Experimental study of occlusion break surge volume in 3 different phacoemulsification systems

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Purpose: To evaluate surge volume after occlusion breaks in 3 different phacoemulsification systems.

Setting: Alcon Research LLC, Lake Forest, California.

Design: Experimental study.

Methods: A mechanical spring eye model was used to test the Centurion with Active Sentry, WhiteStar Signature Pro, and Stellaris PC. Raw oscilloscope data were converted to volumetric and pressure measurements. Fitted average surge traces were generated for each test condition and used to develop an interpolation algorithm to predict transient occlusion break surge events. Two-dimensional heat maps were generated.

Results: During occlusion break surge, the Centurion with Active Sentry had smaller aqueous volume losses than the WhiteStar or Stellaris PC. Maximum surge volumes within the mechanical spring eye model displacement limit were 74.7 µL, 157.5 µL, and 151.7 µL using Centurion with Active Sentry, WhiteStar, and Stellaris PC, respectively. In the aphakic state, heat maps showed that Centurion with Active Sentry had less than 20% aqueous volume loss across all vacuum limits and target intraocular pressure; WhiteStar and Stellaris PC systems had up to 35% and 50% aqueous volume losses, respectively, at the higher vacuum limits. In the phakic state, Centurion with Active Sentry had up to 30% aqueous volume loss and WhiteStar and Stellaris PC systems had up to 50% aqueous volume losses. In addition, predicted transient traces demonstrated that Centurion with Active Sentry had the lowest percentage simulated aqueous volume loss compared with WhiteStar or Stellaris PC.

Conclusions: Centurion with Active Sentry had lower aqueous volume losses after occlusion break than WhiteStar and Stellaris PC systems at all surgical settings.

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Cataract removal by the phacoemulsification technique is a common procedure with a high rate of success and quick recovery time. However, phacoemulsification is known to have a number of safety concerns, including generation of heat, toxins (ie, free radicals), turbulent flow, mechanical trauma to anterior segment structures, and occlusion break surge. An occlusion event occurs when fluid flow through the tip of a phacoemulsification probe is obstructed by lens fragments, iris tissue, or ophthalmic viscosurgical device material, leading to vacuum rise inside the aspiration line and the potential collapse of the tubing. Occlusion break can cause an abrupt clearance of materials from the phacoemulsification tip and a subsequent rapid flow of fluid from the anterior chamber of the eye. The fluid surge from the eye can lead to a number of complications, including anterior chamber collapse, posterior capsule rupture, and vitreous loss. In addition, eyes with a history of capsule rupture and vitreous loss are at increased risk for endophthalmitis and cystoid macular edema.

Factors affecting occlusion surge volume include physical characteristics of the surgical system (ie, compliance of the aspiration tubing, including entrapped air), surgical operating settings (eg, vacuum limit), and eye compliance. Methods to reduce the occlusion break surge response on the system side include using tubing with rigid walls that are resistant to collapse under vacuum, reducing cassette compliance, rapidly replacing the lost volume, and restricting the flow of fluids out of the eye. Occlusion break surge can also be reduced by the surgeon operator by decreasing the aspiration line vacuum or increasing the target intraocular pressure (IOP).

The Centurion system with Active Fluidics (Alcon Research LLC) was designed to maintain a target IOP by modulating...
the pressure of the irrigating fluid. Active Fluidics control of infusion pressure improves anterior chamber stability and enables the use of lower IOPs during cataract surgery, which, in turn, should be associated with improved patient comfort and better outcomes. Furthermore, the Centurion system with Active Sentry can partially compensate for an occlusion break surge by detecting its onset through a handpiece-embedded pressure sensor and partially venting the stored vacuum before volume is demanded from the eye. In addition, the type of pump (peristaltic vs Venturi) can impact outcome. The Centurion with Active Sentry uses a peristaltic pump as can the WhiteStar Signature Pro (Johnson & Johnson Vision) cassette. By contrast, the Stellaris PC (Bausch & Lomb, Inc.) uses a Venturi pump.

Occlusion break surge can be measured for different phacoemulsification systems using controlled laboratory instruments that provide a high level of reproducibility. Laboratory studies need to account for the compliance of the human eye to be realistic. Compliance is the volume change associated with a corresponding pressure change ($\Delta$volume/$\Delta$pressure). The relationship between pressure and volume in human eyes is nonlinear as eyes become more rigid at higher IOPs. Recently, a mechanical spring eye model that mimics the compliance of the human eye was developed (Figure 1). It can be used to measure surge volumes under varying conditions and provide surgically relevant measurements to establish a standard for surgical systems and settings comparisons. The purpose of this study was to use the mechanical spring eye model to evaluate surge volumes after occlusion breaks using 3 different phacoemulsification systems and to develop a prediction model for assessing how different operative settings affect surge volumes.

METHODS

This study was conducted in a laboratory setting using a mechanical spring eye model, evaluating 3 phacoemulsification systems commonly used in the United States.

Phacoemulsification Systems and Fluidics Configurations

The systems tested included the Centurion with Active Sentry that includes Active Fluidics; the WhiteStar Signature Pro (Johnson & Johnson Vision) with the OPO73 cassette; and the Stellaris PC (Bausch & Lomb, Inc.) with the StableChamber cassette (Table 1).

Each phacoemulsification system was tested using 6 different cassettes and 50 configurations per cassette. Configurations included target IOPs of 30 mm Hg, 40 mm Hg, 50 mm Hg, 60 mm Hg, and 80 mm Hg; vacuum settings of 300 mm Hg, 400 mm Hg, 500 mm Hg, 600 mm Hg, and 650 mm Hg (the maximum setting on the Stellaris PC was 600 mm Hg); and aspiration flow rates of 20 mL/min and 40 mL/min on the peristaltic machines. These values were chosen to cover the range of values typically programmed during clinical use. Centurion with Active Sentry and WhiteStar used a peristaltic pump to control the aspiration flow rate. The Stellaris PC used a Venturi pump and, thus, did not have a setting for aspiration flow. Two external pressure transducers were used to measure the IOP in the mechanical spring eye model and the vacuum after occlusion at the handpiece.

Test Configuration

The mechanical spring eye model (Alcon Research LLC) was checked for accuracy per protocol at the beginning of each experiment to ensure that its compliance replicated that of the human eye (Figure 2). The tubing, handpiece block, and mechanical spring eye model were fully primed at the beginning of each experiment to eliminate entrapped air, and the systems were primed again if any air bubbles were found. Occlusion formation and occlusion break speed were simulated in the mechanical eye model and controlled through adjustable needles at the air inlet and outlet of the pneumatic cylinder.

Data Analysis

A digital oscilloscope (LeCroy) was used to capture raw data (IOP and flow rate), which were then processed using a custom MATLAB (Mathworks, Inc.) function. Raw voltage data were converted into volumetric and pressure measurements using known volume and pressure conversions. One system (Stellaris) reached the physical limit of displacement of the mechanical spring eye model (approximately 160 $\mu$L) fairly easily; the exact surge volume that each system was capable of measuring depended on the IOP setting. If a system’s surge reached the mechanical spring eye model’s physical displacement limit and plateaued (bottomed out) data were detected, the probable surge curve was repopulated with predicted data, determined based on a rational function curve fit to provide a prediction of real-world outcomes.

Regression analysis and calculations are described in detail in Supplemental Data (available at, http://links.lww.com/JRS/A355). The mechanical spring eye model’s surge volume was converted to percentage aqueous volume loss using phakic and aphakic anterior chamber volumes of 250 $\mu$L and 465 $\mu$L, respectively, based on the range of volumes reported for model human eyes. These data were presented as prediction curves to enable visualization of the effects of various operative conditions on the percentage aqueous volume loss from occlusion break surge.

![Figure 1. Mechanical spring eye model and average human donor eye model compliance curves. Both were referenced to volume at 0 mm Hg.](image)

| Table 1. Phacoemulsification Systems, Cassettes, and Handpieces Tested. |
|---------------------------------|---------------------|--------------------------|
| Phacoemulsification system      | Fluidics management system used | Handpiece               |
| Centurion with Active Sentry    | Active              | Active Sentry            |
| WhiteStar Signature Pro         | OPO73               | Centurion OZII           |
| Stellaris PC                    | StableChamber       | Centurion OZII           |
Peak Surge Volume Heat Maps
The surface fitting curve used MATLAB’s “poly23” type (quadratic regarding vacuum and cubic regarding IOP) and was color mapped to a maximum 50% of the aqueous volume to provide a 2D heat map in lieu of a 3D surface. Heat maps, based on the analysis of aqueous volume loss as a function of IOP and vacuum settings, can reveal safe operating zones. Heat maps identified safe (blue) and potentially unsafe (red) operating areas within each system. Because the peak surge volume was not strongly dependent on aspiration rate, both aspiration rates tested were included in the surface fit for plotting. The surfaces were fitted for the actual IOP and vacuum measurements recorded just before the occlusion event. When a system’s surge reached the mechanical spring eye model’s physical limit of displacement, the surface fit was extrapolated beyond the measurement capability.

RESULTS
Data are reported for aqueous volume loss during occlusion break, peak surge volume heat maps, and prediction curves for volume loss.

Aqueous Volume Loss During Occlusion Break Surge
Across all settings, Centurion with Active Sentry produced smaller aqueous volume losses during occlusion break than WhiteStar or Stellaris PC phacoemulsification systems (Figure 3, A–C). The small spread of the surge curve observed with the Centurion phacoemulsification system indicated consistency between settings. The smallest surge volume variation between samples was also observed with the Centurion system.

For Centurion with Active Sentry, the largest surge volume was 74.7 μL, measured using a vacuum limit of 650 mm Hg and a target IOP of 30 mm Hg. For WhiteStar,
the largest surge volume was 157.5 μL, measured using a vacuum limit of 650 mm Hg and a target IOP of 40 mm Hg. For Stellaris PC, the largest surge volume was 151.7 μL, measured at a vacuum of 500 mm Hg and a target IOP of 60 mm Hg. These values were taken from test conditions with the largest surges without reaching the mechanical spring eye model’s physical displacement limit.

The percentage aqueous volume loss at the lowest vacuum setting of 300 mm Hg and 30 to 80 mm Hg target IOP was 10.6% to 13.3% (phakic) and 5.7% to 7.2% (aphakic) for Centurion with Active Sentry, 14.9% to 18.0% (phakic) and 8.0% to 9.7% (aphakic) for WhiteStar, and 19.4% to 36.5% (phakic) and 10.4% to 19.6% (aphakic) for Stellaris PC (Figure 3, A–C), respectively. Occlusion break surge volume at the highest vacuum setting (650 mm Hg) and 30 to 80 mm Hg IOP was 26.6% to 29.9% (phakic) and 14.3% to 16.1% (aphakic) for Centurion with Active Sentry and 39.8% to 63.0% (phakic) and 21.4% to 33.9% (aphakic) for WhiteStar (Figure 3, A and B), respectively. Stellaris PC had greater percentage aqueous volume losses than the other 2 phacoemulsification systems at all test points; the greatest percentage aqueous loss that could be measured was 50.2% to 60.7% (phakic) and 27.0% to 32.6% (aphakic) at the 500 mm Hg vacuum limit and 60 to 80 mm Hg target IOP (Figure 3, C). Some surge volumes, particularly with Stellaris PC at high vacuum limits, were limited by fixture capability and could not be measured.

**Peak Surge Volume Heat Maps**

Aqueous volume loss heat maps showed that Centurion had the lowest percentage of aqueous volume loss compared with WhiteStar and Stellaris PC in both the aphakic and phakic (Figures 4 and 5) states. Overall, lower aqueous volume losses were observed at lower vacuum levels and higher target IOPs.

In the aphakic state, Centurion with Active Sentry had less than 20% aqueous volume loss across all vacuum limits and target IOPs; percentage aqueous volume loss was less than 10% at less than 400 mm Hg vacuum (Figure 4, A). For WhiteStar, 25% to 35% aqueous volume loss was observed at more than 600 mm Hg vacuum and less than 50 mm Hg target IOP; percentage aqueous volume loss was approximately less than 10% at less than 400 mm Hg vacuum and more than 45 mm Hg target IOP (Figure 4, B). For Stellaris PC, 50% aqueous volume loss was observed at more than 600 mm Hg vacuum; less than 20% aqueous volume loss was observed at less than 400 mm Hg vacuum and more than 60 mm Hg target IOP (Figure 4, C).

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**Figure 4.** Aqueous volume loss heat maps using the aphakic anterior chamber eye model for Centurion with Active Sentry (A), WhiteStar Signature Pro (B), and Stellaris PC with StableChamber (C). Reference aphakic anterior chamber eye volume was 465 μL. IOP and vacuum measurements were taken before occlusion break.

**Figure 5.** Aqueous volume loss heat maps using the phakic anterior chamber eye model for Centurion with Active Sentry (A), WhiteStar Signature Pro (B), and Stellaris PC with StableChamber (C). Reference phakic eye volume was 250 μL. IOP and vacuum measurements were taken before occlusion break.
In the phakic state, Centurion with Active Sentry had 25% to 30% aqueous volume loss at higher vacuum limits (ie, >600 mm Hg) and across all IOP target pressures; less than 20% aqueous volume loss was observed at less than 450 mm Hg vacuum (Figure 5, A). For WhiteStar, more than 35% aqueous volume loss was observed at more than 600 mm Hg vacuum; more than 45% aqueous volume loss was observed at more than 600 mm Hg vacuum and less than 50 mm Hg target IOP; and less than 20% aqueous volume loss was observed at less than 400 mm Hg vacuum (Figure 5, B). For Stellaris PC, 50% aqueous volume loss was observed at more than 500 mm Hg vacuum across all IOP target pressures; 20% to 30% aqueous volume loss was observed at 300 mm Hg vacuum and 40 to 80 mm Hg target IOP (Figure 5, C).

**Prediction Curves for Volume Loss**

Empirical calculations using the mechanical spring eye model produced the curve in Figure 6, A, where changes in volume are shown as a function of time. Predicted transient traces for aqueous volume loss were calculated in aphakic and phakic eye states for Centurion with Active Sentry, WhiteStar, and Stellaris PC (Figure 6, B–D) systems. Prediction curves for all phacoemulsification systems were calculated at 30 to 80 mm Hg target IOPs in 2 mm Hg increments and vacuums of 300 mm Hg, 450 mm Hg, and 600 mm Hg. The mechanical spring eye model’s physical limit was reached at approximately 160 μL. For Stellaris PC, results with IOP settings less than 60 mm Hg at the 600 mm Hg vacuum were excluded because the mechanical eye model did not recover to measurable volume within the given time window. For all other settings, surge was calculated based on extrapolation in time based on measurable volume.

The prediction plots highlight the range of the simulated aqueous volume losses for the different phacoemulsification systems, in both aphakic and phakic eye states (Figure 6, B–D). For the above-considered range of target IOPs and vacuum settings, Centurion with Active Sentry had the lowest percent simulated aqueous volume loss compared with WhiteStar and Stellaris PC systems.

**DISCUSSION**

Anterior chamber stability is essential during cataract surgery, and near-constant anterior chamber volume needs to be maintained throughout the procedure for the best safety and patient comfort. This study assessed transient changes in anterior chamber volume after occlusion break using a mechanical spring eye model that mimicked compliance of the anterior chamber of a human eye. The results demonstrated that surge volume depended on which phacoemulsification system was used and the specific surgical settings. The Centurion with Active Sentry had smaller percentage aqueous volume loss at all surgical settings than either the WhiteStar Signature Pro or the Stellaris PC. In addition, the Centurion with Active Sentry demonstrated the highest level of case-to-case consistency.
compared with either the WhiteStar or the Stellaris PC. For all phacoemulsification systems, the percentage aqueous volume loss increased with increasing vacuum limit and decreasing target IOP.

The results of this study are consistent with previous findings using the mechanical spring eye model. Centurion without Active Sentry was reported to have the lowest surge volumes at all vacuum limits compared with WhiteStar Signature using the OPO71 cassette, Stellaris PC using the basic vacuum pack, or enhancing visual acuity (EVA; D.O.R.C. International BV) systems.\textsuperscript{10} At 55 mm Hg IOP and 200 to 600 mm Hg vacuum, maximum phakic aqueous volume loss was 31\% for Centurion compared with 41\%, 65\%, and 66\% for WhiteStar, Stellaris PC, and EVA, respectively. Maximum aphakic aqueous volume loss was 17\% for Centurion compared with 22\%, 35\%, and 36\% for WhiteStar, Stellaris PC, and EVA, respectively.\textsuperscript{10}

In this study, the Centurion system included Active Sentry, the WhiteStar Signature Pro used the OPO73 cassette, and the Stellaris PC included the StableChamber pack. Based on the surge prediction plots, phakic aqueous volume loss was 24\% for Centurion with Active Sentry compared with 41\% for WhiteStar at 55 mm Hg IOP and 600 mm Hg vacuum. The predicted aphakic aqueous volume loss was 13\% for Centurion with Active Sentry compared with 22\% for WhiteStar. The Stellaris PC surge did not recover from bottoming out the fixture within the captured period, which prevented surge prediction at IOP of 55 mm Hg. For Centurion with Active Sentry, the prediction curves showed relatively consistent surge volumes across all surgical settings compared with the WhiteStar Signature Pro and the Stellaris PC system.

Centurion with Active Sentry has a surge mitigation feature that was not available with the earlier Centurion systems. When the onset of an occlusion break is detected by the pressure sensor embedded in the Active Sentry handpiece, surge volume demand is reduced through partial venting.\textsuperscript{13} A study that compared the Centurion with and without Active Sentry reported lower percentage aqueous volume loss with Active Sentry, particularly at higher vacuum limits.\textsuperscript{13}

Previous laboratory studies, including those using the mechanical spring eye model or a rigid chamber experimental setup, reported that occlusion break surge volume increased at lower IOP and higher vacuum.\textsuperscript{13,17,18} Specifically, occlusion break surge volume increased with decreasing IOP at each vacuum setting; occlusion break surge also increased as the vacuum limit was raised.\textsuperscript{18} Therefore, dependence of the occlusion surge volume on target IOP and vacuum limit reported in this study is consistent with previous reports. The Centurion with Active Sentry had the lowest aqueous volume loss of 11\% (phakic) and 6\% (aphakic) at the maximum IOP setting of 80 mm Hg and lowest vacuum setting of 300 mm Hg. The highest aqueous volume loss was 30\% (phakic) and 16\% (aphakic) at the lowest IOP setting of 30 mm Hg and highest vacuum setting of 650 mm Hg.

This study presents a number of tools for potential use by surgeons. Specifically, heat map data can be used to help surgeons understand where the safe (tending toward blue) and potentially unsafe (tending toward red) areas are in a given system. In addition, this study generated prediction transient curves for aqueous volume loss using specific parameters for vacuum, IOP, and aspiration flow settings. Prediction curves can be used to visualize the effects of various operative conditions on the percentage aqueous volume loss from occlusion break surge. These tools can help surgeons evaluate different operative settings to minimize surge volumes.

A limitation of the mechanical eye model was its inability to measure the large surge volumes associated with the Stellaris PC. Moreover, the surge results apply only for the compliance inherent in the mechanical eye model. Different eye compliances would result in different surge volumes. Furthermore, aspiration flow data were not collected for Stellaris PC using a Venturi pump in this study.

In conclusion, this study evaluated 3 different phacoemulsification systems at different settings using a mechanical eye model. The Centurion with Active Sentry had the smallest surge volume variation between samples and had a substantially smaller aqueous volume loss associated with occlusion break surge at all surgical settings compared with the WhiteStar Pro and the Stellaris PC with StableChamber.

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**WHAT WAS KNOWN**

- Active Sentry can mitigate surge volume and help maintain a stable anterior chamber.
- Occlusion break surge volumes increase as a function of increasing vacuum limit and decreasing target IOP.

**WHAT THIS PAPER ADDS**

- Centurion with Active Sentry had a lower occlusion break surge response than the WhiteStar and Stellaris PC at a variety of IOP and vacuum limit settings.
- New heat maps demonstrated safe operating zones for each of the instruments.
- The Centurion with Active Sentry provided excellent surge volume consistency.
- Prediction curves provided a tool for surgeons to evaluate different settings to minimize occlusion break surge and improve anterior chamber stability.

**REFERENCES**


Disclosures: K.M. Miller is an investigator and consultant for Alcon Laboratories, Inc.

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