Comparisons of Flow Dynamics of Dual-Blade to Single-Blade Beveled-Tip Vitreous Cutters

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Keywords
Fluid dynamics · High-speed camera · Vitrectomy cutter · Vitrectomy probe

Abstract

Introduction: The aim of this study was to compare the flow dynamics of the dual-blade to the single-blade beveled-tip vitreous cutters. Methods: The aspiration rates of balanced salt solution (BSS) and swine vitreous were measured for the 25-gauge and 27-gauge dual- and single-blade beveled-tip vitreous cutters. The flow dynamics of BSS and diluted vitreous mixed with fluorescent polymer at the maximal cutting rates and the reflux of BSS were measured in images obtained by a high-speed camera. The distal end of the cutter was defined as the head end. Results: The aspiration rates of BSS and vitreous by the 25- and 27-gauge dual-blade cutters were significantly higher than those of both single-blade cutters at the maximal cutting rate (all \( p \leq 0.01 \)). The mean aspiration flow of BSS in front of the port from a lateral view was significantly faster for both dual-blade cutters than for both single-blade cutters (\( p = 0.003, p = 0.019 \)). The angle of the mean flow of BSS of both dual-blade cutters was from the proximal end (\( p < 0.001, p < 0.001 \)) but that of the single-blade cutters was from the distal end. The velocity and angle of the mean reflux flow of both types of cutters were not significantly different. The mean aspiration flow of diluted vitreous was significantly faster for 25-gauge dual-blade cutters with the angle more from the proximal end and 27-gauge dual-blade cutters more from the distal end than both single-blade cutters (\( p = 0.018, p = 0.048 \)). Conclusion: The dual-blade beveled-tip vitreous cutters improve the efficiency of the vitrectomy procedures and maintain the distal aspirating flow by the beveled tip.

Introduction

Small gauge or microincision vitrectomy was introduced in 2002, and it was reported to improve the patient comfort with less conjunctival scarring, less postoperative inflammation, and earlier visual recovery than after 20-gauge vitrectomy [1–7]. The closer distance of the opening port from the tip of the small-gauge vitreous cutters enabled dissection closer to the retina. These cutters served as multifunctional instruments because there was no need for forceps and scissors [8–10]. In addition, the higher cutting rates of the small-gauge vitreous cutters improved the efficiency of vitreous cutting which then reduced tissue traction during the cutting [11–16].
The conventional vitreous cutter has a port on one side and an inner tube moves back and forth to open and close the port which creates guillotine cutting [5, 6]. Changes in the design of the inner tube have been made to increase the flow and cutting rates [17]. These newly designed vitreous cutters with an additional inner opening have been commercially available as a dual-blade cutter which enabled a constant aspiration rate with a higher duty cycle [5, 18, 19]. These changes increased the opening time of the port, and the cutting was from both the proximal (incoming) and distal (outgoing) blades of the cutter [5, 19–23].

Another newly designed beveled-tip cutter has been developed with an oblique-angled head of 30°, while the conventional cutters have flat-head tips [24, 25]. The aspirating flow stream of the conventional flat-tip cutters goes through the opening port, then changes direction through the inner tube by 90° during the cutting and aspiration. The oblique-angle design of the cutter tip allows the surgeon to place the head parallel and closer to the surface of the retina and preretinal tissue [10, 24]. In addition, the beveled cutter led to a straighter aspiration flow stream of the conventional flat-tip cutters [24, 25]. The aspiration rate of the beveled-tip cutters was higher than the conventional flat-tip cutter due to the enhancement of the proximal flow [25]. In addition, the beveled-tip cutters also had a faster reflux flow rate. However, the flow dynamics of dual-blade, beveled-tip vitreous cutters have not been examined in detail. It has also not been determined whether these two alterations of the cutter affected the cutting and aspirating properties. Thus, the purpose of this study was to compare the aspiration rates and flow dynamics of the dual-blade to that of the single-blade cutting and aspirating properties. Thus, the purpose of this study was to compare the aspiration rates and flow dynamics of the dual-blade to that of the single-blade beveled-tip vitreous cutters during the aspiration of balanced salt solution (BSS) and swine vitreous.

**Methods**

**Aspiration Rates of Vitreous Cutters while Aspirating BSS and Swine Vitreous**

The 25-gauge and the 27-gauge beveled dual-blade (HYPER-VIT® dual-blade cutter; Alcon Laboratories, Fort Worth, TX, USA) and the single-blade vitreous cutters (Advanced ULTRAVT® beveled high-speed cutter; Alcon Laboratories) driven by the CONSTELLATION® Vision System (Alcon Laboratories) were studied. To measure the aspiration rates, a 100-mL beaker was filled with approximately 70 mL of BSS or swine vitreous and placed on a weight scale. The vitreous cutter was held vertically by the arms of a support stand, and the tip of the cutter was placed into the BSS or vitreous deep enough from the surface. The weight loss of BSS or vitreous in the beaker was measured every 15 s after an initial 10 s as described [25]. The volume of the BSS or vitreous aspirated by the 25-gauge and 27-gauge cutters was calculated from the reduction of the weight \((n = 9)\) at cutting rates of 5,000, 10,000, 15,000, and 20,000 cuts/min (cpm) for the dual-blade cutters and cutting rates of 2,500, 5,000, 7,500, and 10,000 cpm for the single-blade cutters. Because the dual-blade cutters have an additional port in the inner tube, this led to two cuts per stroke, and the cpm was double that of the single-blade cutter. The aspiration pressure was set at 250, 450, and 650 mm Hg. To calculate of the aspiration rates from the weight loss, the relative density of the BSS was set at 1.06 g/mL and that of swine vitreous as 1.00 g/mL.

**Flow Dynamics during Aspiration of BSS or Swine Vitreous**

To determine the flow dynamics of BSS and swine vitreous, fluorescent polymer microspheres (FLUOstar®; EBM Corp., Tokyo, Japan) were mixed with BSS or swine vitreous. For the flow analysis of the vitreous, the vitreous was diluted with the same amount of BSS (1:1) to mimic core vitrectomy after the infusion was turned on, and the irrigating fluid was infused into the vitreous cavity. The tip of the 25- or 27-gauge dual- or single-blade vitreous cutters was aligned vertically in the BSS or the diluted vitreous in a transparent acrylic cube container with 3-cm sides (Fig. 1). A slit-beam of a green laser (Nd:YAG, wavelength = 532 nm) was projected through a cylindrical lens to create a cross-sectional image of the movement of the fluorescent microspheres. For a lateral view, the slit-beam laser was projected vertically into the container toward the opening port of the cutter, and a cross-sectional image was viewed from the side opposite the opening port. For a bottom view, the slit-beam laser was projected horizontally into the container at the level of the opening port of the cutter, and the cross-sectional image with a bottom view was obtained through a mirror located beneath the container. The aspiration pressure of the vitrectomy device was set at 650 mm Hg, and the cutting rate was set at 0 and 20,000 cpm for the dual-blade cutters and 0 and 10,000 cpm for the single-blade cutters.

Cross-sectional video images of the flow movements were seen as the movements of the fluorescent microspheres that were recorded with a high-speed video camera, HAS-D71 (DITECT, Tokyo, Japan). The velocity and direction of movement of the fluorescent microspheres were analyzed by the Flownizer 2D software (DITECT). The velocity and direction of the mean aspiration flow of BSS or diluted vitreous as parameters of the flow dynamics were extracted with the direction and the length of arrows and also in the color maps \((n = 5)\). The mean aspiration flow was calculated as the velocity and the angle of the mean flow at the measured point within an area in front of the port from the video images of at least 50 cutting cycles \((n = 5)\). The proximal end of the cutter was defined as the body end and the distal end as the head end of the cutter (Fig. 1b). The angle of the flow direction in the lateral view was defined as the horizontal angle with the opening port set at zero and plus on the distal end and minus on the proximal end relative to the horizontal angle.

In the lateral view, the maximum aspiration flow of BSS in an area of \(3 \times 3\) mm around the tip of the vitreous cutter was evaluated when the fastest aspiration flow was seen from the video images during the aspiration of BSS without cutting (0 cpm, aspiration only) and with a maximal cutting rate of 20,000 cpm for the dual-blade cutters and 10,000 cpm for the single-blade cutters. The mean aspiration flow during the aspiration of BSS with a cutting rate of 0 cpm and with the maximal cutting rate was calculated.
within an area of 1 × 2 mm in front of the port (n = 5). The maximum aspiration flow during the removal of diluted vitreous in an area of 5.4 × 3.2 mm around the tip of the vitreous cutter was evaluated with the maximal cutting rate of the dual-blade and the single-blade cutters. The mean aspiration flow of removing diluted vitreous with the maximal cutting rate of the dual-blade and the single-blade cutters was calculated as the average at each velocity and the angle of the aspiration flow at the measured point within an area of 2.5 × 2.5 mm in front of the port (n = 5).

In the bottom view, the mean aspiration flow during the aspiration of BSS with a cutting rate of 20,000 cpm of the dual-blade cutters and 10,000 cpm of the single-blade cutters was calculated by the average of each velocity. The angle of the flow was measured within an area of 2.5 × 2.5 mm around the cutter port (n = 5).

Flow Dynamics of Expelled BSS in Reflux Mode
A glass beaker was filled with 100 mL BSS and set on a weight scale. The changes in the weight of the beaker with the BSS was measured during the reflux of fluid every 15 s after an initial backflushing of at least 10 s. The expelled volume of BSS by the 25-gauge and 27-gauge single- or dual-blade vitreous cutters at an expelling pressure of 40, 80, and 120 mm Hg was calculated from the changes in the weight (n = 5).

To determine the direction and rate of extraction, the tip of the 25-gauge or 27-gauge dual- or single-blade vitreous cutters was placed into a 3-cm transparent acrylic cube filled with BSS mixed with fluorescent polymer microspheres. The expelling pressure of the BSS was set at 40 mm Hg in the reflux mode. Cross-sectional images of the movement of the fluorescent microspheres were recorded with a high-speed camera (HAS-D71; n = 5) during the backflushing of the BSS. The direction of the movement and velocity were analyzed by the Flownizer 2D software, and the mean expelling flow in an area of a 4.2 × 3.5 mm area in front of the opening port of the vitreous cutters from the lateral view was calculated.

Statistical Analyses
The significance of the differences between the 2 types of dual-blade and single-blade vitreous cutters was determined by the Mann-Whitney test. Statistical analyses were performed with the software in the VassarStats website (http://vassarstats.net). A p value of <0.05 was taken to be statistically significant.

Results
Aspiration Rates of Dual-Blade Vitreous Cutters for BSS
The aspiration rate for BSS by the 25-gauge dual-blade cutter did not decrease significantly from that at 0 cpm to that at 5,000 cpm (p = 0.117, Mann-Whitney...
Fig. 2. Aspiration rates of BSS and swine vitreous by dual-blade and single-blade vitreous cutters. a Aspiration rates of BSS by the 25-gauge and 27-gauge dual-blade cutters show higher aspiration rates at lower and higher cutting rates. In contrast, the aspiration rates of BSS by the 25-gauge and 27-gauge single-blade cutters decrease with higher cutting rates. b Aspiration rates of swine vitreous by the 25-gauge and 27-gauge dual-blade and single-blade cutters increase with an increase of the cutting rates more than that of single-blade cutters.

Table 1. Aspiration rates of BSS and swine vitreous (aspiration pressure = 650 mm Hg)

|                | 25G-dual | 25G-single | p value | 27G-dual | 27G-single | p value |
|----------------|----------|------------|---------|----------|------------|---------|
| BSS, mL/min    |          |            |         |          |            |         |
| 0 cpm          | 14.21±0.40 | 14.42±0.30 | 0.092   | 7.98±0.24 | 8.00±0.42 | 0.261   |
| 5,000 cpm*     | 14.08±0.46 | 8.56±0.76 | <0.0001 | 7.73±0.34 | 4.12±0.41 | <0.0001 |
| 10,000 cpm*    | 14.23±0.42 | 9.12±0.71 | <0.0001 | 7.50±0.53 | 4.44±0.45 | <0.0001 |
| Vit, mL/min    |          |            |         |          |            |         |
| 5,000 cpm*     | 3.32±1.07 | 2.33±0.53 | 0.009   | 1.79±0.59 | 1.22±0.44 | 0.010   |
| 10,000 cpm*    | 3.93±0.93 | 2.70±0.77 | 0.001   | 2.23±0.29 | 1.44±0.37 | <0.0001 |

Vit, swine vitreous; dual, dual-blade beveled vitreous cutter; single, single-blade beveled vitreous cutter. * 5,000 cpm for the single-blade cutter = 10,000 cpm for dual-blade cutter. * 10,000 cpm for the single-blade cutter = 20,000 cpm for dual-blade cutter.

Test, Fig. 2), also from that at 5,000 cpm to that at 10,000 cpm (p = 0.413) and from that at 10,000 cpm to that at 15,000 cpm (p = 0.298) and from that at 15,000 cpm to that at 20,000 cpm (p = 0.117) for an aspiration pressure of 650 mm Hg. In contrast, the aspiration rate of BSS by the 25-gauge single-blade cutter at an aspiration pressure of 650 mm Hg decreased significantly from that at 0 cpm to that at 2,500 cpm (p = 0.0002, Mann-Whitney test) and from that at 2,500 cpm to that at 5,000 cpm (p = 0.0002). There was an increase in the aspiration rate of BSS from that at 5,000 cpm to that at 7,500 cpm (p = 0.189) and from that at 7,500 cpm to that at 10,000 cpm (p = 0.3446), but these increases were not significant.
The aspiration rate of BSS by the 27-gauge dual-blade cutter decreased significantly from that at 0 cpm to that at 5,000 cpm ($p = 0.017$, Mann-Whitney test, Fig. 2) but did not decrease significantly from that at 5,000 cpm to that at 10,000 cpm ($p = 0.189$), and from that at 15,000 cpm to that at 20,000 cpm ($p = 0.268$) at an aspiration pressure of 650 mm Hg. The aspiration rate of BSS by the 25-gauge dual-blade cutter at an aspiration pressure of 650 mm Hg was 14.23 ± 0.42 mL/min at 20,000 cpm and 14.08 ± 0.46 mL/min at 10,000 cpm. These were increases of 56% ($p < 0.0001$, Mann-Whitney test, Table 1) and 64% ($p < 0.0001$) compared to that by the single-blade cutters of 9.12 ± 0.71 mL/min at 10,000 cpm and 8.56 ± 0.76 mL/min at 5,000 cpm. The aspiration rate of BSS by the 27-gauge dual-blade cutter at an aspiration pressure of 650 mm Hg was 7.50 ± 0.53 mL/min at 20,000 cpm which were greater than that by the single-blade cutter at 4.44 ± 0.45 mL/min at 10,000 cpm and 4.12 ± 0.41 mL/min at 5,000 cpm. These were increases of 69% ($p < 0.001$) and 88% ($p < 0.0001$), respectively.

**Aspiration Rates of the Vitreous Cutter for Swine Vitreous**

The aspiration rate for swine vitreous by the 25-gauge dual-blade cutter increased with increases of the cutting rates (Fig. 2), and it increased significantly at 20,000 cpm from that at 5,000 cpm ($p = 0.019$, Mann-Whitney test) at an aspiration pressure of 650 mm Hg. However, the in-
crease was not significant from that at 5,000 cpm to that at 10,000 (p = 0.123), that at 10,000 cpm to that at 15,000 (p = 0.181), and that at 15,000 cpm from that at 20,000 cpm (p = 0.468). In contrast, the aspiration rate for swine vitreous by the 25-gauge single-blade cutter did not increase significantly at 10,000 cpm from that at 2,500 cpm (p = 0.111) or from that at 2,500 cpm to that at 5,000 (p = 0.50), from that at 5,000 cpm to that at 7,500 cpm (p = 0.312), and from that at 10,000 cpm to that at 7,500 cpm (p = 0.111).

The aspiration rate for swine vitreous by the 27-gauge dual-blade cutter increased with an increase of the cutting rates (Fig. 2). There was a significant increase at 20,000 cpm and 10,000 cpm from that at 5,000 cpm (p = 0.0001, p = 0.0274) at an aspiration pressure of 650 mm Hg. However, the aspiration rates did not change significantly from that at 15,000 cpm to that at 10,000 cpm (p = 0.164) and from that at 20,000 cpm to that at 15,000 cpm (p = 0.071). In contrast, the flow rate for removing swine vitreous by the 27-gauge single-blade cutter did not increase significantly at 10,000 cpm from that at 2,500 cpm (p = 0.097) and also from that at 2,500 cpm to that at 5,000 cpm (p = 0.397), from that at 5,000 cpm to that at 7,500 cpm (p = 0.113), and from that at 7,500 cpm to that at 10,000 cpm (p = 0.334).

The aspiration rate for swine vitreous by the 25-gauge dual-blade cutter at an aspiration pressure of 650 mm Hg was significantly higher at 10,000 cpm (p = 0.009, Table 1) and at 20,000 cpm (p = 0.001) compared to that by the single-blade cutters at 5,000 and 10,000 cpm. These were increases of 42% (p < 0.0001, Mann-Whitney test) and 46% (p < 0.0001), respectively. The aspiration rate for swine vitreous by the 27-gauge dual-blade cutter at an aspiration pressure of 650 mm Hg was significantly higher.
at 10,000 cpm ($p = 0.010$) and at 20,000 cpm ($p < 0.0001$) than that by the single-blade cutters at 5,000 and 10,000 cpm. These were increases of 47% ($p = 0.0104$, Mann-Whitney test) and 55% ($p < 0.0001$, respectively).

**Lateral View of Flow Dynamics while Aspirating BSS**

The color map analysis of flow dynamics showed that the direction and velocity of aspirating flow changed according to the movement of the inner blade of the vitreous cutter. The maximal aspiration flow of the 25-gauge and 27-gauge dual-blade cutters indicated a faster oblique flow from the distal end of the cutter at 0 cpm (aspiration only) and at 20,000 cpm of the maximal cutting rate at an aspiration pressure of 650 mm Hg. A faster oblique flow from the distal end at 0 cpm but a faster oblique flow from the proximal end at 10,000 cpm.

Because the direction and velocity of the aspirating flow changed with the cutting movement of the cutter, the velocity and angle of the mean aspiration flow were analyzed. The velocity of the mean aspiration flow of the 1 mm × 2 mm area in front of the opening port of the vitreous cutter at 0 cpm (aspiration only) indicated a slightly greater but not significant velocity with the 25-gauge and the 27-gauge dual-blade cutters ($7.60 \pm 0.50$ mm/s and $3.66 \pm 1.08$ mm/s, respectively; Fig. 4) than the 25-gauge and 27-gauge single-blade cutters ($7.1 \pm 2.1$ mm/s, $p = 0.015$ and $3.07 \pm 0.30$ mm/s, $p = 0.136$, respectively). The angle of the mean aspiration flow of the same area indicated a slightly greater angle, but it was not significant with the 25-gauge and the 27-gauge dual-blade cutters ($7.01 \pm 1.63^\circ$ and $6.61 \pm 3.43^\circ$, respectively, Fig. 4) at 0 cpm than the 25-gauge and
27-gauge single-blade cutters (5.42 ± 1.40°, p = 0.052 and 5.43 ± 2.67°, p = 0.248, respectively).

The velocity of the mean aspiration flow of the same area was significantly higher with the 25-gauge and the 27-gauge dual-blade cutters (6.30 ± 0.90 mm/s and 3.58 ± 1.04 mm/s, respectively; Fig. 5) with a maximal cutting rate of 20,000 cpm (dual-blade cutters) and 10,000 cpm (single-blade cutters) than the 25-gauge and 27-gauge single-blade cutters (4.90 ± 0.38 mm/s, p = 0.003 and 2.48 ± 0.23 mm/s, p = 0.019, respectively). The angle of the mean aspiration flow of the same area of the 25-gauge dual-blade cutter was 5.36 ± 2.32° which was greater on the distal end of the cutter than with the 25-gauge single-blade cutter (−3.01 ± 1.65°, p = 0.0005). The angle of the mean aspiration flow of the same area of the 27-gauge dual-blade cutter was 4.31 ± 1.62° which was also greater on the distal end than that with the 27-gauge flat-tip cutter (−8.20 ± 1.80°, p = 0.0001). The angles of the mean aspiration flow of the 25-gauge single-blade cutters were not significantly different from that of the 27-gauge dual-blade cutters (p = 0.176). In contrast, the angles of the mean aspiration flow of the 25-gauge single-blade cutters were significantly greater on the distal end than that of the 27-gauge single-blade cutters (p = 0.0002).

**Bottom View of Flow Dynamics while Aspirating BSS**

The direction and velocity of aspirating flow changed with a wavy movement around the vitreous cutter from a bottom view in association with the cutting movement of the cutter. However, the velocity and angle of the mean aspirating flow were similar among the vitreous cutters with faster aspirating flow from the anterior side of the port of the cutter (Fig. 6). The mean aspirating flow of the 25-gauge and 27-gauge flat-tip cutters appeared to be faster than that of the 25-gauge and 27-gauge single-blade cutters according to the scale bar in Figure 6.

**Flow Dynamics of Expelled BSS in Reflux Mode**

The volume of the expelled fluid in the proportional reflux mode increased as the expelling pressure increased with both types of cutters (Fig. 7). The volume was not significantly different between the 25-gauge
dual-blade and single-blade cutters ($p = 0.301$ at 40 mm Hg; $p = 0.209$ at 80 mm Hg; $p = 0.164$ at 120 mm Hg) and 27-gauge dual-blade and single-blade cutters ($p = 0.122$ at 40 mm Hg; $p = 0.059$ at 80 mm Hg; $p = 0.202$ at 120 mm Hg).

The velocity of the mean expelled flow in the lateral view of 4.2 mm $\times$ 3.5 mm in front of the port of the cutter at a pressure of 40 mm Hg did not differ between the 25-gauge dual-blade and single-blade cutters ($p = 0.149$) and between the 27-gauge dual-blade and single-blade cutters ($p = 0.337$). The angle of the mean expelled flow in the lateral view of the same area also did not differ between the 25-gauge dual-blade and single-blade cutters ($p = 0.072$) and between 27-gauge dual-blade and single-blade cutters ($p = 0.174$).

**Flow Dynamics during Aspiration of Diluted Swine Vitreous**

The movements of the diluted vitreous gel during cutting and aspiration by the vitreous cutters were a combination of rapid and slow movements, depending on the density and structure of the vitreous fibers. Even though we used diluted vitreous, the movement of the vitreous was not uniform during the vitreous cutting, and the duration of smoother movements during the vitreous cutting was used for the flow analysis (online suppl. Videos 1, 2; see www.karger.com/doi/10.1159/000521468 for all online suppl. material). This was detected in the static images that were taken from the video of the high-speed camera at the maximal cutting rate with an aspiration pressure of 650 mm Hg (Fig. 8). The color maps of the
Fig. 8. Color maps at the maximum aspiration flow for diluted swine vitreous in the area from a lateral view. a Color maps of the maximum aspiration flow in a 5.4 × 3.2 mm area from a lateral view of the 25-gauge dual-blade cutter at 20,000 cpm indicates less distal flow than that of 25-gauge single-blade cutter at 10,000 cpm (b). In contrast, the color maps of the maximum aspiration flow from a lateral view of 27-gauge dual-blade cutter at 20,000 cpm indicate more distal flow than that of 27-gauge single-blade cutter at 10,000 cpm (d). e Velocity of the mean aspiration flow in a 2.5 × 2.5 mm area in front of the cutter from a lateral view indicates significantly greater aspiration velocity with the 25-gauge and 27-gauge dual-blade cutters than that with 25-gauge and 27-gauge single-blade cutters. f Angles of the mean aspiration flow with the 25-gauge dual-blade cutter are significantly lower on the proximal end than that of 25-gauge single-blade cutters. In contrast, the angle of the mean aspiration flow with the 27-gauge dual-blade cutter is significantly greater to the distal end than that of 27-gauge single-blade cutters. The horizontal angle was defined as zero and the distal end as plus and the proximal end as minus from the opening port shown in (g). The color map of the mean flow at each measurement point in the lateral view of the 25-gauge dual-blade cutter (g), 25-gauge single-blade cutter (h), 27-gauge dual-blade cutter (i), and 27-gauge single-blade cutter (j).

Fig. 9. Schematic diagram of aspirating flow of the vitreous with 25-gauge and 27-gauge vitreous cutters. The direction of aspirating flow of vitreous with the 25-gauge beveled dual-blade cutter deviated more to the proximal end. This may be because the backward movement of the inner blade of the 25-gauge beveled dual-blade cutter may be dominant, leading to more inflow from the proximal end. This dominancy depends on the relationship between the inner diameter of the cutter to the size of the inner and outer opening ports.
maximum flow in an area of $5.4 \times 3.2$ mm in the lateral view of the 25-gauge dual-blade cutter at 20,000 cpm indicated less distal flow than that of the 25-gauge single-blade cutter at 10,000 cpm. In contrast, the color maps of the maximum flow in a lateral view of the 27-gauge dual-blade cutter at 20,000 cpm indicated more distal flow than that of the 27-gauge single-blade cutter at 10,000 cpm.

The mean velocity in the $2.5 \times 2.5$ mm area in front of the cutter with the lateral view indicated a significantly greater aspiration velocity with the 25-gauge and 27-gauge dual-blade cutters than that with 25-gauge and 27-gauge single-blade cutters ($p = 0.018$ and $p = 0.048$, respectively). The angle of the aspirating flow with the 25-gauge dual-blade cutter was significantly smaller on the proximal end than that of 25-gauge single-blade cutters. In contrast, the angle of the aspirating flow with the 27-gauge dual-blade cutter was significantly greater on the distal end than that of 27-gauge single-blade cutters.

**Discussion**

The results showed that the flow dynamics during vitreous aspiration was dependent on the properties of the aspirated fluid. In addition, the aspirating flow of the vitreous had whip-like movements because of the mixture of collagen fibers, hyaluronic acid, and vitreal fluids [26, 27]. These components make predicting the flow difficult. The aspiration of fluids can be done without a cutting procedure which is different for the vitreous that requires cutting before it can be aspirated into the opening port of the cutter. The higher cutting rates of the vitreous cutters even with smaller instruments can cut the vitreous into smaller pieces to reduce its viscosity to that of fluids and increase the efficiency of removing the vitreous [14–16].

The flow dynamics of the vitreous cutter was evaluated with BSS or saline due to the repeatability of the analyses [12, 13, 23]. It has been reported that the aspiration rates of BSS of the conventional single-blade cutter decreased as the cutting rate increased due to a decrease in the duty cycle [14–16]. In contrast, a flat-tip dual-blade cutter to cut the vitreous in a forward and backward movement during each cycle increased the duty cycle and cutting rates twofold [20–22]. Another innovation of the new vitreous cutter was an oblique angle of the beveled-tip single-blade that led to a more linear aspiration flow than that of the flat-tip cutters which had improved the aspiration rate of BSS at the higher cutting rates and faster aspiration flow by increasing the proximal aspiration flow [25].

We compared the beveled dual-blade and single-blade pneumatic guillotine cutters. The beveled single-blade cutters had significantly lower aspiration rates of BSS at the higher cutting rates as described [4–6]. In contrast, the beveled dual-blade cutters had a constant aspiration rate with BSS from no cutting (aspiration only) to the higher cutting rates (Fig. 2) because the dual-blade cutters had an increased duty cycle of approximately 100% with either port opened. The aspiration rate with the dual-blade cutters for the swine vitreous increased more than that with the single-blade cutters. These results of the flow dynamics of BSS and vitreous with the beveled dual-blade cutters were comparable to that with the flat-tip dual-blade cutters [20, 21].

The lateral view showed a faster aspiration flow of BSS with the 25-gauge and 27-gauge beveled dual-blade cutters at 20,000 cpm of the maximal cutting rate than that with both single-blade cutters (Fig. 5). These findings for the distal flow were similar to the distal aspirating flow with both cutters without cutting (Fig. 4). We assume that the dual-blades with opening of either port produce constant flow and enhance the distal aspirating flow produced with the oblique angle of the cutter tip. The aspiration flow of BSS with the 25-gauge and 27-gauge beveled single-blade cutters showed that a faster oblique flow from the distal end of the cutter without cutting (Fig. 3c, g) but a faster oblique flow from the proximal end with the maximal cutting rates (Fig. 3d, h). The direction of the flow with the maximal cutting rates was more proximal end with the 27-gauge beveled single-blade cutter than that with the 25-gauge beveled single-blade cutter (Fig. 3d vs. h). The proximal aspirating flow may depend on the rapid inward flow when the port of the cutter is fully open especially in the inner tube with a smaller diameter [25].

The lateral view evaluated the aspiration rate in front of the open port of the vitreous cutter. We also recorded the bottom view to evaluate the aspirating flow from the side and backside towards the opening port. However, no significant differences were seen between both the beveled dual-blade and single-blade cutters (Fig. 6). These findings indicated that the differences of aspirating flow were mainly from the front side of the port in the vertical direction. The aspiration flow rate and reflux flow without cutting did not differ between the beveled dual-blade and single-blade cutters (Fig. 7) because the inner tube of the cutter did not move, and these flow dynamics depended on the shape of the outer tube of the cutter which did not differ but may have had minor differences in the size of the port of the dual-blade cutters.
The flow dynamics during vitreous aspiration included various complicated movements of the vitreous which were not uniform and consisted of thick vitreous fibers and uneven hyaluronic acid [27]. We used a slit-beam laser to obtain cross-sectional images of the movement of the fluorescein microspheres. However, the slit-laser beam was scattered by the thick vitreous, and the movements in front and behind the cross-sectional images were also detected. This is why we used diluted vitreous to reduce the effect of uneven movements of the vitreous and also to try to mimic core vitrectomy with infusion of BSS. A faster aspiration flow of diluted vitreous with the 25-gauge and 27-gauge beveled dual-blade cutters than that with both single-blade cutters was observed (Fig. 8e). However, the direction of the aspirating flow of vitreous with the 25-gauge beveled dual-blade cutter deviated more to the proximal end than that with the 25-gauge single-blade cutter (Fig. 8f). In contrast, the direction of aspiration flow of vitreous with the 27-gauge beveled dual-blade cutter deviated to the distal end than that with the 27-gauge single-blade cutter. The differences in the direction between the 25-gauge and 27-gauge beveled single-blade cutters were due to the aspirating flow of BSS of the 25-gauge cutter deviated more to the distal end than that of the 27-gauge cutter (Fig. 4b). The direction of the aspirating flow of BSS with both 25-gauge and 27-gauge beveled dual-blade cutters deviated to the distal end at the maximal cutting rate (Fig. 5b) because of the oblique angle of the cutter tip. The direction of aspirating flow of vitreous with the 27-gauge beveled dual-blade cutter deviated more to the distal end than that with the 27-gauge single-blade cutter (Fig. 8f). The flat-tip dual-blade cutter has been reported to be more efficient with a lower hydraulic resistance of human vitreous than the single-blade cutter at higher cutting rates without a reduction of the viscosity [26]. The hydraulic resistance was reduced more with smaller gauge cutters and acted more like fluid dynamics [26]. The dual-blade cutters have two blades to cut the vitreous for forward and backward movement of the inner tube [21–23]. The backward movement of the blade of the 25-gauge beveled dual-blade cutter may be dominant for the diluted vitreous at the maximal cutting rate, and the dominant inner blade may differ depending on the thickness of vitreous, cutting rates, aspiration pressures, and diameter of the cutter (Fig. 9). The aspirating flow of the vitreous with a dual-blade vitreous cutter of a smaller gauge may enhance the effect of the oblique angle of the cutter tip to produce stable flow similar to the aspirating flow of BSS.

There are limitations in this study. We used one concentration of diluted vitreous to examine the flow dynamics during the cutting of the vitreous because of difficulty of flow analysis due to unpredictable whip-like movements of the vitreous during cutting. Thus, the mechanism of the faster aspirating flow of vitreous need to be further analyzed. However, we found that the differences in the direction of aspirating flow between the two gauges of the vitreous cutter and dual- and single-blade cutters. We used a vitrectomy machine to drive the vitreous cutters with a Venturi pump and not with a peristaltic pump which may influence the flow rate [20].

**Conclusions**

In conclusion, the 25-gauge and 27-gauge beveled-tip dual-blade cutters enable a constant aspirating flow of BSS independent of the cutting rates. This increases the effectiveness of vitreous cutting, especially at higher cutting rates and smaller gauge cutters. The beveled dual-blade cutters produce a greater volume and velocity of aspirating flow by increasing the distal aspirating flow enhanced with the beveled head of the cutter especially in the smaller gauge instruments.

**Acknowledgments**

The authors thank professor Emeritus Duco Hamasaki of the Bascom Palmer Eye Institute, University of Miami, Miami, FL, for discussions and thorough editing of the manuscript.

**Statement of Ethics**

The study has been granted an exemption from requiring ethics approval by the Institutional Review Board of the Kyorin University because the study does not include any human and animal studies.

**Conflict of Interest Statement**

Dr. M. Inoue reports to have received a grant from Alcon Lab and personal lecture fee from Alcon Lab, Novartis, AMO, Santen, Senju, Carl Zeiss Meditec, Bayer, and Kowa. Dr. T. Koto reports to have received personal lecture fee from Alcon Lab, Novartis,
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Bayer, Santen, Carl Zeiss, Santen, and AMO, outside the submitted work. Dr. A. Hirakata reports to have received research fund from Santen outside of the submitted work and personal lecture fee from Alcon Lab, Novartis, Santen, Bayer, Sanwakagaku, Senjyu, and Kowa, outside of the submitted work.

Funding Sources

This study was supported by the research Grant from Alcon Japan Ltd. The authors indicate no government financial support was involved in the work for this submission.

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Author Contributions

M.I. has contributed to the conception and design, acquisition of data, analysis and interruption of data, and drafting and critically reviewing the manuscript. T.K. has contributed to the analysis and interruption of data and drafting the manuscript. A.H. has contributed to the conception and design and critically reviewing the manuscript.

Data Availability Statement

The research data are not publicly available, but it can be available through the personal communication from the authors.