Retina

Instantaneous Flow Rate of Vitreous Cutter Probes

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Purpose. We report on instantaneous volumetric flow rate of vitreous cutters measured by means of particle image velocimetry (PIV).

Methods. In an in vitro experimental study, vitreous cutters mounting a regular blade (RB) or modified Twedge blade (TB) engineered for higher flow were connected to a console machine equipped with a double peristaltic and Venturi pump, and immersed in balanced salt solution (BSS). Instantaneous flow was measured on aspiration tubing sections proximal to the cutter hand piece. Measures settings were as follows: (1) regular functioning at 3000 and 6000 cuts per minute (cpm) with 300 mm Hg aspiration with both pumps, (2) aspiration tubing clamped proximal to pump cassette, and (3) aspiration tubing clamped proximal to hand piece, and (4) flow fluctuation as a function of cut rate also was calculated. For main outcome measures, instantaneous volumetric flow rate in mL/min and flow fluctuation measured as the standard deviation of flow rate were measured.

Results. Regular functioning shows sinusoidal flow oscillating at cut rate frequency, with amplitude between ±50 mL/min at 3000 cpm and ±35 mL/min at 6000 cpm. The TB always determined a bimodal wave and neither blade nor pump type influenced the sinusoidal pattern of flow. Clamping aspiration tubing zeroes flow, but does not influence fluctuation frequency or amplitude. Clamping at the hand piece determined a significantly higher oscillation. Oscillation amplitude retain a typical resonance pattern with significant changes in function of cut rate and resonance occurs at approximately 4000 cpm.

Conclusions. Cutter blade action determines instantaneous flow rate fluctuation that interferes significantly with cutter suction and hampers a steady suction through cutter port. In a surgical scenario, this translates into a higher risk of inadvertent retinal entrapment and lower predictability of cutter behavior, especially at frequency approaching resonance.

Keywords: fluid dynamics, vitrectomy, retinal detachment, flow rate, pars plana vitrectomy, vitreous cutter

The human vitreous gel structure comprises a three-dimensional collagen fibril mesh and hyaluronic acid.[1] Despite its 99% water content, the vitreous behaves as a non-Newtonian fluid whose viscosity varies between 2- and 4-fold that of water, as a function of shear rate.[2]

Vitreous gel removal through increasingly miniaturized cutter probes at high vacuum within narrow bores produces complex fluid dynamics.[3,4] Exhaustive comprehension of such flow is the key to the development of better instrumentation and safer surgery.

We recently applied particle image velocimetry (PIV) to vitreous cutter–induced flows[5] and introduced a modified vitreous cutter blade that substantially improves duty cycle, allowing higher flow and lower fluid acceleration at the probe tip while doubling the effective cut rate.[6] Despite all advancements, presently available cutters generate intermittent flow that pulls on the vitreous and may engage the retina[7] (Supplementary Video S1).

To reduce untoward vitreous traction and avoid inadvertent entrapment of the retina, the golden standard of vitreous cutter should provide effortless severing of collagen fibrils and even aspiration of diverse viscosity fluids (aqueous and vitreous), providing the highest, yet invariant flow rate.

The purpose of present study is to describe the instantaneous volumetric flow rate of vitreous cutters by means of PIV. In an effort to describe flow alteration responsible for retinal shaking when the vitreous cutter approaches it, the study aimed at characterizing flow behavior with the smallest time resolution, to measure the fluctuation of flow and understand if and to what extent blade motion influences it.

Materials and Methods

Experimental Setting

We connected 23-gauge (G) probes mounting a regular guillotine blade (RB) or a double bevel, 100% duty cycle Twedge blade (TB) to the R-Evolution CS vitrectomy machine console (Optikon 2000, Inc., Rome, Italy) equipped with a double Venturi/peristaltic pump and tested under typical surgical settings. Cutters were secured vertically and probe tip immersed in balanced salt solution (BSS; Alcon, Fort Worth,

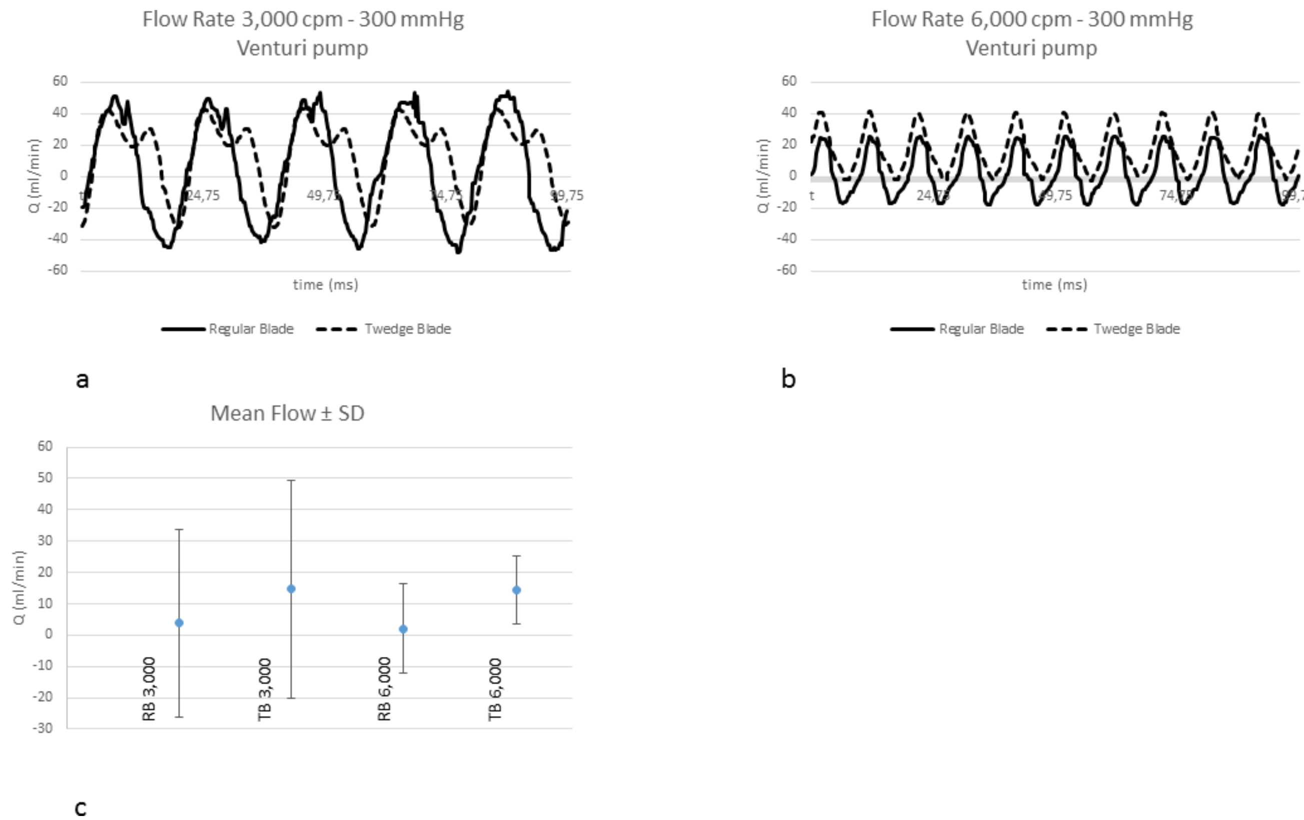

FIGURE 1. Instantaneous flow of RB (*continuous line*) and TB (*dashed line*) using a Venturi pump at different cut rates. (**a**) At 3000 cpm and 300 mm Hg aspiration. (**b**) At 6000 cpm and 300 mm Hg RB versus TB at 6000 cpm and 300 mm Hg aspiration. (**c**) Flow rate value dispersion, reported as mean with *error bars* showing SD. Note that the two blades produce very similar flow behavior despite a bimodal appearance of the TB, while the dispersion of data is always higher at 3000 cpm compared to 6000, regardless of blade design (compare [**a**] to [**b**]). The TB bimodal wave probably is due to the passing of the double-bevelled blade through the port when moving distal to proximal.

TX, USA). To allow fluid motion detection by means of PIV, BSS was seeded with triamcinolone crystals (Kenakort; Brystol Squibb-Meyers, New York, NY, USA) passed through a 40-μm filter.

A 532-nm green laser light slit was shed directly onto the cutter tubing, 10 mm proximal to the hand piece and the camera focused inside the transparent tubing, 90° away from the light-source, as described previously.[6,7]

High-Speed Imaging

Fluid motion within the tubing was recorded for 1 second with a MotionPro high speed camera (Integrated Design Tools, Inc., Tallahassee, FL, USA) and stored as an uncompressed audio-video interleaved format (.avi) movie (frame rate was 2700 frames/s and resolution set at 382 × 1280 pixel). Five seconds were allowed between vitreous cutter onset and video recording, to skip the transitional phase.

Particle Image Velocimetry (PIV)

The PIV measures fluid velocity from high speed movies by recognizing the motion of tracer particles dispersed in fluid (i.e., triamcinolone crystals). Under the assumption that tracers translate in subsequent frames conserving their brightness, corresponding windows on the successive images are compared[8] and the displacement minimizing the dissimilarity between two consecutive frames of the high speed video represents fluid motion. In other words, the matrix of points represented by triamcinolone crystals of each frame is compared to the following frame of recorder high speed movie and velocity computed, based on average displacement and time elapsed in between two consecutive frames. For image analysis we used robust imaging velocimetry (RIV),[9] as applied previously to ophthalmology.[6,7,9]

Main Outcome Measures

Instantaneous volumetric flow rate (hereafter simply referred to as "flow") has been calculated based on particle velocity within the aspiration tubing, whose internal diameter is known (since flow $= V \times A$, where V is the instantaneous fluid velocity averaged on a section orthogonal to the tubing axis and A is the area of the section).

To define the cumulative and relative role of pump action, tubing, and blade motion, we took the following measures under different experimental settings:

1. Regular functioning: This setting mimics surgical theater functioning. Venturi and peristaltic pumps were used with the RB and TB. Cut rate was set at 3000 and 6000 cuts per minute (cpm) and aspiration set at 300 mm Hg and 5 mL/min, with the Venturi and peristaltic pump, respectively.
2. Aspiration tubing clamped at the cassette: To evaluate the role of blade motion alone in generating flow, the aspiration tubing was clamped immediately distal to the aspiration cassette, 2.5 m proximal to the cutter hand piece. This physically excluded any residual pump action, leaving the tubing compliance unaltered.
3. Aspiration tubing clamped at the hand piece: The aspiration tubing was clamped 25 mm proximal to hand

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Table. Flow Rate Fluctuation Amplitude in mL/min

	3000 cpm	6000 cpm	3000 vs. 6000 *P*	RB vs. TB @3000 cpm *P*	RB vs. TB @6000 cpm *P*
Regular functioning RB Venturi	32.28 ± 15.11	14.20 ± 8.54	<0.001	0.001	<0.001
Regular functioning TB Venturi	30.13 ± 12.13	11.56 ± 7.44	<0.001	–	–
Regular functioning RB peristaltic	18.65 ± 9.63	12.92 ± 6.39	<0.001	<0.05	<0.05
Regular functioning TB peristaltic	19.99 ± 10.79	6.22 ± 4.45	<0.001	–	–
Tubing clamped @ cassette RB	25.24 ± 13.34	11.62 ± 6.60	<0.001	<0.001	<0.001
Tubing clamped @ cassette TB	19.05 ± 10.73	9.01 ± 5.61	<0.001	–	–
Tubing clamped @ handpiece RB	19.05 ± 10.73	11.62 ± 6.60	<0.001	<0.001	<0.001
Tubing clamped @ handpiece TB	28.75 ± 15.41	16.70 ± 10.24	<0.001	–	–

Mean ± SD reported in absolute values (i.e., the direction and, therefore, its sign + or − is neglected). The third column reports *t*-test *P* values when 3000 cpm data were compared to 6000 cpm with the same blade, and the fourth and fifth columns show the *P* data when comparing different blades at the same speed. Note that the magnitude of fluctuation is significantly lower at 6000 cpm regardless of blade design and pump type. Even when aspiration is excluded clamping the tubing 3000 cpm yielded a significantly higher fluctuation.

piece (i.e., immediately upstream the area of PIV analysis). This excludes pump action and tubing compliance.

4. Parametric measure of amplitude oscillation with cut rate increase: We measured flow at 1000 cpm intervals to evaluate if and to what extent the intrinsic elasticity of cutter metal shaft and aspiration tubing amplified flow oscillations, and if resonance occurred.

Statistical Analysis

A *t*-test for repeated measures of flow rate was used. *P* values less than 0.05 have been considered statistically significant.

Results

Regular Functioning

Flow is reported in Figure 1 for the RB and TB. Regardless of cut rate and aspiration settings (Figs. 1a–c) the TB showed a higher average flow and significantly lower fluctuation ($P < 0.001$) at 3000 and 6000 cpm (see Table). The TB also shows a bimodal wave at 3000 cpm (Fig. 1b), invariant with cut rate and pump type (see Fig. 2), possibly due to the port geometry that alternatively opens and closes two complementary surfaces on either side of the double bevelled blade, affecting incoming flow.

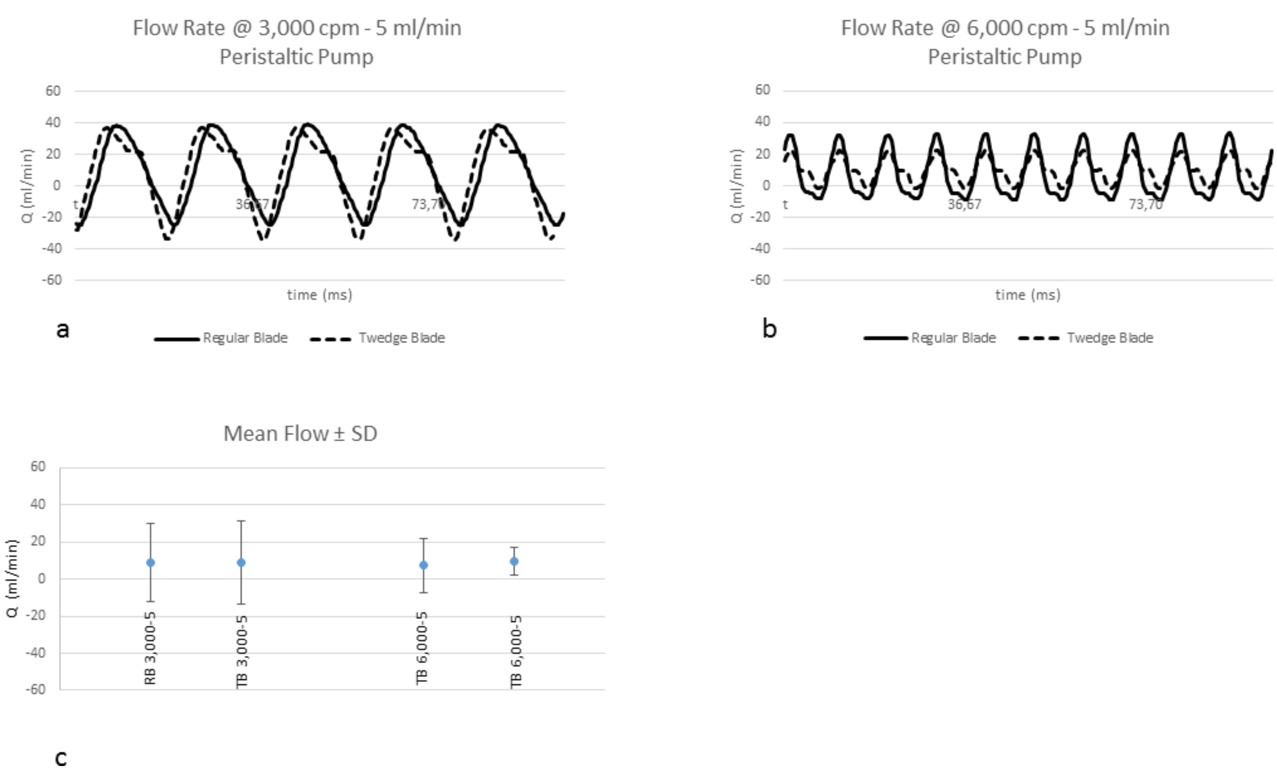

Figure 2. Instantaneous flow of RB (*continuous line*) and TB (*dashed line*) using a peristaltic pump with constant average flow set at 5 mL/min. (**a**) At 3000 cpm and (**b**) 6000 cpm. Dispersion of data as mean ± SD is reported in (**c**). Note that average flow is consistently close to preset value of 5 mm Hg, while amplitude of flow fluctuation has not changed significantly although TB shows its typical bimodal wave. Fluctuation still is greater at 3000 cpm compared to 6000 cpm, regardless of blade type (see *wider error bars* in [**c**]).

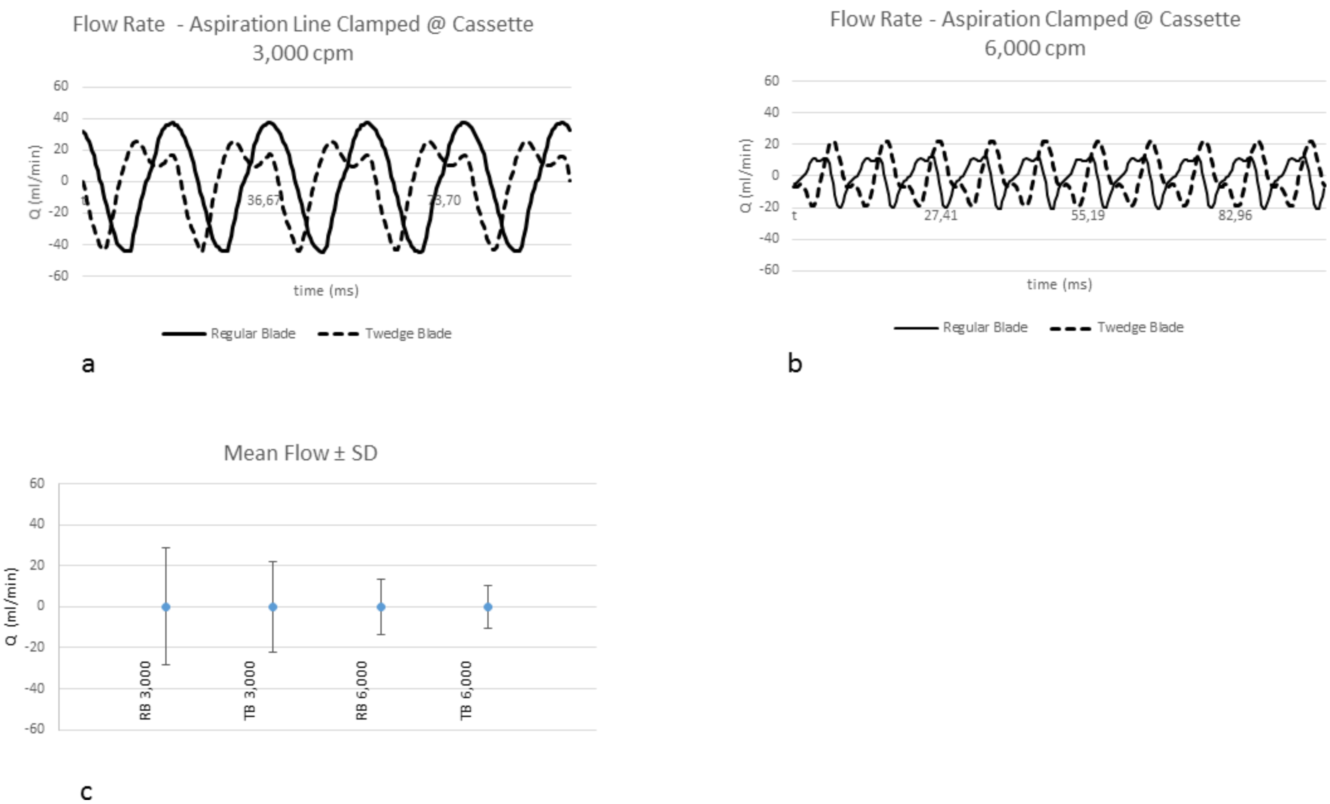

Figure 3. Instantaneous flow of RB (*continuous line*) and TB (*dashed line*) when the aspiration tubing is clamped immediately proximal to the pump cassette (aspiration, therefore, is 0 mm Hg by definition). (**a**) At 3000 cpm and (**b**) 6000 cpm. The TB maintains its bimodal flow and fluctuation is smaller than RB. Dispersion of data as mean ± SD is reported in (**c**). Flow fluctuation at 3000 cpm still is higher than at 6000 cpm regardless of blade design.

Under all tested conditions, flow fluctuation (see Supplemental Video S1) is approximately an order of magnitude greater than average flow, as evidenced in Figure 1c. Fluctuation frequency exactly corresponded to cut rate: 3000 Hertz (Hz) at 3000 cpm (Figs. 1a, 1b) and 6000 Hz at 6000 cpm (Fig. 1c). Venturi and peristaltic pumps behave very similarly (Figs. 1 vs. 2) and flow fluctuation amplitude at 3000 cpm is higher than at 6000 cpm ($P < 0.001$ regardless of blade type; see Table).

Aspiration Tubing Clamped at the Cassette

Flow with aspiration line clamped at the cassette is reported in Figure 3. Average flow is approximately zero in all cases, as expected, although varied instantaneously between ±40 mL/min at 3000 cpm and ±20 to 40 mL/min at 6000 cpm. Flow fluctuation amplitude still was significantly greater at 3000 cpm compared to 6000 ($P > 0.001$, regardless of blade; see Table) and fluctuation frequency was the same: 3000 and 6000 Hz.

Aspiration Tubing Clamped at the Hand Piece

Figure 4 reports flow of TB at 3000 and 6000 cpm with aspiration tubing clamped immediately proximal to the hand piece and compared to flow reported in Figure 3 (when aspiration tubing was clamped at the cassette). Average flow still was close to zero while instantaneous flow greatly fluctuated, between ±40 mL/min at 3000 cpm and between ±20 mL/min at 6000 cpm. Oscillation amplitude when tubing is clamped at the hand piece was significantly greater ($P < 0.001$; see Table) than clamping at the cassette at both cut rates. Frequency was the same as reported in all other measures reported in Figures 1 to 3: 3000 and 6000 Hz.

Parametric Measure of Flow Rate Oscillation Amplitude, as a Function of Cut Rate

Amplitude of flow oscillations at 3000 cpm was significantly higher than at 6000 cpm in all studied conditions ($P > 0.01$ in all cases, see Figs. 1–4). This anecdotic observation prompted a parametric measure of oscillation amplitude as a function of cut rate reported in Figure 5. The graph clearly demonstrates that flow oscillation varied significantly with cut rate, reaching its acme at 4000 cpm, while being significantly lower ($P < 0.01$, see Table) at any other tested cut rate.

Discussion

Accurate control of volumetric flow rate throughout surgery allows efficient vitrectomy.[10] A steady flow, defined as invariant instantaneous fluid speed through cutter sections at any considered time, is the mainstay of safe vitrectomy, since zero fluid acceleration (i.e., velocity change in time) yields no force and, therefore, pressure (or traction) on the retina.

Shaving the vitreous off the detached retina remains a challenging and dangerous task that would greatly benefit from constant flow throughout the duty cycle: a goal presently far from our reach. An unstable detached retina dangerously approaching the port at every cutting cycle[11] is a common surgical experience. Dugel and Coll[12] examined the capacity of attracting a latex membrane, correlating aspiration to distance

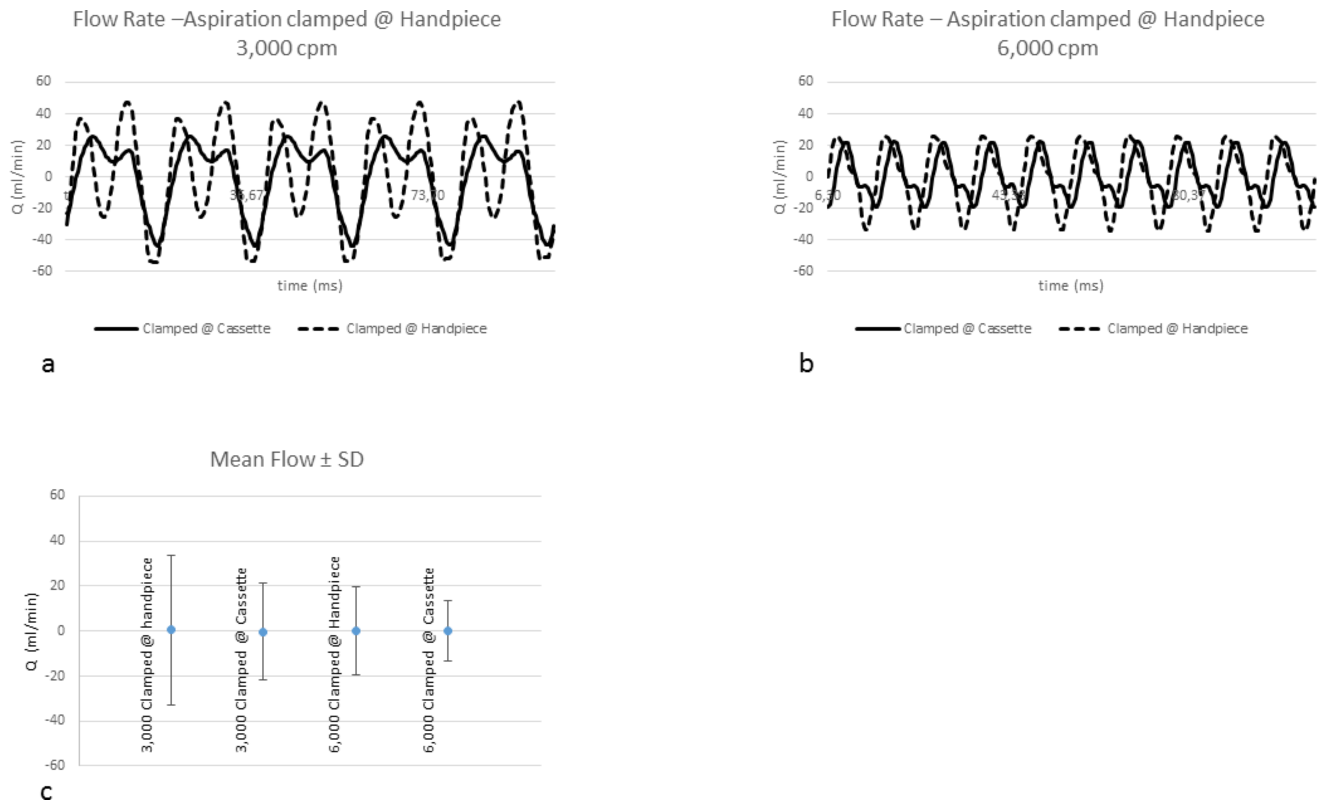

Figure 4. Comparison of the instantaneous flow of TB with aspiration tubing clamped either at the cassette (*continuous line*, same data as in Fig. 3), or immediately distal to the hand piece (*dashed line*), to eliminate tubing compliance effects. (**a**) At 3000 cpm and (**b**) 6000 cpm. Dispersion of data as mean ± SD is reported in (**c**). Note that flow fluctuation at 3000 cpm is higher when the tubing is clamped at the hand piece and bimodality of flow is even more evident. This probably is due to the lack of oscillation damping offered by the PVC tubing compliance.

from cutter port and to probe gauge, but did not study the effects of cut rate alone, purposely turning it off.

Our data clearly showed the presence of macroscopic sinusoidal flow rate fluctuation corresponding to the cut rate frequency and also clarified that neither blade nor pump type is responsible for such fluctuation (Figs. 1, 2). Cut rate also influences flow fluctuation amplitude, being higher at 3000 cpm and lower at 6000 cpm (Figs. 1–4). It should be emphasized that the intrinsic magnitude of flow fluctuation largely outweighs (10 times greater) the average flow when the aspiration pump is on (Fig. 1) and off (Fig. 2), and even when the tubing is clamped (Figs. 3, 4), excluding any residual pump action.

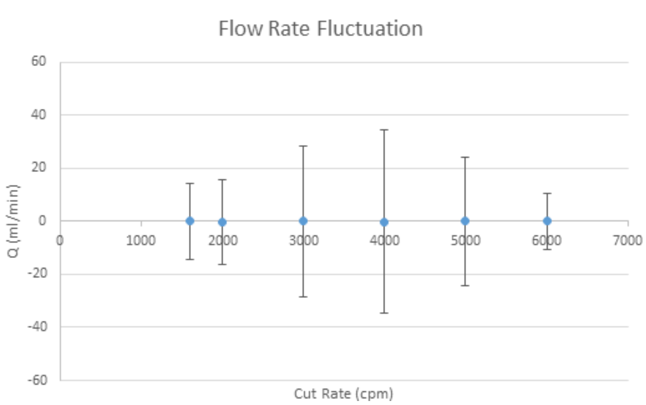

Figure 5. Flow rate fluctuation as a function of cut rate when aspiration tubing is clamped at the pump cassette, reported as mean ± SD. The amplitude significantly varies with a steady increase between 1600 cpm and 4000 cpm when oscillation reaches its acme to decline afterwards at 5000 cpm, reaching its minimum at 6000 cpm. This behavior is clearly due to oscillation amplification by the hand piece-tubing complex that resonates at a frequency close to 4000 cpm. At this cut rate the blade-dependent flow interferes the most with pump aspiration, making the cutter functioning less accurate.

This behavior demonstrates that flow fluctuation entirely depends on blade motion and is actually its consequence. Teixeira and Coll[13] recorded retinal traction exerted by vitreous cutter with a strain gauge. Interestingly they also recorded fluctuation at frequency compatible with blade motion even with aspiration off.[14] Unfortunately, the time resolution of their data does not allow any comparison and the issue is neglected.

Friction between the inner surface of the reciprocating blade and the column of fluid within the cylinder itself, explains instantaneous flow fluctuation. The inner blade, a cave cylinder, transfers motion to the "boundary" fluid layer in contact with it and subsequently to all concentric fluid layers, as a function of viscosity and contact surface. The amount of transferred kinetic energy (i.e., velocity) is, therefore, directly proportional to fluid viscosity, blade velocity, inner (contact) surface, and length of blade excursion, while it is inversely proportional to inner cylinder (i.e., blade) radius.[15] Fluid laminae more distant from the moving parts (i.e., toward the center of the water column and blade cylinder) receive less energy. Therefore, the smaller the instrument gauge, the higher the interference of blade motion on flow.

As we mentioned, the magnitude of what we shall define "blade-dependent" flow is 10 times greater than the average flow and clarifies why despite advancements, today's cutters still determine a macroscopic trembling of the detached retina, and shaving remains a dangerous maneuver. In proximity of the cutter port, the vitreous and detached retina are subject to waves that alternately move in opposite directions as the blade does, making a steady flow literally impossible.

While flow data reported in Figures 1 and 2 support the thesis that blade motion alone is responsible for flow fluctuation, clamping the aspiration tubing before the pump (Fig. 3) or distal to the hand piece (Fig. 4) clarifies that the cassette role is negligible (compare Figs. 3 and 2), while tubing compliance only influences amplitude (Fig. 4). Sato and Coll[16] studied different cutters with a high speed camera and concluded that average flow was correlated not only to port surface and inner diameter but also to duty cycle.

As of today, cut rate increase has been used as a way to reduce retinal oscillation (which is nothing but the surgical evidence of blade-induced flow fluctuation in the two opposite directions). Increasing reciprocation frequency may reduce the amplitude (as shown in Figs. 1–4 where 6000 cpm fluctuation amplitude is smaller than 3000), but cannot solve the problem and could even worsen it, if resonance frequency is inadvertently approached.

Resonance is most likely the explanation for fluctuation amplitude variation reported in Figure 5: at 4000 cpm oscillation is more than twice that recorded at 2000 and almost triple than at 6000 cpm. This phenomenon has important surgical consequences: first, shaving at cut rate close to resonance frequency should not be attempted because flow (and, therefore, retina) fluctuation is maximal and may compromise efficacy and safety. The second clinical consequence is that the highest available cut rate may not be the best choice to minimize retinal motion if this serendipitously approaches resonance frequency. Every manufacturer should specify resonance frequency for cutter-tubing set, to let the surgeon work at cut rates that minimize flow oscillation.

Pitfalls of present study include the use of a single machine console (although several measures with two type of blades have been performed), and of BSS. We believe those limitations do not alter the essence of observed phenomenon and proposed conclusion, since blade motion mechanism of all available cutters is the same. Different brands, in fact, share the same probe architecture with an inner cutting cylinder reciprocating along the major axis and same dimensions. Small difference in structure stiffness, blade excursion, and tubing compliance could only result in different resonance frequency.

The use of BSS, a Newtonian fluid with smaller (but constant) viscosity, does not alter the observed phenomenon either, since the higher vitreous viscosity would only transfer more efficiently motion from the reciprocating blade to the contained fluid. The elastic properties of vitreous could at best partially damp blade-dependent flow at sections far from the blade. We nonetheless believe that further study with different machines in BSS and in vitreous are warranted to characterize flow oscillation and propose ways to solve it.

In conclusion, instantaneous flow rate within the tubing demonstrated flow fluctuations 10 times greater than the resulting average flow generated by the aspiration pump. Such flow reciprocates in the opposite exactly at cut rate pace and is, indeed, generated by blade motion. Flow fluctuation varies as a function of cut rate and resonance occurs, amplifying flow rate oscillation at a given frequency. A better understanding of cutter fluidics allowing a drastic reduction in flow oscillation would greatly affect surgery efficacy and safety, allowing more precise vitreous shaving and faster procedures.

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