The Future of Small-gauge Vitrectomy

How fast can we cut and how small can we go?

BY STANISLAO RIZZO, MD; AND FRANCESCO FARALDI, MD

Since the development of pars plana vitrectomy by Machemer in 1970,[1,2] vitreoretinal surgeons have been involved in a continual effort to reduce the size of our instrumentation with the primary goal of reducing surgical trauma. Robert Machemer, MD, developed the original 17-gauge instrumentation with an external diameter of 1.5 mm. In the early 1970s, a 20-gauge vitrectomy probe with a 0.9-mm exterior and 0.47 mm interior diameter were described by O'Malley and Heintz.[3]

Twenty-gauge surgery remained the standard for more than a quarter century, until a flurry of innovative activity in the past decade-plus since 2002, as vitrectomy systems and instruments have become available in 23-, 25- and 27-gauge with a reduction of external diameter from 0.9 mm to 0.4 mm.[4-6]

The rationale for the development of these increasingly smaller-diameter instruments is a move toward less-invasive surgical procedures. Smaller wounds lead to less postoperative discomfort for the patient and faster recovery times.

NEAR PAST AND PRESENT

Introducing the 25-gauge transconjuctival sutureless vitrectomy system, Fujii and colleagues[4] demonstrated that this smaller-gauge system could outperform conventional 20-gauge systems, achieving better vitreous flow rate by raising the aspiration and the cut rate. However, the amount of vitreous viscosity reduction that was achievable by raising the cut rate was limited because of vitrectomy systems' inefficiencies, with steep decline of vitreous flow above 1500 cuts per minute (cpm). Pneumatic drives were slow and featured inefficient springs; electric drives could guarantee fixed duty cycles of 50% but presented several problems related to unfavorable energy-per-mass ratio and the necessity to use reusable probes.[5-7]

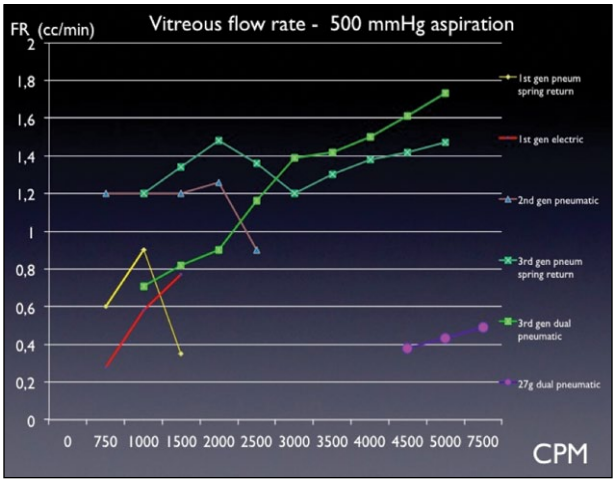

Figure 1. Vitreous flow rate (cc/min) at different cut rates with 3 generations of 25-gauge vitrectomy systems and the recently introduced 27-gauge system.

Better duty cycles and vitreous flow rate were obtained by optimizing the pneumatic spring return systems in what can be defined as a second generation of pneumatic instruments, allowing these instruments to maintain a stable flow, up to 2000 cpm.[8]

The introduction of dual–pneumatic-driven vitrectomy systems with 2 separate pneumatic pumps has enabled high cut rates and duty cycle modulation with-

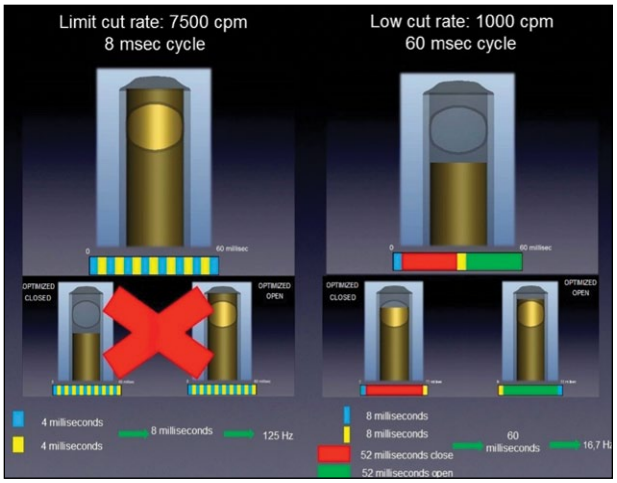

Figure 2. Cycle phases and duty cycle control at different cut rates with the 7500 cpm dual pneumatic vitreous cutter.

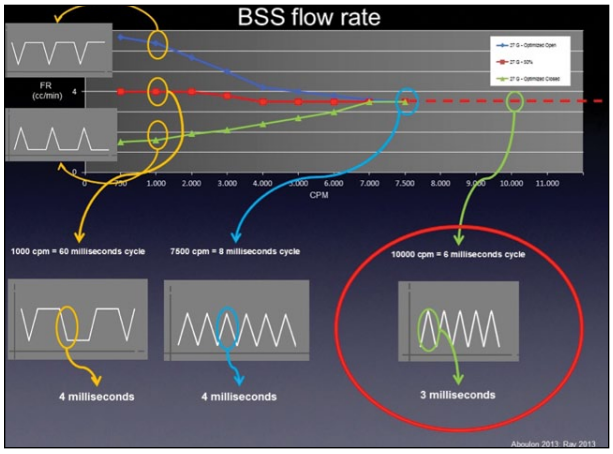

Figure 3. At 7500 cpm the duty cycle is fixed at 50%. If we want to go faster we need a faster blade.

out inefficiency up to maximum blade speed. In vitro studies have demonstrated a progressive increase in vitreous flow rate as cut rate increases (Figure 1).[9]

Hardware and software modifications have been recently introduced to allow increases in blade speed, affecting the closing and opening phases and therefore allowing speeds to reach up to 7500 cpm, with a frequency of 125 Hz and a cycle duration of 8 ms.

With the latest additions, the control of the duty cycle has been pushed toward higher cut frequencies for all calibers, and further reduction in probe size down to 27 gauge became possible. On the other hand, the reduction of 0.1 mm in external diameter from 25 to 27 gauge at 7500 cpm has necessitated a step back to the maximum flow rates achievable with the first-generation 25 gauge.

In the continuous quest for a true sutureless surgery, free from risks of sclerotomy leakage and related complications and aimed toward a new era of minimally invasive macular surgery and subretinal injection treatments, further size reduction of vitrectomy probes and instruments will still be required.

Given that reduction in the size of a pipe means a very significant reduction in the volume of flow of a viscous fluid (flow rate is directly proportional to the inner radius of the tube to the fourth power), we have to modify other flow-conditioning parameters in order to counterbalance this effect: by decreasing the length of the pipe, by increasing the difference in pressure (vacuum), or by decreasing the viscosity of the liquid.

Increasing the vacuum would mean increasing traction; this is evident if we consider that the effect on both balanced salt solution and vitreous flow would increase, with a ratio in favor of the nonviscous liquid.

Reducing the viscosity of the vitreous is a potentially more advantageous strategy, yielding both an improvement of the flow of the viscoelastic component and a reduction in difference between the saline solution and vitreous flow, with a reduction in traction as a result. The importance of viscosity reduction can be inferred by the difference between vitreous flow and the flow of balanced saline solution; although it can be seen that with increasing cut rate the difference decreases, the gap between the 2 is still very significant, and this will hold true in the future if gauges continue to become smaller.

Possible means of achieving a decrease in the viscosity of the vitreous include mechanical cutting of the vitreous, use of ultrasound, and use of an electrochemical or enzymatic process.

Efforts to date have been directed toward the first method, decreasing viscosity of the vitreous by increasing the cut rate of vitreous chopping. Intact vitreous has a viscosity of 908.1 Pascal-seconds (Pa-s). By contrast, the viscosity of chopped vitreous is 0.039 Pa-s.[10,11]

However, there is a mechanical speed limit: the speed of the vitreous cutter blade. This conditions the maximum cut rate.

As previously noted, with current technologies the maximum speed achievable is 7500 cpm. Stated simply, at the highest cut rate, the vitreous cutter blade is always moving, opening in 4 ms and closing in 4 ms, and the duty cycle is fixed at 50%. When the cut rate is lower, the cycle is longer than the opening/closing time of the blade (this does not change at higher and lower cut rates), which allows us to play with the duty cycle by varying the closed and opened phases (Figure 2). This is evident if we look at duty cycle modes at different cut rates. When we reach the fastest speed, the duty cycle is 50%, no matter what duty cycle mode we choose (Figure 3).

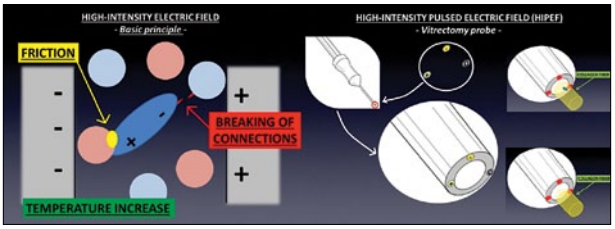

Figure 4. High-intensity pulsed electric field (HIPEF) could be used for electrochemical viscosity modification.

FUTURE DIRECTIONS

If we want to go faster, we need a more efficient system to increase the speed of the blade, for instance to 10 000 cpm, so that the blade can open and close in 3 ms.[12,13]

To exceed the actual mechanical speed limit, we need new ideas, such as a faster pneumatic drive, a hydraulic drive, or possibly a piezoelectrically driven probe. If a piezoelectric motor were driven up to ultrasonic frequencies, as in an anterior chamber phacoemulsification device, it could deliver speeds of up to 45 kHz—that is, 3 million cpm. Unfortunately, such a device would not provide sufficient tip elongation to realize a proper vitreous cutting action. However, if the frequency of the piezo were reduced to 375 Hz—that is, 22 500 cpm—it could provide enough blade movement and still be 3 times faster than the fastest technology in use today.

Another approach would be to use ultrasound to make the vitreous more liquid. A prototype for this approach was described by Carl Awh, MD, at Euretina 2013.[14] The Ultrasonic Vitreous Cutter would have a "cut rate" of more than 1 000 000 cycles per minute with 100% duty cycle; the port is always open.

Electrochemical viscosity modification is another possibility, with the application of a high-intensity electric field with a very–high-frequency variation of charge between 2 or more electrodes mounted at the end of a vitrectomy probe. This could modify the nature of the vitreous, making it fluid and allowing smooth suction (Figure 4).

A few years ago, we proposed a simpler and more economical approach.[15] By adding a guillotine port on the internal sleeve of the vitrectomy probe, we can double the speed limit. A sharp-edged hole in the inner sleeve of the cutter allows the device to cut vitreous in both directions, downstroke and return stroke, thus automatically doubling the cut rate (Figure 5). This will, therefore, also increase flow and potentially reduce traction on the retina from the vitrectomy probe. Flow would be constant and duty cycle would be 100%.

CONCLUSION

Is there a limit to how fast we can cut and how small we can go? The limits are set by the laws of physics, the inventiveness of ophthalmologists and materials scientists, and the economics of health care equipment manufacturing. As we move forward, improvements to current technologies will define our path toward safer, more efficient, and more effective vitreoretinal surgery. ■

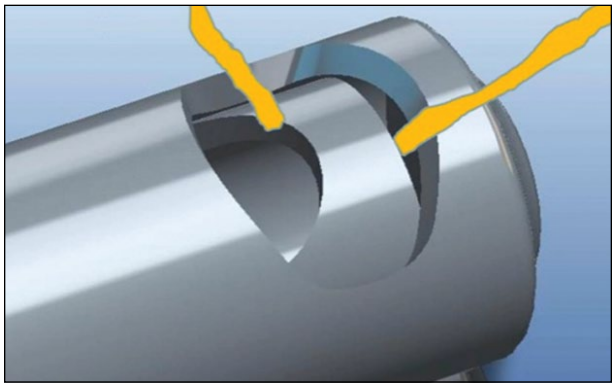

Figure 5. Modified probe with a guillotine port on the internal sleeve of the vitrectomy probe.

Stanislao Rizzo, MD, is Director of U.O. Chirurgia Oftalmica, Ospedale Cisanello, Azienda Ospedaliero Universitaria Pisana in Pisa, Italy. He states that he has no financial interests relevant to the content of this article. Dr. Rizzo is a member of the Retina Today *Editorial Board. He may be reached via email at stanislao.rizzo@gmail.com.*

Francesco Faraldi, MD, is Director of U.O. Oculistica C, Ospedale Oftalmico, Turin, Italy. He states that he has no financial interests relevant to the content of this article.

1. Machemer R, Buettner H, Norton EW, Parel JM. Vitrectomy: a pars plana approach. *Trans Am Acad Ophthalmol Otolaryngol*. 1971;75(4):813-820.
2. Machemer R. The development of pars plana vitrectomy: a personal account. *Graefes Arch Clin Exp Ophthalmol*. 1995;233(8):453-468.
3. O'Malley C, Heintz RM Sr. Vitrectomy with an alternative instrument system. *Ann Ophthalmol*. 1975;7(4):585-588, 591-594.
4. Fujii GY, De Juan E Jr, Humayun MS, et al. A new 25-gauge instrument system for transconjunctival sutureless vitrectomy surgery. *Ophthalmology*. 2002;109(10):1807-1812; discussion 1813.
5. Charles S. An engineering approach to vitreoretinal surgery. *Retina*. 2004;24(3):435-444.
6. Magalhaes O Jr, Chong L, DeBoer C, et al. Vitreous dynamics: vitreous flow analysis in 20-, 23-, and 25-gauge cutters. *Retina*. 2008;28(2):236-241.
7. Hubschman JP, Gupta A, Bourla DH, Culjat M, Yu F, Schwartz SD. 20-, 23-, and 25-gauge vitreous cutters: performance and characteristics evaluation. *Retina*. 2008;28(2):249-257.
8. Fang SY, DeBoer CM, Humayun MS. Performance analysis of new-generation vitreous cutters. *Graefes Arch Clin Exp Ophthalmol*. 2008;246(1):61-67.
9. Diniz B, Ribeiro RM, Fernandes RB, et al. Fluidics in a dual pneumatic ultra high-speed vitreous cutter system. *Ophthalmologica*. 2013;229(1):15-20.
10. Sharif-Kashani P, Nishida K, Pirouz Kavehpour H, Schwartz SD, Hubschman JP. Effect of cut rates on fluidic behavior of chopped vitreous. *Retina*. 2013;33(1):166-169.
11. Charles S. An engineering approach to vitreoretinal surgery. *Retina*. 2004;24(3):435-444.
12. Abulon DJK, Buboltz DC. Porcine vitreous flow behavior during high speed vitrectomy up to 7500 cuts per minute. *Invest Ophthalmol Vis Sci*. 2012;53:E-Abstract 36915.
13. Ray A, Abulon DJK, Dimalanta R, Buboltz DC. Intraocular Pressure and BSS Flow Rates at High Vitrectomy Probe Cut Rates. Poster presented at Association for Research in Vision and Ophthalmology annual meeting; May 8, 2012; Fort Lauderdale, FL.
14. Awh C. Advances in vitreoretinal surgery instrumentation. Paper presented at: Euretina 2013; September 28, 2013; Hamburg, Germany.
15. Rizzo S. Performance of a modified vitrectomy probe in small gauge vitrectomy: an experimental and clinical study. Paper presented at: American Society of Retina Specialists annual meeting; August 20-24, 2011; Boston.