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FLUIDIC PERFORMANCE OF A DUAL-ACTION VITRECTOMY PROBE COMPARED WITH A SINGLE-ACTION PROBE

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Purpose: To assess flow rates, nearfield effects, and traction of a dual-cutting 20,000 cpm vitrectomy probe (HYPERVIT, Alcon) versus a single-cutting 10,000 cpm probe (Advanced ULTRAVIT, Alcon).

Methods: Flow rates were evaluated for 25+ and 27+ gauge probes using balanced salt solution or porcine cadaver vitreous (biased open, 50/50, and biased closed duty cycles). Probes were suspended in an open beaker, and flow rates were calculated using a precision balance. Nearfield effects and flow pulsatility were assessed using a validated simulation model based on experimental microparticle image velocimetry. Traction was assessed by attaching vitreous to a cantilever beam and measuring the deflection of the beam.

Results: For HYPERVIT probes, aqueous flow rates were similar across all cutting rates. Vitreous flow rates increased with increasing cutting rates. At maximum cutting rates, aqueous flow was 62%–67% greater (25+) and 63% greater (27+) with HYPERVIT versus Advanced ULTRAVIT ($P < 0.05$); vitreous flow was 44%–47% greater (25+) and 26%–32% greater (27+) with HYPERVIT versus Advanced ULTRAVIT ($P < 0.05$). Nearfield effects were reduced, and peak traction forces were significantly lower for HYPERVIT versus Advanced ULTRAVIT ($P < 0.05$).

Conclusion: Significantly greater aspiration flow, reduced nearfield effects, and reduced traction were observed with dual-action versus single-action probes.

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Vitreous cutter technology has evolved rapidly over the past 10 years in response to the need for smaller-gauge instruments and reduced retinal traction. Minimally invasive sutureless microincision vitrectomy using small-gauge probes has improved recovery time and patient comfort and reduced the risk of entry site complications.[1–3] Studies with small-gauge probes reported no increased risk of endophthalmitis and demonstrated good long-term visual outcomes and safety.[4,5]

Small-gauge vitrectomy requires aspiration flow rates that are similar to larger-diameter vitreous cutters. Aspiration flow can be increased by maximizing the inner lumen diameter of the instrument and increasing vacuum; however, these variables are constrained by physical limits.[6,7] Furthermore, increased vacuum and a corresponding increase in vitreous acceleration are associated with increased retinal traction.[8,9] Increasing the cutting rate of the vitrectomy probe reduces vitreous bite size and resultant traction but comes at the expense of reducing the port duty cycle, ie, time the vitrectomy port is open.[6]

Engineers partially addressed this issue by introducing and improving dual pneumatically driven cutters, leading to better control of duty cycle, greater achievable open port times, and improvements in flow. In biased open duty cycle, the pneumatic cutters have the maximum port open time; in 50/50 duty cycle, the port is opened 50% of the time; and in biased closed duty cycle, the cutters have the minimum open port time. Previous generation dual-pneumatic probes with increasing maximum cutting rates of 5,000, 7,500, and 10,000 cuts per minute (cpm) demonstrated increased vitreous flow rate with increasing cutting rates in a biased open duty cycle mode.[10,11]

Dual-action vitrectomy probes, which cut vitreous on both close and open strokes using a double-edged blade, can effectively double the cutting rate and significantly increase flow rates.[12,13] However, the exact effects of dual-action cutters on fluidic performance have not been fully elucidated. Although vitreous movement assessments can provide gross information on flow rate and localized effects of the probe within the eye, it cannot accurately quantify more subtle effects, such as pulsatile vitreoretinal traction and near and far-field effects. When switching to a new vitrectomy probe, surgeons should take into consideration precise fluidic parameters and be prepared to adjust their settings to maintain performance.

HYPERVIT (Alcon Vision LLC, Fort Worth, TX) is a novel dual-action pneumatic probe with a 20,000 cpm cutting rate. An additional port in the blade allows cutting on both edges (Figure 1), meaning that the HYPERVIT probe makes two cuts during an operating cycle. The resulting near-continuous open port duty cycle may improve flow and reduce pulsatility during vitrectomy. This study assessed flow rates, nearfield effects, and vitreoretinal traction when using HYPERVIT and compared these parameters with a conventional single-action 10,000 cpm cutter (Advanced ULTRAVIT, Alcon Vision LLC). Equivalent settings and parameters were evaluated to provide comparison of the two systems for 25+ and 27+ gauge probes in sterile irrigating solution and vitreous.

Fig. 1. HYPERVIT dual-cutting probe. Additional port in the internal cutter allows for cutting on both edges.

Methods

Aqueous and Vitreous Flow Rates

Aqueous and vitreous flow rates were evaluated for 25+ and 27+ gauge HYPERVIT 20,000 cpm and Advanced ULTRAVIT 10,000 cpm probes. For aqueous flow rates, balanced salt solution was used. For vitreous flow rates, porcine cadaver vitreous extracted through an incision of the pars plana was used. Porcine eyes (Sierra for Medical Science, Whittier, CA) were refrigerated before vitreous retrieval and used within 12 hours of sacrifice. Vitrectomy probes were suspended in an open beaker containing either balanced salt solution or porcine vitreous.[14] In brief, a surgical blade was used to perform an open sky procedure. An incision was made 2 to 3 mm below the sclera. Once the anterior part of the eye was removed, any remaining vitreous still attached was scraped off using a scalpel. Curved tweezers were used to transfer vitreous from the porcine eye socket into a petri dish. Cotton swabs were used to remove the residual retinal tissue on the vitreous. A precision balance was used to measure the mass of vitreous in an open beaker.

Flow rates were calculated using a precision balance and LabVIEW VI program (National Instruments, Austin, TX) over a range of cutting rates and vacuum

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settings based on weight changes during the aspiration. There was no infusion, and new cutters were used for every test. The vitrectomy probes were primed before testing. Testing conditions were repeated ≥3 times; all tests were evaluated for 60 seconds. For each duty cycle (biased open, biased closed, and 50/50), mean flow rates and SD were reported for 25+ and 27+ probes at 650 mmHg vacuum and varying cutting rates. Mean flow rates and SD were reported for HYPERVIT probes at 20,000 cpm and varying vacuum settings in a biased open duty cycle.

Nearfield Effect and Pulsatility of Flow

A simulated computational model of 25+ gauge Advanced ULTRAVIT 10,000 cpm vitrectomy probes was validated with an experimental microparticle image velocimetry setup. Parameters included balanced salt solution at <650 mmHg vacuum with cutter off and a thin sheet of laser (PurePoint, 532 nm at 500 mW) used to illuminate dispersed polyamide particles ($\rho = 1.00$ g/cc, $D_{\text{mean}} = 75\text{–}90\ \mu\text{m}$) in a beaker. Movement of particles was captured using a high-speed CCD camera at 2000 fps. Velocity profiles on lines normal to the probe port and parallel to the probe port were used to compare particle image velocimetry scatter data with the simulation. The computational fluid dynamic model was in good agreement with the particle image velocimetry velocity data (Figure 2). Reynolds number, a nondimensional number that compares the fluid inertial forces based on fluid density, flow velocity, and probe diameter versus the fluid viscosity, was used for assessing nearfield effects. In the nearfield, the fluid inertial forces caused by the probe vacuum are larger or of the same order of magnitude as the viscous forces of the fluid. The validated simulation model was used to compare mean Reynolds number as a function of distance from the probe tip for the 25+ gauge Advanced ULTRAVIT 10,000 cpm (beveled tip) and HYPERVIT 20,000 cpm (flat tip) under matched vacuum and flow conditions.[14] The maximum values were recorded. A dynamic mesh was used to simulate the motion of the cutter. Flow was assumed to be incompressible and laminar. The results were extracted for one cut cycle after cyclic flow was established. The boundary of the nearfield effects was obtained at a distance from the probe tip where the Reynolds number approached unity. The flow pulsatility was quantified by root mean square of velocity over a cycle normalized by the mean velocity, providing root mean square velocity intensity at each spatial point in the flow field.

Traction

A mechanical force measurement system was developed to quantify tractional forces applied to vitreous by a vitrectomy cutter. Traction forces were calculated by attaching vitreous to a cantilever beam using a proprietary adherent bonding technique and measuring the deflection of the beam as the vitrectomy probe–induced aspiration pulled on the vitreous (Figure 3). The probe was moved toward the vitreous at a speed of 0.16 mm/s for 27+ gauge and 0.14 mm/s for 25+. Traction measurements were performed *ex situ* using vitreous harvested from fresh porcine eyes; 30 tests were conducted in biased open, 50/50, and biased closed duty cycles. Matched flow rates were used; to achieve the same flow rate, 380 mmHg vacuum with 25+ HYPERVIT probes was used to match 600 mmHg vacuum of 25+ Advanced ULTRAVIT probes. For 27+ probes, 450 mmHg vacuum with HYPERVIT was used to match 650 mmHg vacuum of Advanced ULTRAVIT. Peak traction data at the maximum cutting rate were averaged.

Statistical Analysis

Significant differences in aspiration flow and traction forces between the HYPERVIT and Advanced ULTRAVIT groups at their maximum cutting rates were tested using a Welch t test with significance level of $P \leq 0.05$.

Results

Aqueous Flow

Aqueous flow rates for the 20,000 cpm 25+ HYPERVIT probe were similar for all cutting rates in the biased open, 50/50, and biased closed duty cycle, ranging from 15.34 ± 0.69 to 15.82 ± 0.65 cc/min (Figure 4A). Aqueous flow rates for the 27+ HYPERVIT probe were also similar for all cutting rates in the biased open, 50/50, and biased closed duty cycle, ranging from 8.27 ± 0.34 to 8.65 ± 0.29 cc/min (Figure 4A). Changing duty cycle and cutting rate did not significantly influence aqueous flow rate for the 25+ or 27+ gauge HYPERVIT probes ($P > 0.05$). At 20,000 cpm, flow rates for 25+ and 27+ gauge HYPERVIT probes increased with increasing vacuum (Figure 4B and see **Figure 1, Supplemental Digital Content 1**, http://links.lww.com/IAE/B760).

At maximum cutting rates, 20,000 cpm 25+ HYPERVIT generated significantly greater aqueous flow than the 10,000 cpm 25+ Advanced ULTRAVIT probe ($P < 0.0001$; Figure 4C). Aqueous flow rates

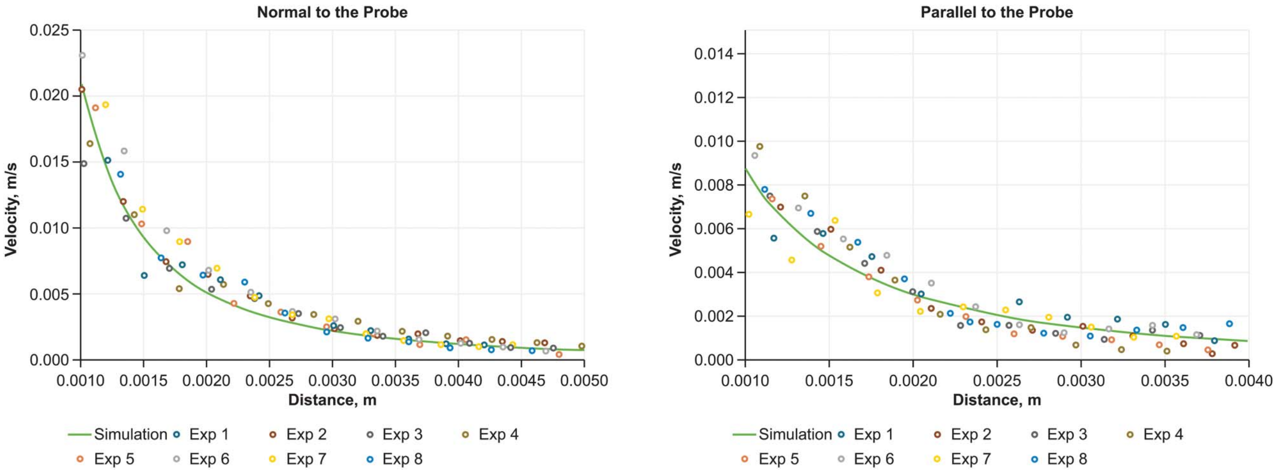

Fig. 2. Comparison of fluid velocity profiles on lines normal and parallel with respect to the probe port.

with 25+ HYPERVIT at 20,000 cpm were 67%, 62%, and 65% greater compared with Advanced ULTRAVIT probes at 10,000 cpm in the biased open, 50/50, and biased closed duty cycles, respectively. At maximum cutting rates, 20,000 cpm 27+ HYPERVIT generated significantly greater aqueous flow compared with the 10,000 cpm 27+ Advanced ULTRAVIT ($P < 0.0001$; Figure 4D). Aqueous flow rate with the 27+ HYPERVIT at 20,000 cpm was 63% greater compared with the Advanced ULTRAVIT probes at 10,000 cpm in all duty cycles.

Vitreous Flow

Vitreous flow rates for the 25+ HYPERVIT probe increased as cutting rate increased; the greatest aspiration flow was observed at 20,000 cpm for all duty cycles (Figure 5A). Flow rate ranged from 2.95 ± 0.32 to 3.98 ± 0.28 cc/min in the biased open duty cycle, from 2.70 ± 0.41 to 3.96 ± 0.29 cc/min in the 50/50 duty cycle, and from 2.45 ± 0.37 to 4.08 ± 0.48 cc/min in the biased closed duty cycle. Although change in duty cycle did not have a significant effect on vitreous flow rate ($P > 0.05$ for biased open vs. 50/50, biased open vs. biased closed, and 50/50 vs. biased closed), increase in flow rate as a function of cutting rate was significant in all duty cycles.

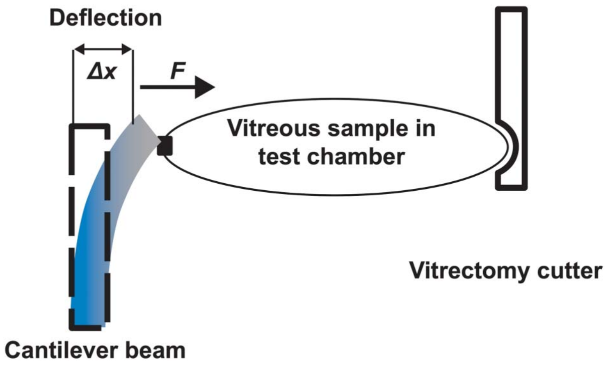

Fig. 3. Traction force measurement system. F = traction force; Δx = change in the cantilever beam.

Vitreous flow rates for the 27+ HYPERVIT probe increased as cutting rate increased; the greatest aspiration flow was observed at 20,000 cpm for all duty cycles (Figure 5A). The flow rate ranged from 1.54 ± 0.18 to 2.15 ± 0.13 cc/min in the biased open duty cycle, from 1.38 ± 0.21 to 2.17 ± 0.13 cc/min in the 50/50 duty cycle, and from 1.41 ± 0.21 to 2.17 ± 0.18 cc/min in the biased closed duty cycle.

For 25+ and 27+ gauge HYPERVIT probes in the biased open and 50/50 duty cycle, the vitreous flow rate was significantly less for cutting rates under 10,000 cpm compared with 20,000 cpm ($P < 0.05$). For biased closed duty cycle, the vitreous flow rate was significantly less for cutting rates under 7,500 cpm compared with 20,000 cpm ($P < 0.05$). As the cutting rate increased, the differences in vitreous flow were less significant.

At 20,000 cpm, flow rates for 25+ and 27+ gauge HYPERVIT probes increased with increasing vacuum (Figure 5B). For 25+ probes at maximum cutting rates, HYPERVIT required 15% less vacuum to match the flow rate of the Advanced ULTRAVIT probes at 650 mmHg. For 27+ probes, HYPERVIT required 31% less vacuum to match the flow rate of the Advanced ULTRAVIT probes at 650 mmHg. HYPERVIT vacuum settings can be adjusted to achieve similar vitreous flow as the previous-generation Advanced ULTRAVIT probe.

At maximum cutting rates, the 20,000 cpm 25+ HYPERVIT generated significantly greater vitreous flow than the 10,000 cpm 25+ Advanced ULTRAVIT probe ($P < 0.05$; Figure 5C). Vitreous flow rates were 44%, 46%, and 47% higher for HYPERVIT at

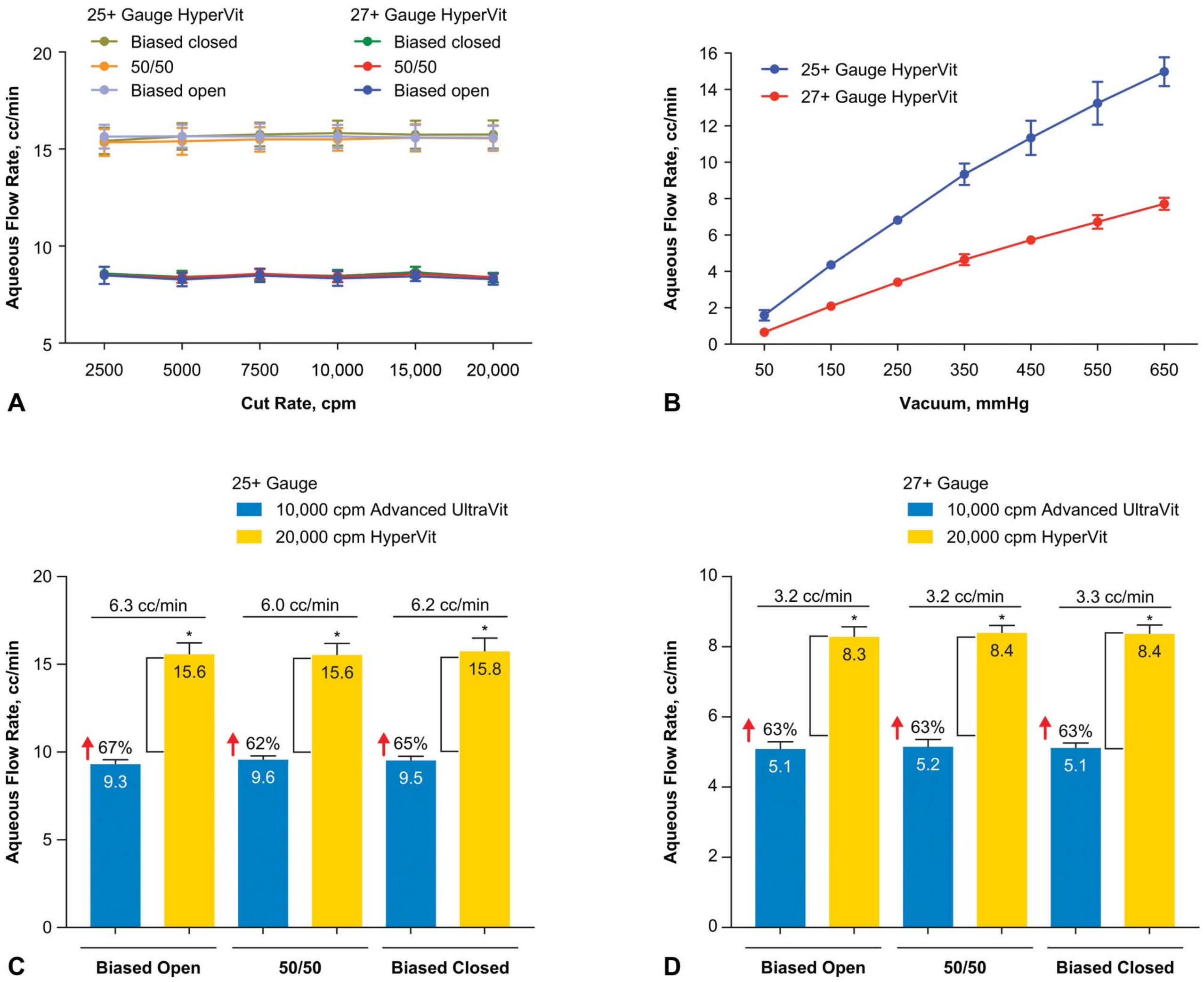

Fig. 4. Average aqueous flow rate with HYPERVIT 25+ and 27+ gauge probes at 650 mmHg vacuum as a function of cutting rate (**A**), n = 6, and at 20,000 cpm as a function of vacuum (**B**), n = 3. Aqueous flow rate at maximum cutting rate and 650 mmHg vacuum for 20,000 cpm HYPERVIT versus 10,000 cpm ULTRAVIT probes with 25+ gauge (**C**) and 27+ gauge (**D**). Error bars represent standard deviation. $^*P < 0.0001$.

20,000 cpm versus Advanced ULTRAVIT at 10,000 cpm in the biased open, 50/50, and biased closed duty cycles, respectively ($P < 0.0001$). At maximum cutting rates, the 20,000 cpm 27+ HYPERVIT generated greater vitreous flow compared with the 10,000 cpm 27+ Advanced ULTRAVIT probe (Figure 5D). Vitreous flow rates were 26%, 26%, and 32% higher for HYPERVIT at 20,000 cpm versus Advanced ULTRAVIT at 10,000 cpm in the biased open, 50/50, and biased closed duty cycles, respectively ($P < 0.001$).

Nearfield Effects and Variability in Flow

Nearfield effects and intensity of pulsatile motion were obtained from the computational fluid dynamic simulations and were measured on spheres of increasing radius from probe tips. The HYPERVIT probes had a stronger flow field in the near field ($r < 4$ mm). At $r = 4$ mm, the local Reynolds number dropped below unity (boundary of nearfield effects; Figure 6, A and B). Root mean square velocity intensity was assessed both under vacuum and flow matched conditions (Figure 6, C and D). HYPERVIT had lower flow pulsatility, as indicated by lower root mean square velocity intensity and stayed constant at distances >1.5 mm in the nearfield of the probe tip. At 650 mmHg vacuum, based on the mean Reynolds numbers, the HYPERVIT nearfield was larger compared with the Advanced ULTRAVIT: approximately 3.8 versus 3.2 mm, respectively (Figure 6, C and D). Based on simulations, flow performance of the 25+ gauge HYPERVIT probe had more stable aspiration, shown by the reduction in the pulse intensity of velocity during fluid aspiration.

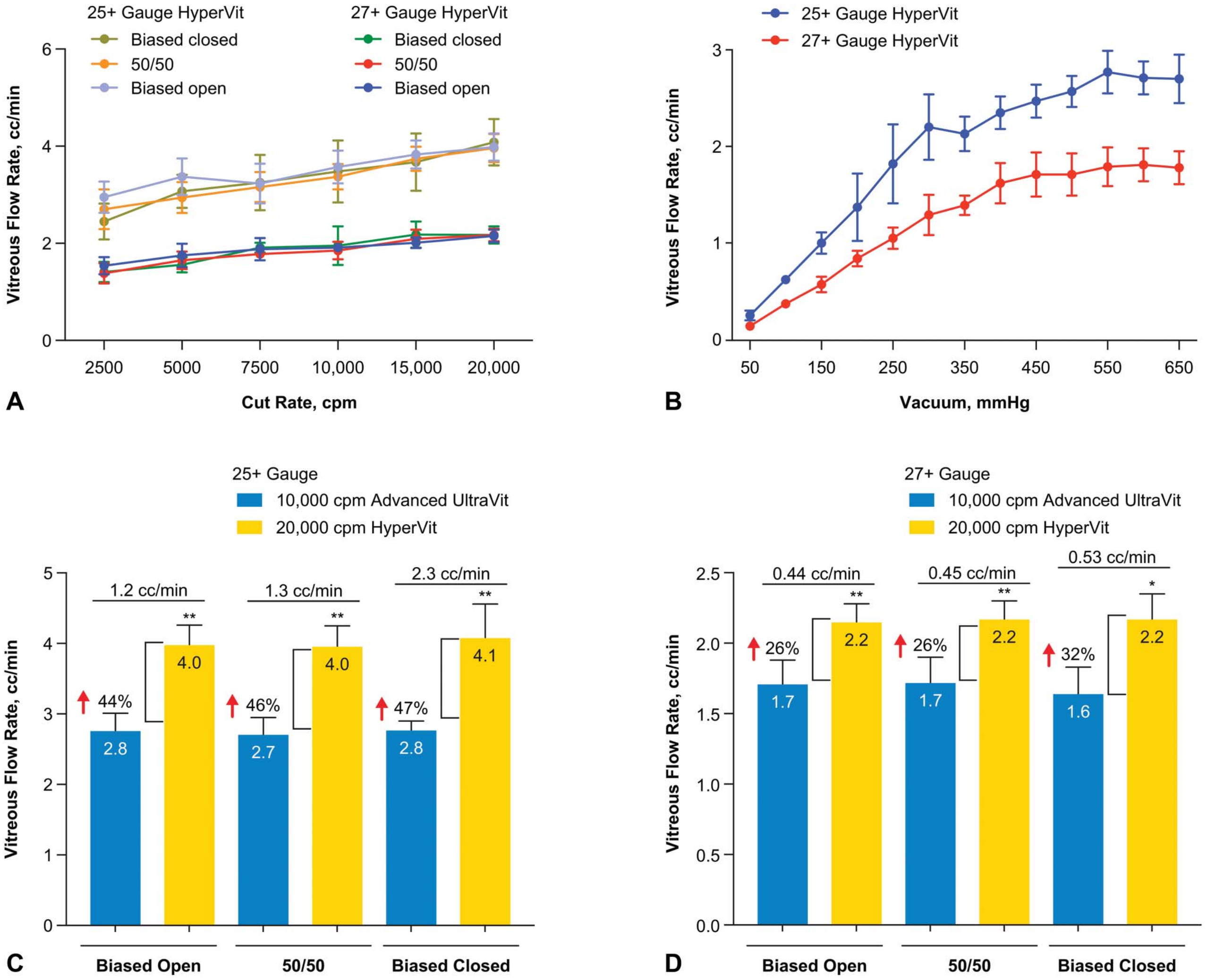

Fig. 5. Average vitreous flow rate with HYPERVIT 25+ and 27+ gauge probes at 650 mmHg vacuum as a function of cutting rate (**A**), n = 8 for 25+ gauge and n = 6 for 27+ gauge, and at 20,000 cpm as a function of vacuum (**B**), n = 8. Vitreous flow rate at maximum cutting rate and 650 mmHg vacuum for 20,000 cpm HYPERVIT versus 10,000 cpm ULTRAVIT probes with 25+ gauge (**C**) and 27+ gauge (**D**). Error bars represent standard deviation. $^{**}P < 0.0001$; $^{*}P < 0.001$.

Although the nearfield effects for the probes were similar over the entire cycle, the maximum size of the region of high-velocity flow around the probe occurred when the cutter reached its most retracted position. In Figure 7, this region was visualized using isosurface of Reynolds number of 10 around the probe tip for matched flow condition. The region of high velocity was considerably smaller for the HYPERVIT probes compared with Advanced ULTRAVIT probes (Figure 7, A and B), primarily because of lower vacuum compared with the Advanced ULTRAVIT probe.

Traction

At matched flow rates and maximum cutting rates, the 25+ gauge 20,000 cpm HYPERVIT probes generated 28%, 21%, and 20% less peak traction forces compared with the 10,000 cpm Advanced ULTRAVIT probes (Figure 8A) in biased open, 50/50, and biased closed duty cycle, respectively. Peak traction forces were significantly greater with the Advanced ULTRAVIT probes compared with the HYPERVIT probes ($P < 0.05$ for all). At similar flow rates and maximum cutting rates, the 27+ gauge 20,000 cpm HYPERVIT probes generated 31%, 25%, and 41% less peak traction forces (Figure 8B) compared with the 10,000 cpm Advanced ULTRAVIT probes in biased open, 50/50, and biased closed duty cycle, respectively ($P < 0.05$ for all).

Discussion

This study assessed the performance of the dual-cutting 20,000 cpm HYPERVIT probe and found that

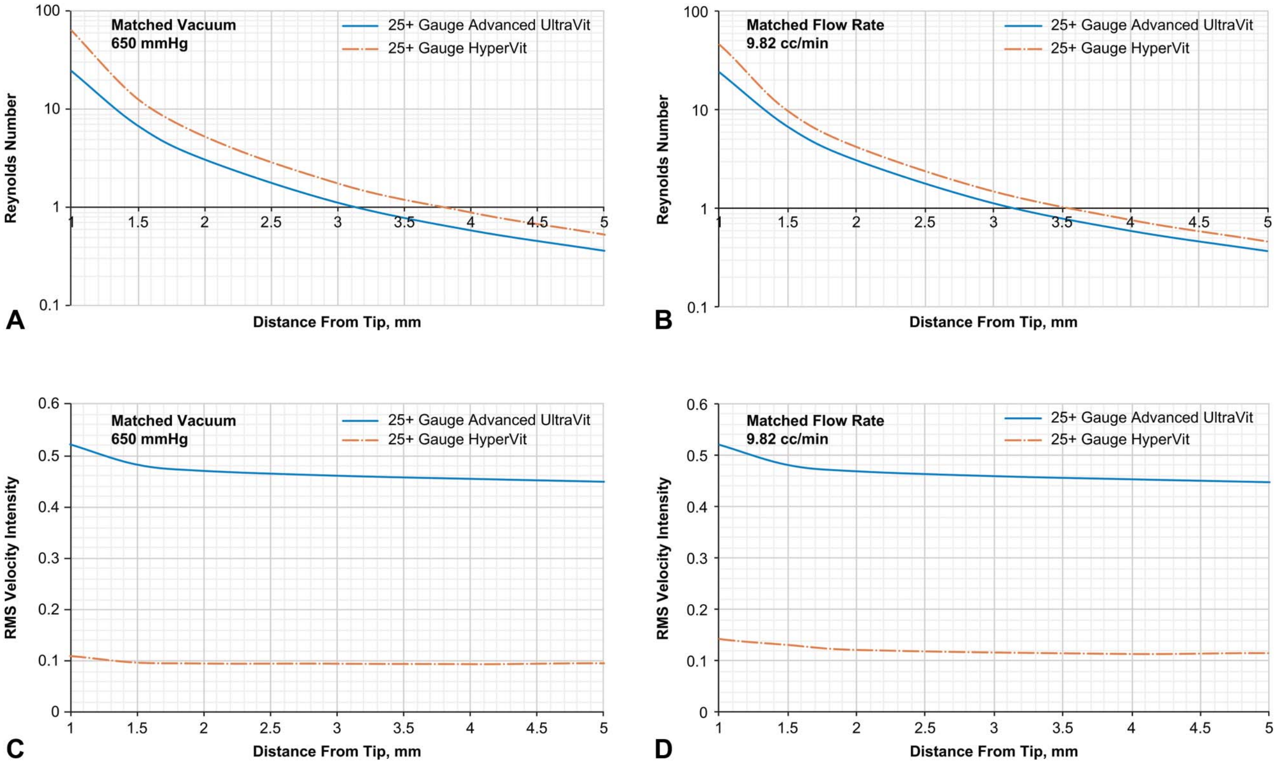

Fig. 6. Simulation for the HYPERVIT and Advanced ULTRAVIT probes using 50/50 duty cycle and 10,000 cpm cutting rate showing mean Reynolds number for matched vacuum of 650 mmHg (**A**) and matched flow rate of 9.82 cc/min (**B**) and RMS velocity intensity for matched vacuum of 650 mmHg (**C**) and matched flow rate of 9.82 cc/min (**D**). RMS, root mean square.

it achieved improved fluidic performance compared with Advanced ULTRAVIT. Aqueous flow rates with the 20,000 cpm HYPERVIT were similar for all cutting rates tested (near-constant open duty cycle). Vitreous flow rates for the 20,000 cpm 25+ and 27+ HYPERVIT probes had an increasing trend as cutting rate increased. Changing duty cycle did not have a significant effect on vitreous or aqueous flow rates. Furthermore, at maximum cutting rate, HYPERVIT probes had significantly greater aspiration flow rates compared with Advanced ULTRAVIT. With dual-cutting HYPERVIT probes, significantly less vacuum was required to achieve comparable flow rates; therefore, settings must be adjusted to achieve similar flow as previous-generation cutters. Peak traction forces for HYPERVIT were lower compared with the Advanced ULTRAVIT at matched flow rates. Furthermore, the HYPERVIT probes had more stable aspiration and reduced pulsatility compared with the Advanced ULTRAVIT probes.

No significant differences in aqueous flow rates were observed across cutting rates or for individual duty cycles with 25+ and 27+ HYPERVIT probes because of near-constant open duty cycle of the dual-action blade. By contrast, previous-generation 5,000 and 7,500 cpm ULTRAVIT and 10,000 cpm Advanced ULTRAVIT probes demonstrated that aqueous flow rate increased with increasing cutting rate in the biased closed duty cycle, remained relatively stable in the 50/50 duty cycle, and decreased in the biased open duty cycle.[15] Similarly, although no significant differences in vitreous flow rates were observed for individual duty cycles with 25+ and 27+ HYPERVIT probes, vitreous flow rate increased with higher cutting rates in all duty cycles. By contrast, for Advanced ULTRAVIT probes, vitreous flow rate was more dependent on cutting rate in the biased closed duty cycle (flow rates increased with higher cutting rate) and less dependent on cutting rate in the 50/50 and biased open duty cycle. Previous studies of vitreous flow rates with 5,000 and 7,500 cpm ULTRAVIT probes similarly reported that flow rates were affected by both cutting rate and duty cycle.[10,11]

At maximum cutting rates, aqueous and vitreous flow rates were significantly greater with the 20,000 cpm HYPERVIT compared with the 10,000 cpm Advanced ULTRAVIT probes. Aqueous flow rates increased by 62%–67% for 25+ gauge and 63% for 27+ gauge probes; vitreous flow rates increased by 44%–47% for 25+ gauge and by 26%–32% for 27+ gauge probes. These results are consistent with the higher port open time and cut rate of the HYPERVIT

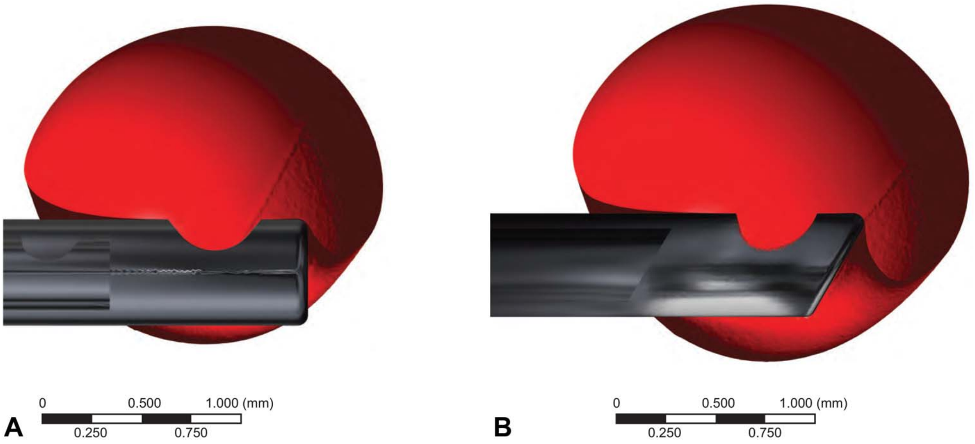

Fig. 7. Visualization of nearfield effects by the area of Reynolds number >10 for HYPERVIT (**A**) and Advanced ULTRAVIT (**B**) probes under matched flow conditions (cutter in the retracted position, 50/50 duty cycle, and 10,000 cpm cutting rate).

probes leading to greater vitreous fragmentation, reduced viscosity, and higher flow.[16]

Nearfield effects are typically reduced with smaller gauge size; however, the effect of cutting rate and dual-action vitrectomy cutter is unclear.[17] The nearfield effects were smaller with the 20,000 cpm HYPERVIT compared with the 10,000 cpm Advanced ULTRAVIT probe with the cutters in the retracted positions, likely a result of the lower vacuum used with the HYPERVIT versus Advanced ULTRAVIT probes under matched flow conditions.

Vitreous is nonhomogenous and has viscoelastic properties. Maintaining a consistent flow rate may help avoid pressure variations and vitreoretinal tractions, preventing complications such as inadvertent retinal trauma.[6,13,18] During surgery, aspiration pressure can be adjusted to compensate for macroscopic flow changes, and high cutting rates can also reduce vitreoretinal traction and vitreous movement by port-based flow limitation. Higher cutting rates reduce traction by generating smaller vitreous fragments.[6,7] In this study, peak traction forces were significantly lower for the HYPERVIT probe compared with the Advanced ULTRAVIT probe ($P < 0.05$). Furthermore, HYPERVIT had lower flow pulsatility and was associated with a reduction in retropulsion. These are likely the result of near-constant open duty cycle allowing more consistent flow and a reduced blade volume.

The decrease in traction forces is consistent with reports that traction decreases with increasing cutting rate for pneumatically driven spring return (Accurus; Alcon), electrically driven (Millennium Microsurgical System; Bausch & Lomb Inc, Rochester, NY) vitrectomy cutters, and ULTRAVIT dual-actuated pneumatic cutters.[9,19] Simulated vitreous traction force data also demonstrated a decrease in traction force with increasing cutting rate in

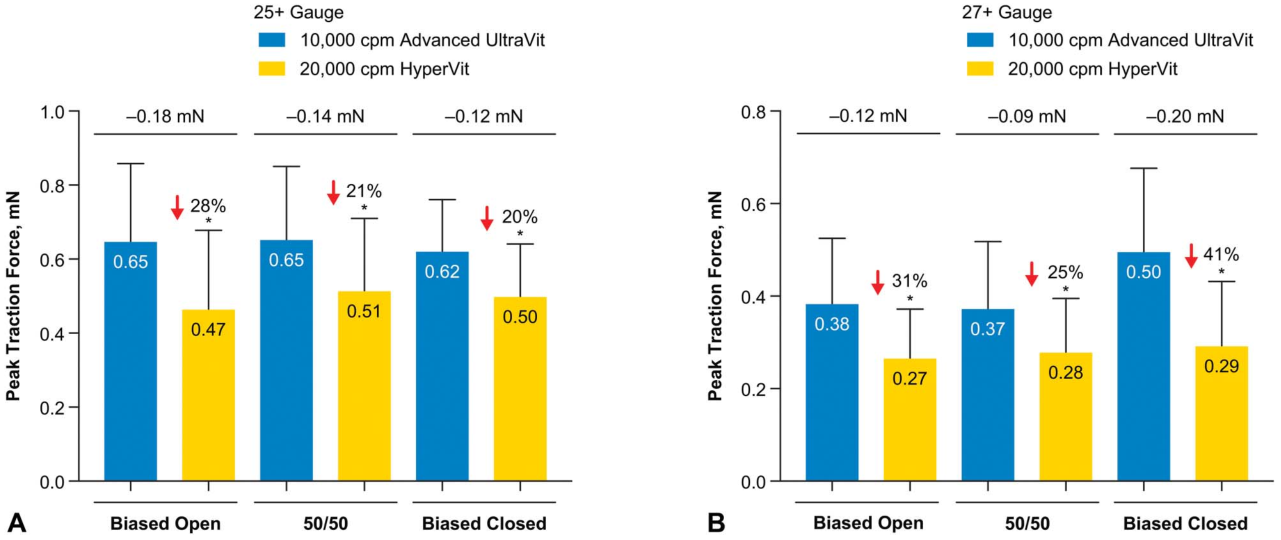

Fig. 8. Peak traction forces for advanced 25+ gauge (**A**) and 27+ gauge (**B**) HYPERVIT and Advanced ULTRAVIT probes; n = 30. Error bars represent standard deviation. Differences in peak traction forces were calculated using nonrounded values. $^*P < 0.05$.

a study that used a computational model for simulating vitreoretinal traction during vitrectomy.[20] However, another recent study reported that traction was not significantly dependent on the cutting rate.[21] Additional studies are needed to investigate fluidics parameters during vitrectomy, including tractional forces and retropulsive movements.

Limitations of this study included the use of porcine vitreous and an in vitro open-chamber experimental design without infusion. Vitreous flow may be affected by postmortem changes in refrigerated porcine eyes; furthermore, changes in the saline-to-vitreous ratio during vitrectomy were not taken into account. Potential differences in properties of porcine versus human vitreous (i.e., at the vitreous base and over the detached retina) may also affect vitreous flow. Differences in tip design (Advanced ULTRAVIT had a beveled tip and HYPERVIT had a flat tip) may affect measurements but are unlikely to be clinically meaningful for flow rates and traction. In addition, this traction study was only performed under matched flow rate conditions; higher vacuum with increased flow rate may result in a higher mean traction force. Further testing is needed to assess nearfield effects at matched vacuum and to explore the critical point of superiority.

In conclusion, the 25+ and 27+ gauge dual-cutting 20,000 cpm HYPERVIT probes had greater achievable aspiration flow rates and reduced traction at matched flow rates compared with the previous-generation single-cutting 10,000 cpm Advanced ULTRAVIT probes. Careful adjustment of vacuum settings is needed when transitioning from single-cutting probes to dual-cutting probes, with significantly less vacuum required to achieve comparable flow rates. The 20,000 cpm HYPERVIT probes demonstrated a stable fluidic performance that may help optimize surgical outcomes.

Key words: dual-action vitrectomy probes, flow rates, high-speed vitrectomy, nearfield effects, pulsatility, traction.

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