New Parameters in Vitreoretinal Surgery

Safer intraoperative IOP regulation may help to avoid iatrogenic injury.

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Goals for safety in vitrectomy surgery include avoiding iatrogenic retinal tears or iatrogenic incarceration of retinal tissue and maintaining safe levels of intraocular pressure (IOP). These safety goals are affected by the rate and character of infusion flow and aspiration flow. Therefore, vitreoretinal surgeons should have a good understanding of fluid dynamics—the science of fluids in motion. Recent advances in vitreoretinal surgery have introduced new parameters. It is imperative that the vitreoretinal surgeon understand these new parameters in order to best utilize them.

This article explores the physics of fluid dynamics of vitrectomy and attempts to highlight the science of modern vitrectomy systems. It includes an examination of the scientific principles that govern fluid mechanics, in order to provide a foundation for the understanding of the complex interaction of ocular tissue, surgical technique, and equipment functionality.

PRINCIPLES OF FLUID MECHANICS

Fluid Statics. Gas and liquid molecules are in motion at all times. Molecules that collide with a solid boundary or arbitrary section generate a force called pressure. Pressure is a fundamental parameter of fluid mechanics principles that can be defined as a force per unit area, as shown in Equation 1:

\[ \text{Pressure} = \frac{\text{Force}}{\text{Area}} \]

The unit of pressure measurement most frequently used in the scientific community is the pascal (Pa), which is equal to one Newton (N) per square meter. A Newton is approximately equal to the weight of an apple. Other units of pressure include pounds per square inch (unit = psi), atmospheres (unit = atm), and bars (unit = bar). One atmosphere of pressure is equal to the atmospheric pressure at sea level on a day with standard temperature and atmospheric pressure, one atmosphere is equal to 14.7 psi or 1.0 bar.

Liquid pressures are often measured as the height of a given fluid (ie, mm Hg or cm H2O), due to the method originally use to measure pressure. Figure 1 shows a typical manometer (an instrument used to measure pressure). As a pressure (P) is applied to the reservoir, a column of fluid is pushed up the tube. The height of the column (h) is proportional to the pressure.

The relationship between pressure (P) and the column height (h) is defined by Equation 2:

\[ P = \rho g h \]

where \( \rho \) is the density of fluid in the column and \( g \) is the gravitational constant.

Absolute and Gauge Pressure. Pressure measurement devices such as manometers indicate the difference between the measured pressure and the atmospheric pressure. Figure 2 shows the relationship between the absolute pressure and the gauge pressure.

Because pressure is an absolute quantity, the gauge pressure varies indirectly with the atmospheric pressure. As an example, the absolute pressure of a gas tank displays a lower gauge pressure on a day with high atmospheric pres-
sure than on a day with low atmospheric pressure.

Like gauge pressure, vacuum is a reference to atmospheric pressure. The level of pressure below atmosphere is vacuum. The theoretical maximum vacuum can only be equal and opposite to the atmospheric pressure because it is impossible to achieve a pressure less than absolute zero. However, the vacuum could theoretically be greater than one atmosphere if the ambient pressure were above the standard pressure.

The relationship between ambient pressure and vacuum level is important when considering pars plana vitrectomy, during which the IOP can be considered the ambient atmospheric pressure. The infusion pressure and the aspiration vacuum add together to form an analogous absolute pressure across the vitrectomy probe. The total pressure differential across the vitrectomy probe is what drives fluid dynamics.

**Fluid Dynamics.** As discussed in the previous sections, pressure in a static system can be characterized by the weight of a column of fluid. In contrast, pressure in a dynamic system is a function of the fluid flow rate, due to resistance to flow and the associated pressure drops. Hagen-Poiseuille’s law defines the flow through a tube in terms of flow rate, pressure drop ($\Delta P$), and resistance to flow, as shown in Equation 3:

$$\text{Flow rate} = \frac{\text{Pressure drop}}{\text{Resistance factor}}$$

This equation is analogous to Ohm’s law for electrical circuits. The resistance inside the tube is affected by the length of the tube ($L$) and the internal radius of the tube ($r$), as shown in Figure 3.

The resistance is also affected by the viscosity of the aspirated liquid ($\eta$) so Equation 3 can be rewritten with more details as follows, where $\pi$ is a mathematical constant ($\approx 3.14$):

$$\text{Flow rate} = \frac{\eta \cdot L \cdot \Delta P}{\pi \cdot r^4}$$

By rearranging terms, Equation 4 can be rewritten as Equation 5:

$$\text{Flow rate} = \frac{\eta \cdot L \cdot \Delta P}{8 \cdot \eta \cdot L}$$

Equation 5 shows some important dependencies of flow rate on several factors. First, the flow rate is proportional to the fourth power of the inner radius of the tube. In terms of vitrectomy instruments, that means that larger gauge vitrectomy cutters have higher flow rates than smaller gauge instruments under similar conditions and vacuum levels. Second, the viscosity directly affects the flow rate; lower viscosities allow higher flow rates at any given pressure differential. The consequence of viscosity during vitrectomy is that flow increases when the probe port leaves the vitreous face and enters clear fluid, and, conversely, flow decreases when the probe port leaves clear fluid and enters vitreous.

**Fluid Flow Through Vitreous Cutters**

The relationship defined by Hagen-Poiseuille’s law applies to flow through the vitreous cutter. The pressure differential is equal to the IOP plus the applied aspiration vacuum. The pressure differential drives the flow through the probe port according to Equation 3. As the IOP or the aspiration vacuum is increased, the flow increases proportionally.

The flow through the port is limited by the design characteristics of the probe.12 The inner lumen radius of the probe has a fourth-order effect on the flow (see Equation 5). Consequently, smaller-gauge probes, such as 25-gauge probes, have a far slower flow than 20-gauge probes at any aspiration vacuum setting. The probe port dimensions restrict the flow only if the port area is smaller than the inner lumen area. Most modern probes have port openings that exceed the inner lumen area and do not geometrically restrict the flow.
Dynamic design characteristics also create port-based flow limits. Because the cutter must physically close off the port to create the guillotine-like cutting action, the port cannot remain open 100% of the time. To fully understand this flow restriction, surgeons must understand the concept of port duty cycle.

The cutting action of most vitrectomy probes is generated as the inner lumen of a vitrectomy probe moves across a port opening. When the cutter is in action, the inner lumen is repeatedly forced past the port opening, which generates a shearing action. Tissues are drawn into the port by the pressure differential when the port is in the open configuration. When the inner lumen is forced across the port opening, the tissues are sheared and aspirated through the inner lumen. During the time the port is closed by the inner lumen, no flow can pass through the probe port. Aspiration flow rates match the duty cycle; the higher the duty cycle, the higher the aspiration flow at any given vacuum level.

The amount of time the port remains open is referred to as the port duty cycle. Duty cycle is frequently misunderstood as the amount of time the port remains open divided by the amount of time closed. The correct definition of duty cycle is the amount of time the port is open divided by the time of one complete cut cycle, as shown in Equation 6:

\[
\text{Duty cycle} = \frac{\text{Duration port open}}{\text{Duration of total cutting cycle}}
\]

The duty cycle of an electrically driven cutter is constant at just below 50%. The linear motion of the guillotine-like cutter is tied mechanically to the rotary motion of an electric motor. The duty cycle is slightly less than 50% because the cutter must over-travel across the port. While the duty cycle remains constant across cut rates, the cutter velocity decreases with slower cut rates due to the reduced speed of the rotary motor driving the cutter.

For pneumatically driven vitreous cutters, certain physical phenomena related to cut rate affect the duty cycle; these include how quickly the pneumatic pulse is vented, the frictional forces within the probe, and inertial forces as the cut rate increases. Typically, the duty cycle of pneumatic cutters decreases as cut rate increases. At slower cut rates, duty cycles of 80% or more are common. At faster cut rates, such as 2500 cuts per minute (cpm), duty cycles can drop to 40% or lower.

Pneumatic probe design affects the relationship between duty cycle and cut rate. A pressure pulse enters the rear cavity of the probe and acts upon a diaphragm, which in turn compresses a spring. Attached to the diaphragm is the inner lumen that is forced across the probe port opening, thus producing the guillotine-like cutting action. When the pneumatic pulse is vented, the return spring pushes the diaphragm back, opening the cutter port. The repetition of this drive sequence defines the cut rate. The cut rate of first-generation pneumatic cutters is limited by the drive pulse rising edge, venting of the pressure pulse, and mechanical spring characteristics.

Recent advancements in dual pneumatic drive cutter technologies have employed a second pneumatic drive to replace the return spring that is used in a single-drive pneumatic probe. Figure 4 shows a cutaway view of a dual pneumatic drive probe. A pneumatic pulse enters the chamber behind the diaphragm, driving the cutter port closed. A second pulse, the return pulse, then acts on the front side of the diaphragm to return the cutter to the open position.

The duty cycle of a dual pneumatic drive probe is controlled by varying the pneumatic pulses. With this technology, cut rates greater than 5000 cpm are possible with duty cycle control. By increasing the width of the pneumatic pulse that opens the port, the amount of time the port is open is increased, resulting in a biased-open duty cycle. When the pneumatic pulse that closes the port is increased, the duty cycle of the port is biased closed.

Because the time required to open and close the port is somewhat fixed by the physical phenomena described above, the duty cycle is affected by cut rate. When the duty cycle is biased open, the cutter closes as fast as physically possible and then immediately returns open as fast as physically possible. In order to increase the cut rate, the only time segment that can be reduced to accommodate an increased number of cut cycles is the dwell open time. Consequently, the duty cycle is reduced. Likewise, to increase the cut rate of a biased-closed duty cycle, the amount of time the port dwells closed is reduced and the duty cycle increases. Figure 5 shows the effects of cut rate on duty cycle. As cut rate is increased, both biased-open and biased-closed duty cycles approach 50% duty cycle.

It makes sense that aspiration flow rates match the duty cycle. If the port is open for a longer period of time (biased open) more flow is allowed through the port. If the port is biased...
closed, less flow occurs. Figure 6 shows this relationship between flow and duty cycle.

**Effects of Cut Rate on Vitrectomy.** For the past 2 decades, many vitreoretinal surgeons have intuitively assumed that a faster cut rate allows safer surgery. Without cutting action, the vitreous is highly viscous, and the probe would unintentionally pull on collagen within the vitreous cavity. This vitreous pull could cause retinal traction and subsequent tears or retinal incarceration. We can assume that the greater the length of collagen pull, the greater the vitreous traction and the greater the likelihood of iatrogenic retinal tears and retinal incarceration. In other words, the greater the length of collagen pull, the less secure the surgery. Conversely, the shorter the length of collagen pull, the less the vitreous traction and the safer the surgery. This relationship is described in a surprisingly simple mathematical formula:

\[
\text{Length of Traction} = \frac{\text{Aspiration flow rate} \times \text{Internal lumen area of probe}}{\text{Cut rate}}
\]

The internal lumen area is related to the inner radius of the probe, \( r \), by the familiar equation \( \text{area} = \pi r^2 \). When the internal lumen area is held constant, only the aspiration flow and the cut rate affect the length of the traction pull, which is related to the viscosity of the aspirated liquid.

Equation 7 indicates that increasing the flow rate will increase the length of collagen pull. That relationship makes it evident that a very high flow rate is not necessarily beneficial and may in fact be dangerous. High flow rates increase the vitreous traction and the subsequent potential for retinal tears and incarceration. Especially when one is working near the retina, the slowest flow rate possible in order to get the job done would be desired. On the other hand, the higher the cut rate, the less the length of collagen pull, the less the viscosity of the vitreous, and the less the vitreous traction. Therefore, the highest cut rate possible would be desirable.

Increasing the cut rate not only reduces the length of pull; it also reduces the “bite” size—the size of a piece of aspirated vitreous. Bite size, or discrete aspirated volume, is another way to consider viscosity. A fluid composed of large pieces would be highly viscous, while a fluid composed of tiny pieces would have low viscosity. The discrete aspirated volume, defined as the volume aspirated in a single cycle of the vitreous cutter opening and closing, is calculated by dividing the flow rate by the cut rate. Figure 7 shows the results of our modeling to reveal how bite size decreases as cut rate increases.

The reduction in bite size is dramatic at slower cut rates (up to 2500 cpm), and the bite size continues to decrease all the way up to 5000 cpm, at which point the discrete aspirated volume is only 1.6 µL. As the cut rate doubles, the discrete aspirated volume is reduced twofold.

To visualize the effect of cut rate on bite size and length of pull, simulated bites of equal volume are overlaid on the photographs in Figure 8. Three successive bites are overlaid for 5000 and 2500 cpm. While each successive bite is the same volume, the traction, or length of pull, becomes smaller at farther distances from the port for both cut rates. Additionally, the length of pull is less at higher cut rates. This dynamic study is consistent with the mathematical formula
shown in Equation 7; that is, the faster the cut rate, the less the length of pull at all distances from the port.

INFUSION FLOW AND PRESSURE DROP

To maintain intraoperative IOP, the volume of aspirated tissue and fluid must be replaced. In pars plana vitrectomy, this volume is replaced by infusion fluids through an infusion cannula. As with aspiration flow, infusion flow is governed by Hagen-Poiseuille’s law. However, instead of a pressure differential creating a flow, the flow induced by aspiration creates a pressure drop across the infusion cannula. Equation 3, Hagen-Poiseuille’s law, can be rewritten as follows:

\[ \Delta P = \frac{\text{Flow Rate}}{\text{Resistance Factor}} \]

In this case, the resistance factor is based on the cannula geometry and the fluid viscosity. When the applied aspiration vacuum generates increasing flow, the pressure drop across the infusion cannula increases. The higher the aspiration flow, the greater the infusion cannula pressure drop. Figure 9 shows the relationship between the infusion cannula pressure drop and infusion flow rate.

Typical flow values for a 25-gauge core vitrectomy are approximately 3 to 4 mL/min. Figure 9 indicates that the...
induced pressure drop at this flow rate and gauge is approximately 20 mm Hg. This pressure drop means that the infusion pressure must be set 20 mm Hg higher than the desired IOP in order to account for the lows in IOP during periods of high aspiration rates. Therefore, if a minimum of 25 mm Hg were the desired IOP in this case, the infusion would have to be set at 45 mm Hg to accommodate the pressure drop across the infusion cannula.

**INTRAOPERATIVE INTRAOCULAR PRESSURE**

During vitreoretinal surgery, IOP depends on the fluid flow rate into the eye from the infusion line and out of the eye through the vitrectomy probe. If the fluid flow into the eye is faster than the fluid removal by the probe, hypotony can occur. When high infusion pressures (30 to 40 mm Hg) are used while operating on eyes with poor blood flow, such as the eyes of diabetics or glaucoma patients, hypotony may cause the blood vessels of the optic nerve to pulsate or lack perfusion. Conversely, if fluid flow into the eye is slower than the fluid removal by the probe, hypotony can occur. Intraoperative hypotony during vitreoretinal surgery has been associated with choroidal detachment and suprachoroidal hemorrhage. Corneal folds due to intraoperative hypotony can make visualization difficult for the surgeon and can damage the patient’s corneal endothelium.  

Traditional vitreoretinal instrumentation makes regulation of intraoperative IOP difficult for surgeons. The measurable applied infusion pressure at the console does not necessarily equal the resultant IOP, and the multiple factors that affect flow rate out of the eye through the vitrectomy probe are not apparent from the instrumental settings. Recent advancements in IOP compensation remove these unknown parameters and uncertainties. An IOP compensation feature maintains the IOP at the desired IOP regardless of flow conditions. This feature is intended to reduce IOP fluctuations while the surgeon is exchanging instruments and to reduce the chance of globe collapse during deep scleral depression or use of high flow rates. Instead of applying 30 mm Hg at the bottle and hoping for 15 mm Hg at the eye after adjusting for pressure drop, a surgeon can apply 20 mm Hg and expect to get 20 mm Hg with the IOP compensation feature.

**CONCLUSION AND SUMMARY**

Some key points of this article are as follows:

- Pressure is the force exerted over an area; pressure drives flow, while resistance impedes flow.
- Resistance to flow depends on the size and shape of the tube that the fluid flows through and on the viscosity of the flowing liquid.
- In a vitrectomy probe, flow also depends on duty cycle, where biased-open duty cycles yield higher flow biased-closed duty cycles yield lower flow, and on cut rate, where faster cut speeds reduce viscosity, bite size, and traction.
- In an infusion cannula, flow depends on the pressure drop.

During vitreoretinal surgery, IOP is a function of aspiration rate and infusion flow and must be controlled at a normotonic level for safety. These principles can be applied to surgical techniques, including choice of instruments and instrumental settings, in order to maintain safer intraoperative IOPs and to avoid iatrogenic retinal tears or incarceration. Additionally, understanding new vitreoretinal parameters will allow the surgeon to be not only safer but more efficient.

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