mesh; ■: Lagrangian points representing the boundary of the object. The Navier-Stokes equations are solved on the Cartesian mesh as the no-slip boundary condition on the surface of the object is enforced by applying body force on the Lagrangian points.

2. Figure 2: Sketch of model. (a) drawing of the sample cutter; (b) sketch of the computational domain; (c) close look at the cutter opening (♦:Lagrangian points, □:remaining part of the inner shaft in zone I).

3. Figure 3: The cutting cycle can be divided into four phases: (a) opening, the guillotine moving toward the handle and the cutter’s mouth being revealed; (b) opened, the cutter remaining stationary and the mouth (usually) being fully opened; (c) closing, the cutter moving toward the probe’s tip and the mouth reducing in area; (d) closed, the guillotine having no motion and the mouth being fully closed.

4. Figure 4: Mean flow rates for different cutting rates at different vacuumed pressures.

5. Figure 5: Time-varying flow rate ($10^{-5}$m$^2$/sec, 2-dimensional) of A20 in one complete cycle at various cutting rates with different vacuumed pressures. (The dotted line indicates the cutter mouth is more than 0% open).

6. Figure 6: Velocity field at different instants during the opening, opened and closing phases of A20 at (a) 1500 cpm and applied vacuum pressure of 14.8688 mmHg; (b)
1500 cpm and applied vacuum pressure of 22.303 mmHg; (c) at 500 cpm and applied vacuum pressure of 14.869 mmHg.

7. Figure 7: Vorticity contour at different instants during the opening, opened and closing phases of A20 for (a)1500 cpm at vacuum pressure of 14.869 mmHg; (b) 1500 cpm at vacuum pressure of 22.303 mmHg.

8. Figure 8: Vorticity contours of cycle 3 at opening and opened phases.

9. Figure 9: Time varying mean flow rate for opening/closing transition test. Between the dash-dot lines, it is one complete cycle.

10. Figure 10: Transorifice pressure distribution at the opening and closing phases. (P_2=14.869 mmHg and P_3=22.303 mmHg).
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2. Table 2: Duty cycle of the probe A20 by HSF camera (10^4 frames/sec).

3. Table 3: Mean flow rate (10^{-6} m^2/sec) for A20 at various cutting rate and with different vacuum pressures.

4. Table 4: Cutting cycles and mean flow rates at 1500 cpm for opening/closing transition test.