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Analysis of a 23-gauge ultra high-speed cutter with duty cycle control

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Abstract

Purpose—Determine the performance of dual pneumatic ultra high-speed 23-gauge cutters operated with variable duty cycle (DC) settings.

Methods—Frame-by-frame analysis of high-speed video was used to determine the DC in core, 50-50 and shave modes. Using three cutters at various cycles per minute (CPM) and aspiration levels, mass of water or vitreous removed from a vial was measured within a specified time period. Average flow rates were calculated for each aspiration level and cut-rate with the different DC options.

Results—The DC increased with increasing cut rate in shave mode, was relatively stable in the 50-50 mode and decreased for the core mode. The DC converged at 5000 CPM for the three different modes. Water flow curves followed the DC variation. Vitreous flow rates for all the DC modes increased with increasing cut rates and peaked at 5000 CPM ($P<0.05$). The results of the 50-50 mode, that had isolated the DC influence, showed that increasing aspiration and/or cut rate, independently increased the vitreous flow rate.

Conclusion—Progressive values of aspiration and/or cut rate, increases the vitreous flow rate, independently of the DC. DC control also has an important effect on the vitreous flow; but this effect was reduced at high cut rates due to convergence of the DC modes.

Keywords

Vitrectomy; duty cycle; cut rate; aspiration

Choosing the optimal instruments and parameters for vitrectomy has become increasingly challenging because of the variety of modifications and improvements recently introduced.

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Small-gauge vitreous instruments have improved pars plana vitrectomy considerably. These new instruments minimize surgically induced trauma to ocular tissue, resulting in quicker recovery and less postoperative discomfort for the patient.[1] On the other hand, decreasing instrument size imposes significant constraints on the functionality of the surgical instruments. [2]

Efforts to improve the efficiency of smaller diameter vitreous cutters have focused on increasing cut speed, maximizing cutting port surface area, and enlarging the diameter of the internal shaft to enable higher flow rates.[3] Ultra high-speed cutters (up to 5000 cycles per minute [CPM]) have been developed. The underlying premise for these ultra-high-speed cutters is that increasing the cut rate reduces the size of the vitreous pieces; and the resulting less viscous gel is more easily aspirated and removed, despite the dramatically reduced diameter of the vitreous cutters.[4]

Efforts also have been made to improve the duty cycle (DC) of vitreous cutters, particularly at higher cut rates. At high-speed velocity, most conventional cutters decrease their DC, or percent of port open time, throughout the cut cycle; and consequently, there is an expected decrease in the water and vitreous flow rates and a corresponding increase in the surgical time required.[5, 6] In most vitrectomy machines, while the aspiration rate and cut rate can be controlled, the DC cannot.

Recently, a new vitrectomy system with dual pneumatic cutters made DC control available. With the introduction of this new variable, different DC settings may be used, affecting the surgical technique and the flow behavior during surgery. The purpose of this study is to determine the performance of ultra-high-speed cutters operated with this variable DC setting.

Methods

The performance of 23-gauge cutters was tested with the Constellation Vision System (Alcon, Fort-Worth-TX), which utilizes a dual pneumatic drive, using the three different available DCs (core, 50-50 and shave). Three different cutters were used for each duty cycle tested.

The DC was evaluated using a stop-action camera (Motionscope M1, Red Lake, Tokyo, Japan) with resolution of 1000 frames per second. Frame-by-frame analysis of the video was used to determine DC as a function of speed. Two masked investigators independently analyzed the frames to determine the cutting phases (totally open, opening, closing, and totally closed) of the 3 different DCs options: 1-the system core (maximum port open time); 2-50-50 (half port open time and half port close time); 3-shave (minimum port open time). The opening time was defined as the time between the first frame of guillotine opening and the last frame of guillotine disappearance. The open time was measured between the end of the opening time and the start of closing time. The closing time was defined as when the guillotine reappeared through the cutting port until it was completely closed. The closed time started from the end of closing time and ended at the start of opening time. The final DC was generated by the equation: DC = [open time + 1/2 (opening time + closing time)]/ DC duration.

For flow rate tests, each cutter was suspended in a vial of either water or porcine vitreous. The vitreous used for the experiments was carefully removed en bloc from porcine eyes enucleated less than 12 hours postmortem (Sierra for Medical Science, Whittier, CA). All eyes were kept at 4° C before use.

The vials were placed on a precision (0.01 g) balance (Ohaus Corp. Parsippany, NJ) that continually measured the weight of the remaining water or vitreous throughout each trial. Using a high-sampling (2 samples/second) 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 - flow rate (ml/sec). The density of the porcine vitreous was assumed to be approximately equal to the density of water (d=1g/ml). Thirty trials were conducted for each cutter at different cut rates (1000, 2000, 3000, 4000 and 5000 CPM) and aspiration levels (100, 200, 300, 400, 500 and 600 mmHg) in both water and vitreous. A total of 150 measurements (75 seconds) were taken for water and 300 measurements (150 seconds) for vitreous flow in each trial.

The water and vitreous flow rate averages and standard deviations were calculated for each aspiration level and cut rate with the different DC options. Repeated measures analysis of variance tested mean vitreous and water flow rates between aspiration rates by DC and CPM. Mixed models with repeated measures were used to obtain regression equations for predicting mean vitreous and water flow rates. SAS V9.2 programming language (SAS Inst. Cary NC) was used for all analyses. Accepted level of significance for all tests was $P < 0.05$.

Results

Duty Cycle for core, 50-50, and shave options

DC increased with increasing cut rate when using the shave option and decreased with core mode. In the core mode the DC ranged from 78% (1000 CPM) to 54% (5000 CPM); in shave mode from 17% (1000 CPM) to 50% (5000 CPM); and in 50/50 mode, the DC remained stable during the test (54% to 50%). DC for the three different modes converged at 5000 CPM (Figure 1).

Water Flow for core, 50-50, and shave settings

Water flow rate for the 23-gauge cutters at various cut rates and different aspiration levels is depicted in Figure 2. Water flow rates for the core peaked at 1000 CPM and dropped with increasing cut rate for the same aspiration ($P < 0.001$). In 50-50 mode, the water flow was maintained relatively constant when changing cut rate using the same aspiration levels, with slight decrease at high cut rates for low aspiration and slight increase for high aspirations ($P < 0.001$). In the shave mode, the flow increased with increasing cut rate, peaking at 5000 CPM ($P < 0.001$).

In core mode, the water flow rate increased proportionately 0.039 mL/sec for every 100 mmHg increase in aspiration level ($P < 0.001$) and decreased proportionately 0.021 mL/sec for every 1000 CPM increase ($P < 0.001$). For 50-50 mode, the flow increased proportionately 0.033 mL/sec for every 100 mmHg increase in aspiration level ($P < 0.001$) and decreased proportionately 0.003 mL/sec for every 1000 CPM increase ($P = 0.002$). For the shave mode, the flow increased proportionately 0.023 mL/sec for every 100 mmHg increase in aspiration level increase ($P < 0.001$) and increased proportionately 0.017 mL/sec for every 1000 CPM increase ($P < 0.001$) (Table 1).

When testing for differences between the three different DC flow rates, there was a significant difference for all aspiration and cut rate levels ($P \leq 0.01$)(Table 2). The average water flow rate was greatest in core mode, followed by the 50-50, and shave ($P < 0.001$ for all comparisons)(Table 3).

Vitreous Flow for Core, 50-50 and Shave Settings

Vitreous flow rates for the cutters at various cut rates and different aspiration levels are depicted in Figure 2. Vitreous flow rates for all DC modes increased with increasing cut rates and peaked at 5000 CPM ($P < 0.001$).

In the core mode, vitreous flow rates increased proportionately 0.008 mL/sec for every 100 mmHg increase in aspiration level and increased proportionately 0.003 mL/sec for every 1000 CPM increase. For 50-50 mode, the flow increased proportionately 0.007 mL/sec for every 100 mmHg increase in aspiration and increased proportionately 0.005 mL/sec for every 1000 CPM increase. For the shave mode, flow increased proportionately 0.006 mL/sec for every 100 mmHg increase in aspiration and increased proportionately 0.006 mL/sec for every 1000 CPM increase ($P < 0.001$ for all)(Table 1).

When testing for differences between the three different DC, there was a significant difference in the vitreous flow rates at almost all aspiration and cut rate levels, except at 4000 CPM and 100 mmHg and 600 mmHg, and at 5000 CPM and 300 mmHg and 600 mmHg (Table 2). The average vitreous flow was greater in core mode, followed by the 50-50 and shave modes ($P < 0.05$ for all the comparisons)(Table 3).

Discussion

This study demonstrates the effects of different duty cycles on 23-gauge vitrectomy probe fluidics. Many independent factors influence flow rates, such as viscosity of the aspirated fluid, inner diameter of the vitrectomy probe, size of the fragmented vitreous, turbulence of the fluid inside and outside of the probe and aspiration tube, size of the cutting port, structure of the instruments, aspiration level, cut rate, and DC. [7, 8] Physical instrument parameters such as size and shape cannot be changed during surgery. Until the advent of these dual pneumatic cutters, the only two parameters that could be changed were the cut rate and the aspiration level. Now, using the latest generation cutters, one may also partially control the DC, independent of aspiration and cut rate.

Water flow tests more predictably and accurately reflect Poiseuille’s law of flow.[9] In this study, the water flow curve reflects the DC variation. Both DC and water flow rates decreased with increasing cut rate in the core mode and increased with increasing cut rate in the shave. In 50-50 mode, although the graph shows a relatively constant flow trend when the cut rate is increased, statistically significant differences between the values were discovered. Slight variances in the flow rates seen at high cut rates might not be clinically significant, and the significant P values could be justified by the small variation observed in the water flow tests, with small standard deviations.

Vitreous flow drastically differs from that of water or balanced salt irrigation solution. Vitreous is a semisolid mixture of water, collagen fibers, and hyaluronic acid.[10] The complex nature of vitreous makes its behavior unpredictable during vitrectomy, sometimes generating high standard deviations between the tests. Higher cut rates fragment the vitreous into smaller segments, resulting in reduced flow obstruction.[2] Conversely, lower cut rates generate less vitreous fragmentation and more flow obstruction due to increased resistance. Viscoelastic behaviors directly affect the flow rate in the cutter’s tubing and the performance of the vitrectomy system during surgery. Both elasticity and viscosity are lower in cut vitreous compared to those of intact vitreous gel, but while elasticity decreases according to cut rate, viscosity seems to decrease proportionally to the port and tubing size.[11]

The vitreous flow rate in this study were mainly determined by the aspiration and cut rates. Using the 50-50 mode to isolate the DC influence, increasing aspiration and/or cut rate, increases the vitreous flow rate, independent of the DC. However, DC also has an important effect on vitreous flow.

When comparing DC modes, we notice that even at lower cut rates, using higher DC results in higher proportional flow rates, as the port stays open most of the time. The vitreous flow rates at low cut rates were significantly higher in the core mode than in the 50-50 mode, and this one, higher than the shave at equivalent settings. Although the influence of the DC is clear, the difference between the three settings in the studied machine is reduced at higher cut rates, mainly due to convergence of DC at around 50%. Maximum vitreous flow was similar between the three different DC settings at 4000 and 5000 CPM.

DC of conventional cutters drops significantly at higher cut-rates.[12] Newer generation dual pneumatic cutters have partially overcome this problem by using separate air lines to close and open the cutter port, allowing DC to be controlled independent of cut rate.[13] However, even in these cutters, DC drops as measured in the ultra-high-speed core mode. The highest average water and vitreous flow were found in core mode, mainly influenced by the high vitreous flow at the low cut rates (78% DC) when comparing to other modes.

In the multiple regression table, the estimated change in flow by increasing aspiration is 2.39x higher than by increasing the cut rate for the core mode. In the shave mode, where DC increases with cut rate, the estimated change in flow by increasing the cut rate is slightly higher than when increasing aspiration. From this study, a cutter that works with increasing DC (>50%) at high cut-rate speeds could further improve vitreous flow. Vitreoretinal traction studies show that the vitreous traction decreases with increasing cut rates.[14] However, the effect of increasing DC and open port time at high cut rates and its association with tractional complications has not yet been established.

The increase in vitreous flow of the referenced 23-gauge cutter was significantly dependent upon aspiration, cut rate and DC. However, the effect of reduced DC with high cut rate was not as significant since the vitreous flow rate could be maintained. Our results indicate that keeping the port open longer at lower cut rates improves the flow; but the effect was offset by the increased resistance to the flow of larger vitreous pieces. Higher cut rates associated with more frequently open port allow increased vitreous flow by reducing viscosity. These findings should aid surgeons in selecting the optimal probe and parameters by weighing the various advantages and limitations of DC control.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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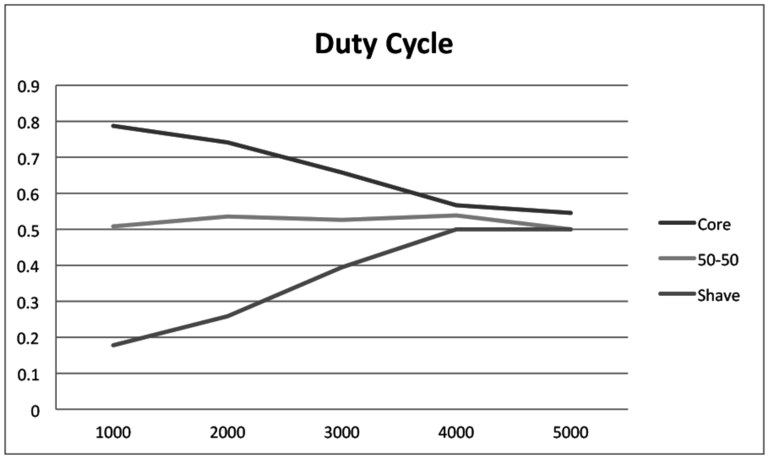

Figure 1.
Duty cycle of Core, 50-50 and Shave modes. The DC increased with increasing cut rate when using the shave option, was relatively stable in the 50-50 mode and decreased for the core mode. It converged at 5000 CPM for the three different modes.

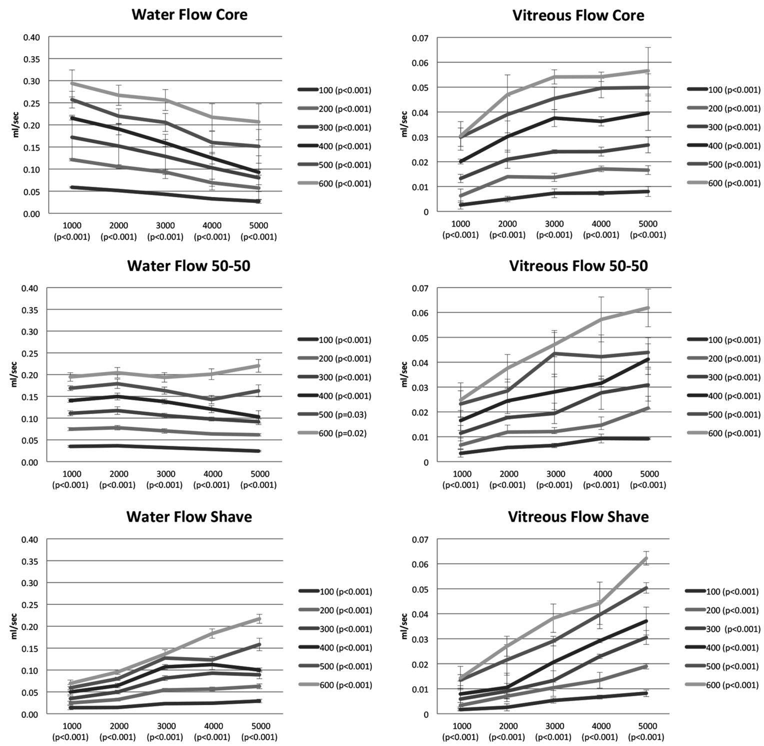

Figure 2.

Water and vitreous flow rates of Core, 50-50 and Shave (mean±standard deviation). *P* values represent analysis of variance by aspiration (vertical axis) and cut rate (horizontal axis). Water flow curves followed the DC variation. Vitreous flow rates for all the DC modes increased with increasing cut rates and peaked at 5000 CPM.

Table 1

Multiple Regression Models Using Mixed Repeated Measures Models, Predicting Vitreous and Water Flow Rates for Increasing Aspiration and Cut Rates.

	Parameter estimate±SE	P-value
Vitreous flow rates		
Core - $R^2 = 0.91$		
Intercept	-0.01461	
Aspiration (per 100 mmHg increase)	0.008873±0.000270	<0.001
CPM (per 1000 increase)	0.003703±0.000541	<0.001
50-50 - $R^2 = 0.87$		
Intercept	-0.01680	
Aspiration (per 100 mmHg increase)	0.007717±0.000360	<0.001
CPM (per 1000 increase)	0.005035±0.000434	<0.001
Shave - $R^2 = 0.86$		
Intercept	-0.02253	
Aspiration (per 100 mmHg increase)	0.006478±0.000363	<0.001
CPM (per 1000 increase)	0.006666±0.000439	<0.001
Water flow rates		
Core - $R^2 = 0.94$		
Intercept	0.06928	
Aspiration (per 100 mmHg increase)	0.03961 ±0.0001029	<0.001
CPM (per 1000 increase)	-0.02142±0.002126	<0.001
50-50 - $R^2 = 0.96$		
Intercept	0.01224	
Aspiration (per 100 mmHg increase)	0.03325±0.000633	<0.001
CPM (per 1000 increase)	-0.00386±0.001191	0.002
Shave - $R^2 = 0.86$		
Intercept	-0.05495	
Aspiration (per 100 mmHg increase)	0.02300±0.001146	<0.001
CPM (per 1000 increase)	0.01775±0.001384	<0.001

R^2 = coefficient of determination, CPM = cuts per minute, SE= standard error

Table 2

Differences Among Duty Cycles by Aspiration and Cut Rates.

Aspiration (mmHg)	1000 CPM	2000 CPM	3000 CPM	4000 CPM	5000 CPM
Vitreous flow rates					
100	0.01	<0.001	0.01	0.06	<0.001
200	0.007	<0.001	0.001	0.01	0.003
300	0.01	<0.001	<0.001	<0.001	0.08
400	<0.001	<0.001	<0.001	<0.001	<0.001
500	<0.001	<0.001	<0.001	<0.001	0.01
600	<0.001	<0.001	<0.001	0.12	0.23
Water flow rates					
100	<0.001	<0.001	<0.001	<0.001	0.01
200	<0.001	<0.001	<0.001	<0.001	<0.001
300	<0.001	<0.001	<0.001	<0.001	<0.001
400	<0.001	<0.001	<0.001	<0.001	<0.001
500	<0.001	<0.001	<0.001	<0.001	<0.001
600	<0.001	<0.001	<0.001	<0.001	0.01

*Repeated measures analysis of covariance.

Table 3

Average Flow Rate Differences Among Duty Cycles, Adjusting for Aspiration and Cut Rate.

	Least square means ± SE	P-value*
Vitreous flow rates		
Core	0.0275±0.0009	Core vs. 50-50 P=0.015
50-50	0.0253±0.0006	50-50 vs. Shave P<0.001
Shave	0.0201±0.0007	Core vs. Shave P<0.001
Water flow rates		
Core	0.1437±0.0075	Core vs. 50-50 P<0.001
50-50	0.1170±0.0018	50-50 vs. Shave P<0.001
Shave	0.0788±0.0076	Core vs. Shave P<0.001

*Repeated measures analysis of covariance.