EFFECTS OF A MODIFIED VITRECTOMY PROBE IN SMALL-GAUGE VITRECTOMY

An Experimental Study on the Flow and on the Traction Exerted on the Retina

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Purpose: Thorough this experimental study, the physic features of a modified 23-gauge vitrectomy probe were evaluated in vitro.

Methods: A modified vitrectomy probe to increase vitreous outflow rate with a small-diameter probe, that also minimized tractional forces on the retina, was created and tested. The "new" probe was created by drilling an opening into the inner duct of a traditional 23-gauge probe with electrochemical or electrodischarge micromachining. Both vitreous outflow and tractional forces on the retina were examined using experimental models of vitreous surgery.

Results: The additional opening allowed the modified probe to have a cutting rate of 5,000 cuts per minute, while sustaining an outflow approximately 45% higher than in conventional 23-gauge probes. The modified probe performed two cutting actions per cycle, not one, as in standard probes. Because tractional force is influenced by cutting rate, retinal forces were 2.2 times lower than those observed with traditional cutters.

Conclusion: The modified probe could be useful in vitreoretinal surgery. It allows for faster vitreous removal while minimizing tractional forces on the retina. Moreover, any available probe can be modified by creating a hole in the inner duct.

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Sutureless pars plana vitrectomy (PPV) reduces postoperative inflammation at sclerotomy sites, decreasing patient postoperative discomfort and recovery time.[1–6] Unfortunately, these advantages are often mitigated by longer operation times, which are mainly caused by reduced vitreous outflow rates. The smaller diameter of the probe leads to a decreased vitreous outflow and possibly exposes the surrounding retinal tissue to higher tractional forces because of the resulting higher aspiration pressures.[7,8] Poiseuille law, which governs flow inside of a pipe, is applicable to a vitrectomy probe and states that volumetric flow is proportional to tube radius to the fourth power (r^4). Therefore, the vitreous aspiration rate is decreased by a factor of 6.6 with a 25-gauge vitreous cutter, compared with the aspiration rate obtained with a 23-gauge vitreous cutter, because of its smaller port and tube radius. To achieve acceptable values of the vitreous outflow, higher aspiration values (at least 600 mmHg) can be used and, because flow is also inversely proportional to tube length, the length of both the probe tube and the aspiration ducts can be reduced. Vitrectomy probes are pipes that are not always open. The end of the probe is equipped with a guillotine that continuously opens and closes, and the percentage of

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time that the cutter port is open is called the duty cycle.[9] Guillotines can either be pneumatically or electrically driven and each type has different duty cycle curves and cycle rates. The duty cycle greatly influences vitreous outflow. Both new- and past-generation spring-return pneumatic vitreous cutters have decreasing duty cycles with increasing cut speeds.[10] However, there is an intrinsic upper limit for the blade speed that prevents the full control of the duty cycle at all the cut rates. In an attempt to solve the problem of decreased flow during the cutter closure times, a conventional vitrectomy probe was modified by creating a hole in the internal guillotine blade that remains open whether or not the guillotine is opened or closed. Actually when the cutter port is open the vitreous can flow in through the port, conversely when the guillotine closes the port, the hole in the guillotine, allows the vitreous to be aspirated into the vitrectomy probe. Previous studies on "dual port cutters" oriented to increase cutter flow rate can be found in late 1990 but a new interest has only been recently noticed.[11,12]

The goal of this modification was to increase vitreous outflow during the closed phase of the vitreous cutter. This article describes our experimental observations and results with the modified vitrectomy probe at level of both vitreous outflow and retina traction.

Materials and Methods

The main outcome measures assessed the safety and efficacy of the modified vitreous cutter. Pars plana vitrectomy flow rates and tractional forces exerted on the retina were evaluated in porcine eye using an experimental setup to mimic physical conditions in the eye and in porcine eyes, respectively. Probes from 2 widely used 23-gauge vitrectomy systems (Stellaris PC [Bausch & Lomb, St. Louis, MO] and Constellation [Alcon Laboratories, Inc, Fort Worth, TX]) were modified by creating a hole (0.28–0.32 mm in diameter) in the internal guillotine blade (Figure 1). Electrochemical and electrodischarge micromachining were used to drill the guillotine blade in a total of 15 probes.

Five modified Stellaris PC probes (Bausch & Lomb) and five modified Constellation probes (Alcon) were used to examine flow (besides both Stellaris PC and Constellation traditional probes), four modified Constellation probes were used to measure tractional forces on the retina, and one modified Constellation probe was used for fatigue testing. Flow assessments included suction time of 10 cc of balanced saline solution and vitreous handling at cutting speeds varying between 100 and 5,000 cuts per minute (cpm). Assessments were also made in standard probes and these served as comparative, control data. Traction on the retina was quantified using the modified vitreous cutter during PPV at the Eye Concepts Laboratory at the University of Southern California Doheny Eye Institute (Los Angeles, CA). An evolved version of a previously described experimental eye set-up was used for tractional force testing and is briefly described below.[13]

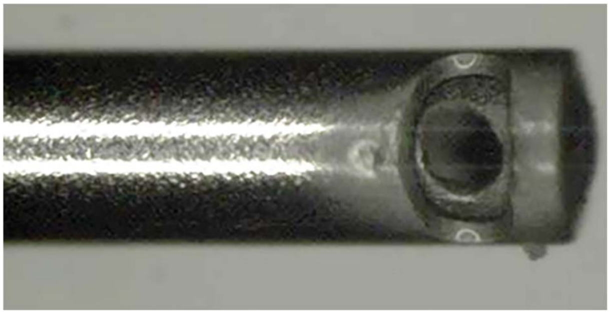

Fig. 1. Photograph of a modified probe. The hole made in the guillotine blade is clearly visible. This probe was modified using electrochemical micromachining.

The fluidics performance of the 23-gauge cutters was tested with a Spring Return vitrectomy system (Stellaris PC system; Bausch & Lomb) and a Dual Pneumatics system (Constellation Vision System; Alcon Labs Inc) using the standard DC setting (CORE-biased open), according to methodology previously developed by Diniz et al.[14,15]

Briefly, for the flow tests, each cutter was suspended in a vial of either water or porcine vitreous. The vials were placed on a high-sampling (2 samples/second), precision (0.01 g) balance (Ohaus Corp, Parsippany, NJ) that measured the weight of the remaining water or vitreous throughout each experiment. Using data acquisition software (LabVIEW; National Instruments, Austin, TX), the remaining mass was recorded in real time, and the results were converted to volume removed as a function of time, that is flow rate. The average and SD of the water and vitreous flow rates were calculated for each size, aspiration level, and cut rate. Repeated measures of analysis of variance tested mean water and vitreous flow rates across aspirations and cut rates. Student's *t* test was used to compare low and maximum cut rate. Mixed models with repeated measures were used to obtain regression equations to predict mean water and vitreous flow rates. SAS V9.1 programming language (SAS Institute Inc, Cary, NC) was used for all analyses.

The accepted level of significance for all tests was a P value of <0.05.

Measurement of Tractional Forces on the Retina

The Constellation and Stellaris PC systems were used to drive a vitreous cutter for testing. The "core" setting for the Constellation system and the equivalent default setting for the Stellaris PC system were used. Cutting rates of 1,000 cpm, 2,000 cpm, 3,000 cpm, 4,000 cpm, and 5,000 cpm and aspiration rates of 100 mmHg, 200 mmHg, 300 mmHg, 400 mmHg, 500 mmHg, and 600 mmHg were examined in each probe and with each system. The foot switch was used to control cutting and aspiration. Before beginning the test, the foot-switch limits of either the cutting rate or the aspiration rate were assigned to avoid the foot-switch travel (ramping slope) factor. Vitreous harvested from porcine eyes within 12 hours of death was used as the test media. The vitreous used for the experiments was carefully removed en bloc from porcine eyes enucleated and kept at 4°C (Celsius scale) before use. A fixture with a vacuum holder was built to fit an existing Bose load cell. Vitreous from a single eye was held in place near the ora serrata (close to vitreous base) by vacuum with the fixture's 16-gauge tip. At harvest, a portion of the detached ora serrata was left on the vitreous as a positional marker of the holding point. The test tissue was supported and floated in a bath of additional vitreous material (Figure 2, B and C) to achieve nearly weightless conditions for the vacuum holder and make sure that the bioproperties and density of ions and collagen in the vitreous were identical as it was in vivo. All vitreous material tested was securely held during all tractional force experiments and no material falls occurred during

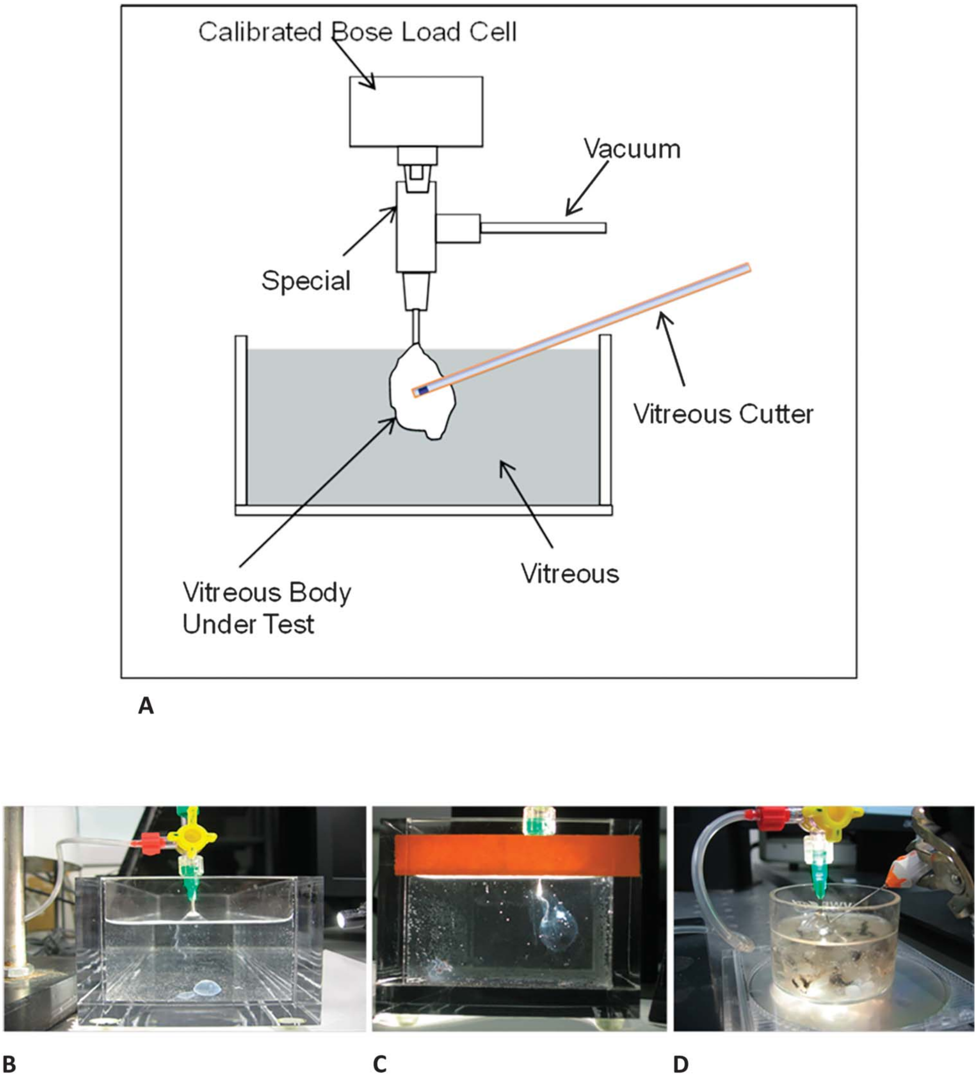

Fig. 2. Experimental setup used to measure the tractional forces on the retina. **A.** Schematic of the setup. **B** and **C.** Photograph of the setup with a porcine vitreous body in place for testing. The vitreous is floating (almost weightless) in a bath of other vitreous material while being held in place by the vacuum holder. **D.** Photograph of the experimental setup used for tractional force measurements on porcine eyes.

experimentation. The vitreous cutter was placed at an angle of 60° about the vacuum holder (Figure 2D). The dynamic weight change was recorded by the Bose load cell and longitudinal tractional forces from vitreous cutter use were sensed by the load cell. Data acquisition rate was 835 samples per second and the measurement resolution of the system was approximately 1 g-cm/s^2 (1 dyne). The tests were performed at room temperature. The pigs were Yorkshire crossed approximately 6 months old and their weight was between 200 lbs and 250 lbs. The porcine eyes that were used were harvested freshly for research purposes by the Company Sierra for Medical Science in Altadena, CA They were harvested in the early morning and delivered to us in the same afternoon. The information about the care and well-being of the animals can be provided by the said company (please see the following link: http://www.sierra-medical.com/About.aspx).

The weight change curve over time was recorded and saved to a computer as a text data file. Data from multiple trials were merged and analyzed using Excel software (Microsoft Corp, Redmond, WA).

Micro Electrical Discharge Machining

The machine we used is an Agie Elox 20 (generator: Futura 2), a standard electrical discharge machining (EDM) machine usually used for engraving dies, medals, or other analogous material. The tool is a cylinder in copper, 150 μm in diameter. The dielectric medium is dielectric oil. We decided to adopt EDM for drilling the smallest microhole we manufactured (around 210 μm) while we adopted an EDM milling/contouring strategy for bigger holes. The idea was to reduce the overcut and debris around the hole. The used parameters are the standard for micro EDM in case of copper–steel couple during finishing processes. Table 1 contains all the settings. In the present case, the EDM machine is a standard one used in finishing mode for stainless steel, new, and clean dielectric oil has been used.

Table 1. Micro Electrical Discharge Machining Working Parameters and Expected Results

Working Parameters	Values
EDM voltage	100 V
Polarity	+ (direct)
EDM current	5°
Pulse-on duration	13 ms
Pulse-off duration	2 ms
Expected Results	**Values**
Average roughness—lateral	1.5 μm
Average roughness—front	1.9 μm
Two sides gap	0.055 mm

Micro Electrochemical Micromachining

In case of electrochemical micromachining, a custom workcell has been developed (Figure 3). It consists of an electrical function generator, an oscilloscope, a three dof guide system for feeding the tool, and the workpiece.[16–20] The guides were controlled by a three-axes microstep controller system. The specifications of the testing equipment are given in Table 2. To avoid the physical contact between the tool (tungsten) and the workpiece (vitrectomy probe), a tailored electronic circuit was used to automatically stop and retract the tool in case of tool–workpiece contact and then automatically start the manufacturing process. Moreover, the function generator, the oscilloscope, and the tailored circuit were used as signal source, signal analyzer, and tool feed controller, respectively, for inprocess monitoring and controlling systems. The manufacturing of the holes was performed at room temperature. No circulation system was integrated during experimentation as μ electrochemical micromachining process involved negligible heat generation and the amount of precipitation was very small.

The workpiece (i.e., the entire the vitrectomy probe) was horizontally immersed into an HCl 0.2 molar solution, in a way that the surface of the inner cannula to be drilled was completely covered by the fluid. Then, said surface was connected to the positive pole of a waveform generator; the cylindrical tool of the machine, which has a diameter $\varphi \approx 40$ μm, was the negative pole. An oscilloscope monitored the entire process.

At the initial time of machining, the interelectrode gap was kept in the range of 10 μm to 12 μm, and to perform micromachining effectively, microtool feed rate was adjusted with the material removal rate. Microtool feeding was controlled by the servo-controlled feed mechanism of ML 40, z- axis travel guide (Micos, now Physic Instruments), while the workpiece was positioned horizontally by x–y axes travel guides, if required. The machining conditions applied in microdrilling process are summarized in Table 3.

Results

Comparison of Micromachining Methods

The two methods used to modify vitrectomy probes (electrochemical and electrodischarge micromachining) were compared. Electrochemical micromachining resulted in a hole with a smooth, regular surface

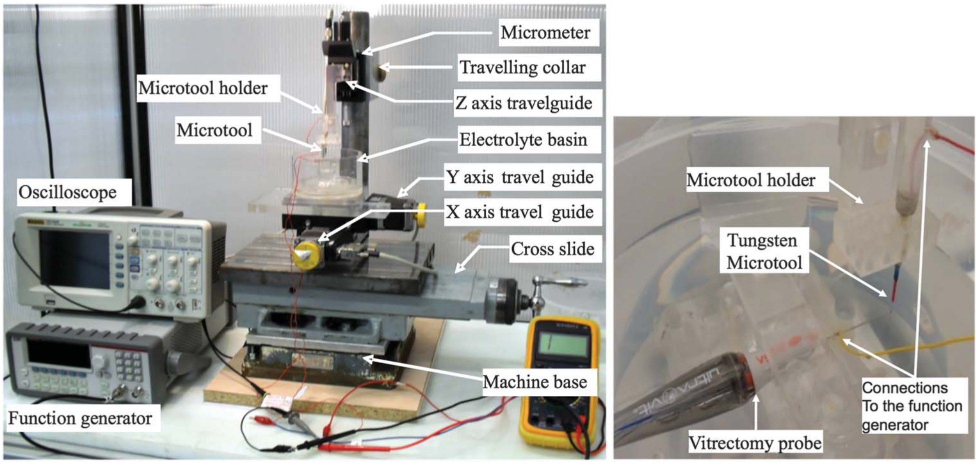

Fig. 3. Electrochemical micromachining workcell and detail of the machining tool-workpiece.

(Figure 4, A and B). In addition, a heat-altered zone was not present and no guillotine sticking problems occurred. However, this process was complex and time consuming. Conversely, electrodischarge micromachining is faster and more established than electrochemical micromachining. The hole shape and dimensions obtained with this method were highly controllable, but the drilled surface was rough and had a heat-altered zone. As a result, sticking problems occurred because of interference from solidified metal debris (Figure 4, C and D), therefore micro EDM has not been used in this study.

Vitreous Outflow

The Constellation (Alcon) system was used to examine and compare the time needed for the system to aspirate 10 cc of balanced saline solution with modified and standard cutters at 650 mmHg and at different cutting rates (100, 1,000, 3,000, and 5,000). Each test has been repeated 5 times, the average SD is 0.97 seconds whereas the maximum value of SD was 2.62 seconds. This low value of SD (with respect to the average values: all above 20 seconds) demonstrated how the phenomenon measured in balanced saline solution has a low variability (mainly introduced by the human operator).

In the modified cutter, outflow remained nearly unchanged when the cutting rate was varied between 100 and 5,000 cpm. In contrast, aspiration time increased (outflow decreased) as the cut rate increased in the standard probe. At 5,000 cpm, the modified probe had an aspiration time that was approximately 45% less than that of the standard probe (Table 4). Because of the low value of SD, the data are plotted

Table 2. Specifications of Testing Equipment Used for the Electrochemical Machining Workcell

Test Equipment	Specifications
Function generator	Keithley 3390 50 MHz; frequency resolution, 1 μHz; amplitude, $10mV_{pp}$–$10V_{pp}$; 4 digits resolution; phase range, −360° to +360°; accuracy, 8 ns
Oscilloscope	Rigol DS1000E, 1 GHz, 2 channel, digital storage, 64 K color display
Linear travel guide	PLS-85, x- and y- axes, maximum travel 155 mm, resolution 0.1 μm, unidirectional repeatability 0.05 μm, maximum 100 mm/seconds, and ML 40, z- axis, maximum travel 40 mm, resolution of 0.1 μm, maximum 5 mm/seconds
Microcontroller	SMC corvus eco, 3-axes closed loop control, velocity < 0.1 μm/seconds, 15 to 25 rev/seconds, linear interpolation, miCos GmbH

Table 3. Machining Conditions for Microhole Fabrication

Factors	Parameters/Values
Working materials	Tool material: Tungsten microtool Work material: stainless steel vitrectomy probe
Electrolyte concentration	0.2 (M/L) HCl solution (without circulation)
Electrical parameters	Frequency: 1 MHz Duty cycle: 30% Pulse on time: 0.3 μs V_{pp}: 16.1 V V_{max}: 10.6 V V_{base}: −5.0 V
Tool insert position	Vertically downward, perpendicular to the workpiece
Tool feed rate	0.1 to 0.5 μm/second, computer controlled
Tool advancement	80 to 200 μm, vertically downward

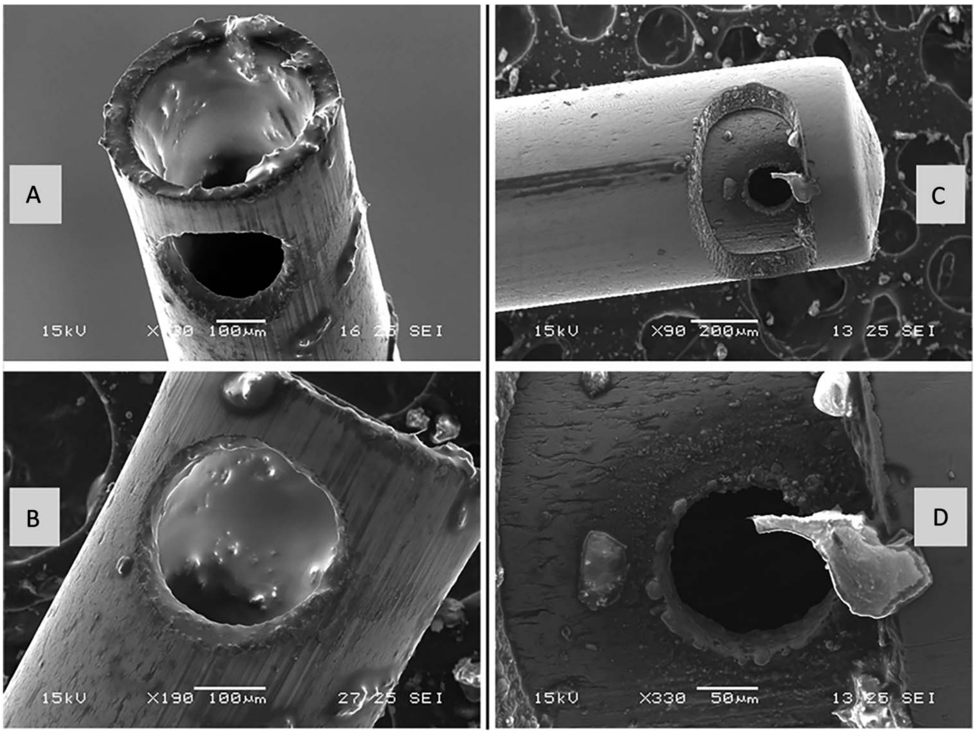

Fig. 4. Scanning electron microscope images of guillotine holes drilled by electrochemical micromachining (**A** and **B**) and electrodischarge micromachining (**C** and **D**).

without recurring to a boxplot representation but only the mean values have been plotted (Figure 5A).

When a similar set of experiments was performed using the Stellaris PC (Bausch & Lomb) probe, almost identical results were obtained (Table 5 and Figure 5B). Aspiration time was essentially constant with the modified probe cutting rate varying between 100 cpm and 5,000 cpm. This was not the case with the standard probe, in which aspiration time increased as the cutting rate increased. At 5,000 cpm, the modified probe had an aspiration time that was approximately 45% lower than that of the standard probe.

Tractional Forces on the Retina

Four vitrectomy probes were modified (by electrochemical micromachining) to examine potential tractional forces placed on the retina during PPV with the modified probe. Measurements were made on porcine eyes, in which a force sensor was placed (Figure 2D).

The diameters of the manufactured holes were in the range 0.30 mm ± 0.02 mm while a standard opening is s rounded square 0.48 mm wide and 0.37 mm high. It means the ratio between the hole surface and the area of a fully opened port is around 40%. Three of the 4 vitrectomy probes properly functioned during durability testing, but one malfunctioned and was not used to make experimental measurements (Figure 6).

In the full open position (Figure 7, Position 3), tractional force was at its maximum value in both the standard and modified probe. When in a partially open position (internal mobile needle moving toward the distal tip [Figure 7, Position 4]), the tractional force decreased because of a smaller suction area (i.e., reduced area of the internal hole —modified after market— in comparison with the opening in the outer probe lumen). The tractional force never goes to zero owing to the presence of the additional hole that is fully open when the guillotine closes the port (Figure 7, Position 1).

Table 4. Seconds Necessary for the Aspiration of 10 mL of Balanced Saline Solution Between Modified and Standard 23-Gauge Vitrectomy Probes at Different Cutting Rates With the Constellation Vitrectomy System

	100 cpm, Seconds	1,000 cpm, Seconds	3,000 cpm, Seconds	5,000 cpm, Seconds
23-G standard vitrectomy probe	30.3	30.3	36.7	48.7
23-G modified vitrectomy probe	27.3	26.0	26.7	26.3

G, gauge.

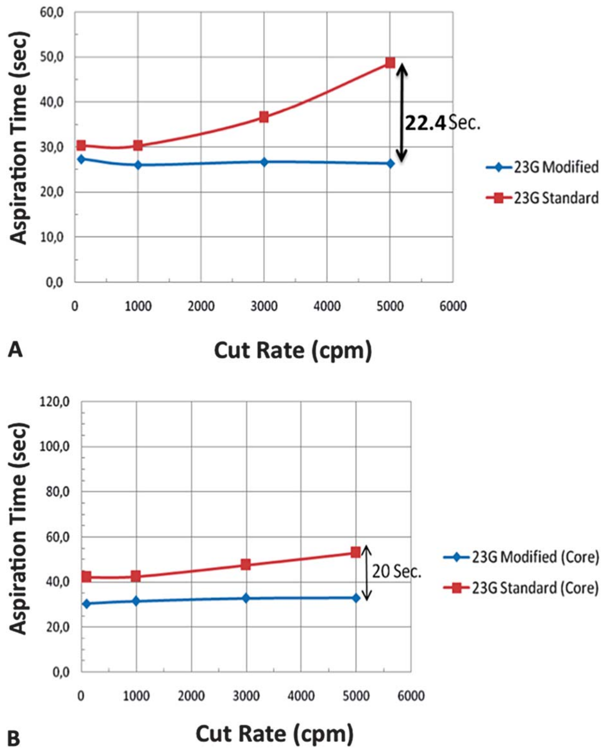

Fig. 5. Comparison of aspiration times of 10 cc of balanced saline solution between modified and standard 23-gauge vitrectomy probes at different cutting rates (100, 1,000, 3,000, and 5,000 cpm) with 650 mmHg; at 5,000 cpm the modified probe aspirated the saline solution 45% faster than the standard probe in both the Constellation (**A**) and stellaris PC (**B**) vitrectomy systems.

The behavior of the modified probe in the open position (Figure 7, Position 3) was almost identical to that of a standard probe (Figure 8). The probe then moved into the "closed" phase (Figure 7, Position 1) passing through an intermediate position (Figure 7, Position 4) when the vitreous is aspirated simultaneously through the space between the blade and the port, and through the hole.

When the standard probe is in the "closed" phase no suction occurs in the standard probe; conversely in the modified probe in the same "closed" position (Figure 7, Position 1) suction exclusively occurs through the internal mobile duct hole. While in standard probe the force reaches a minimum, in the modified probe we notice a second peak in which tractional force increased (Figure 8). However, the force was not as high as when the probe was in the full open position, likely because of the smaller suction area. When the internal needle moved toward the end of the probe (Figure 7, Position 2), tractional force substantially decreased (Figure 8), possibly because vitreous humor had to pass through a smaller suction opening.

However, the main experimental result is that the highest peaks in the modified vitrectomy probes have an average value lower than 30% with respect to a standard one (the accepted level of significance for all tests was a P value of <0.05). It can be explained "by analogy": in standard probes the tractional force reduces when the number of cmp increases. Analogously, during one cutting cycle, a standard vitrectomy probe cuts only one time per cycle (distal cutting edge of inner needle), whereas the modified vitrectomy probe cuts two times per cycle (distal cutting edge of inner needle, drilled hole).[21–23]

Actually the presence of an additional hole could correspond to a theoretical double number of cuts per time unit because the vitreous is cut twice in a cycle the first time thanks to the guillotine and the second thanks to the hole. The increased number of cuts should be the reason why we measured such a reduction of the force on the retina (lower values of the traction force peaks). Although the second hole has a different shape, exposed surface, and the cutting conditions of the hole are probably different with respect to those performed by the guillotine, the hole plays also a supplementary cutting action that brings to a reduction in the peak values that we observed and measured.

It is worth noting that the second peak, corresponding to the hole, has a value lower than the first one and such behavior can be ascribed to a smaller area with respect to the full opening.

No statistical difference has been observed between the modified Bausch & Lomb probes (with the Stellaris and the modified Alcon probes [with the Constellation]).

Even if the previous observations are correct at the beginning of the use of the modified vitrectomy probes, different behaviors can happen in time: actually while the vitrectomy probe guillotine is

Table 5. Time Necessary for the Aspiration of 10 mL of Balanced Saline Solution Between Modified and Standard 23-Gauge Vitrectomy Probes at Different Cutting Rates With the Stellaris Vitrectomy System

	100 cpm, Seconds	1,000 cpm, Seconds	3,000 cpm, Seconds	5,000 cpm, Seconds
23-G standard vitrectomy probe	41.3	41.7	46.8	53.0 second
23-G modified vitrectomy probe	30.2	31.6	32.8	33.0

G, gauge.

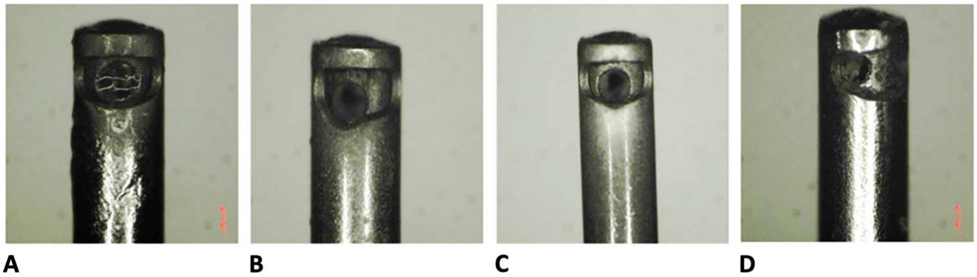

Fig. 6. Photographs of the four vitrectomy probes used for the tractional force measurements. In particular, with reference to figure, it is worth noting that in (**A** and **C**) no measurable and observable enlargement of the opening can be observed (in the Case C, the alteration is only on the external surface of the external tube but not on the internal one, therefore no variation in the port size), whereas the probe in Figure 5B presents an enlargement and Figure 5D presents mainly a positioning issue with a reduced enlargement. Therefore, the size of the final opening of Figure 5, B and D resulted around 10% bigger than the standard one. Even if it is clear that every enlargement induces a higher aspiration, indeed, the traction depends on the dimension of the opening and on the time the port is open. Therefore, theoretically all the four cases should present slightly different values of the force owing to slightly different openings. However, the cutting phenomenon is highly affected by the behavior of the eye and by its conditions. Therefore the gathered data are quite noisy and it is almost impossible to measure such small differences. However, the presence of an additional hole reduces the average traction exerted on the retina. Even in the case of the force analysis (**B** and **D**), the enlarged opening should have produced higher first peaks with respect to an unmodified probe. However, because of the additional hole, the average value of all the peak values reduces in all the 4 cases of Figure 5, B and D included.

reported to be self-sharpening when bought on the market, the after-market modification may not be and may experience a decreased performance with time. Therefore even if, theoretically, the modified vitrectomy probes cut two times per cycle (and it can be considered true also at the beginning of its life), a self-sharpening process cannot be guaranteed also for the hole in the guillotine. The dependency of the cut quality over the time has not been investigated in the present article.

Discussion

Vitrectomy-based systems have significantly changed and improved over recent years. Development of new vitrectomy instrumentation has been largely driven by the desire for smaller instruments with greater functionality and improved safety profiles. Because instruments have become smaller, disposable, safer, and more efficient, surgeons are now able to perform microincisional vitrectomy. To satisfy the requirements of smaller gauge instruments, higher cutting rates and higher aspiration level have been pursued in the last decades. Recent advances to further increase cutting rates, better understand flow dynamics within the probe, improve cutter port geometry, and optimize the duty cycle have further improved the vitrectomy procedure.[10–12]

Despite these advantages, smaller-diameter systems have a decreased vitreous outflow during vitreous removal compared with the outflow achieved with larger standard 20-gauge systems. Reduced flow rates with smaller gauge instruments often result in longer operative times because it takes more time for bulk vitreous removal. This often

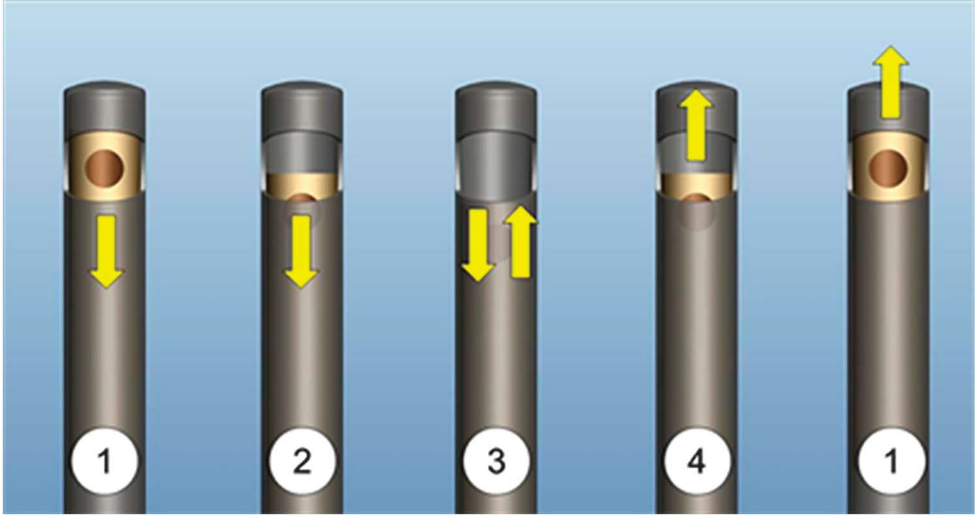

Fig. 7. Schematic of the modified probe during its cutting cycle. Position 1: Closed position. Suction occurs through the drilled hole. Position 2: Inner needle moving toward the proximal end of the probe. Position 3: Open position. Position 4: Inner needle moving toward the distal end of the probe. Yellow arrows indicate the direction in which the inner needle is moving.

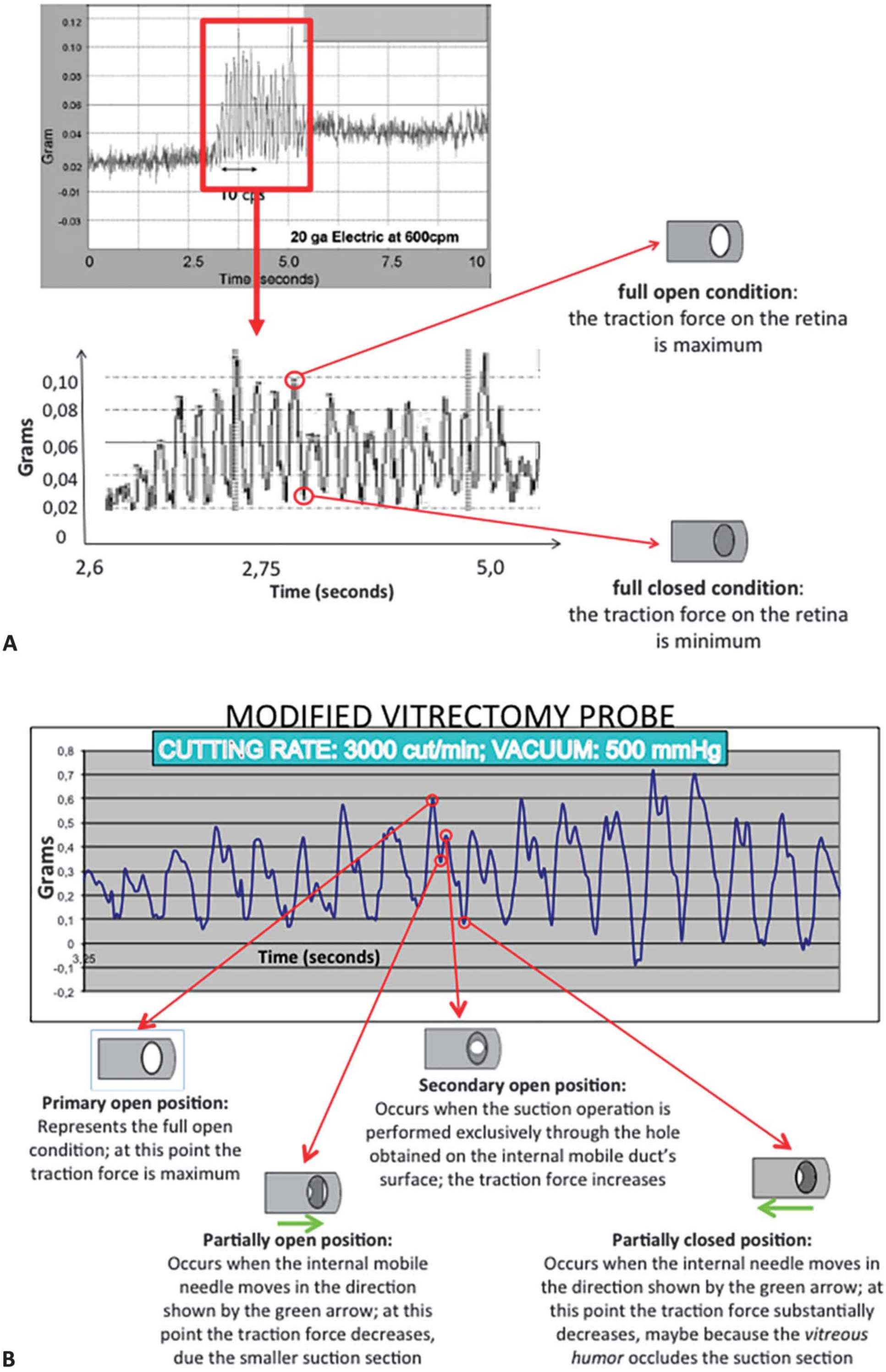

Fig. 8. A. Tractional forces exerted by a standard vitrectomy probe (**A**: adapted from Teixeira et al 2010) and by a modified vitrectomy probe (**B**) during the cutting cycle. Schematics showing inner needle position are shown for reference. Measurements made at the Doheny Eye Institute. Please note that the values of the forces shown within the two graphs (**A** and **B**) were obtained using different sized probes (20 G for **A** and 23 G for **B**) and setting different vacuum level and cutting rates, and this is the reason why they are quite diverse. Then, they cannot be compared and neither be used to achieve tractional force numerical values, but those two graphs should be used only for a qualitative comparison between traditional and modified probes behavior. Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

counteracts the time reductions achieved by not having to create and close scleral wounds. The probe modification presented in this study allows the use of smaller gauge vitrectomy systems while maintaining higher flow rates. We showed that flow rates with the modified probes remain relatively constant, even at very high cutting speeds.

Unfortunately, instrumentation improvements have not included tractional force measurements during PPV. Quantifying tractional forces on the retina created by vitreous cutters during vitrectomy has been a challenge and the only reproducible data were reported by Teixeira et al.[13,23] In their study, an ocular model allowed measurement of vitreoretinal traction during vitreous removal with a vitrectomy probe (measured in dynes). They determined that vitreoretinal forces decrease by 2.5 dynes for every cutting speed increase of 500 cpm ($P < 0.05$). Therefore, as the cutting rate increased, traction decreased by an average factor of 2.2 for the cutter tested.[23] Thus, tractional forces on the retina can be minimized by increasing the cutting speed. In addition, traditional vitrectomy probes produce minimum traction when the mouth of the cutter is fully closed and maximum traction when the mouth of the cutter is fully open.

We collaborated with the Doheny Eye Institute at the University of Southern California to use the established system for measuring tractional forces exerted on the retina by vitreous cutters during PPV. With this system, the behavior of the modified vitrectomy probe was analyzed and shown to differ from the conventional probe (Figure 8). First, modified probes had higher cutting frequencies than conventional ones, which resulted in decreased tractional forces on the retina. In addition, the magnitude of the tractional wave (maximum traction–minimum traction) is decreased. Moreover, during a complete guillotine travel cycle, the modified vitrectomy probe performs two cutting actions rather than one, as in the conventional probe. In conclusion, our modified probe may be useful in vitreoretinal surgery because it may improve the safety (less traction on the retina) and efficacy (surgery time) of currently available vitrectomy cutters. Moreover, the proposed modification can be made on any available probe. Future steps of the research will be devoted to the optimization of the dimension of the hole, of its shape, cutting conditions, and to the investigation of the cutting phenomena related to the hole.

Key words: flow rate, holed vitrectomy probe, modified vitrectomy probe, surgical cutter, tractional force, vitrectomy probe, vitreoretinal surgery.

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References

1. Chen JC. Sutureless pars plana vitrectomy through self-sealing sclerotomies. Arch Ophthalmol 1996;114:1273–1275.
2. Kwok AK, Tham CC, Lam DS, et al. Modified sutureless sclerotomies in pars plana vitrectomy. Am J Ophthalmol 1999;127:731–733.
3. Jackson T. Modified sutureless sclerotomies in pars plana vitrectomy. Am J Ophthalmol 2000;129:116–117.
4. Lam DS, Chua JK, Leung AT, et al. Sutureless pars plana anterior vitrectomy through self-sealing sclerotomies in children. Arch Ophthalmol 2000;118:850–851.
5. Rahman R, Rosen PH, Riddell C, Towler H. Self-sealing sclerotomies for sutureless pars plana vitrectomy. Ophthalmic Surg Lasers 2000;31:462–466.
6. Fujii GY, De Juan E, Humayun MS, et al. Initial experience using the transconjunctival sutureless vitrectomy system for vitreoretinal surgery. Ophthalmology 2002;109:1814–1820.
7. Fujii GY, De Juan E, Humayun MS, et al. A new 25-gauge instrument system for transconjunctival sutureless vitrectomy surgery. Ophthalmology 2002;109:1807–1812.
8. Hubschman JP. Comparison of different vitrectomy systems. J Fr Ophtalmol 2005;28:606–609.
9. Charles S. An engineering approach to vitreoretinal surgery. Retina 2004;24:435–444.
10. Fang SY, De Boer CMT, Humayun MS. Performance analysis of new-generation vitreous cutters. Graefes Arch Clin Exp Ophthalmol 2008;246:61–67.
11. de Juan E Jr, Hickingbotham D. Refinements in microinstrumentation for vitreous surgery. Am J Ophthalmol 1990;109:218–220.
12. Lima LH, Deboer C, McCormick M, et al. A new dual port cutter system for vitrectomy surgery. Retina 2010;30:1515–1519.
13. Teixeira A, Chong L, Matsuoka N, et al. Novel method to quantify traction in a vitrectomy procedure. Br J Ophthalmol 2010;94:1226–1229.
14. Diniz B, Fernandes RB, Ribeiro RM, et al. Analysis of a 23-gauge ultra highspeed cutter with duty cycle control. Retina 2013;33:933–938.
15. Ribeiro RM, Teixeira AG, Diniz B, et al. Performance analysis of ultrahigh-speed vitreous cutter system. Retina 2013;33:928–933.
16. Bhattacharyya B. Electrochemical Micromachining for Nanofabrication, MEMS and Nanotechnology. 2015. William Andrew; 1–296.
17. Mithu MA, Fantoni G, Ciampi J. The effect of high frequency and duty cycle in electrochemical microdrilling. Int J Adv Manuf Technol 2011;55:921–933.
18. Mithu MA, Fantoni G, Ciampi J. Fabrication of micro nozzles and micro pockets by electrochemical micromachining. Int J Machining Machinability Mater 2012;11:353–370.
19. Mithu MA, Fantoni G. Etching behaviour of tungsten microtool and its applications in electrochemical micromachining. Int J Precision Technol 2011;2:301–312.
20. Mithu MA, Fantoni G, Ciampi J. How microtool dimension influences electrochemical micromachining. The Int J Adv Manuf Technol 2014;70:1303–1312.
21. DeBoer C, Fang S, Lima LH, et al. Port geometry and its influence on vitrectomy. Retina 2008;28:1061–1067.
22. Hubschman JP, Gupta A, Bourla DH, et al. 20-, 23-, and 25-gauge vitreous cutters: performance and characteristics evaluation. Retina 2008;28:249–257.
23. Teixeira A, Chong LP, Matsuoka N, et al. Vitreoretinal traction created by conventional cutters during vitrectomy. Ophthalmology 2010;117:1387–1392.