LABORATORY SCIENCE

Volume-based characterization of postocclusion surge

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PURPOSE: To propose an alternative method to characterize postocclusion surge using a collapsible artificial anterior chamber to replace the currently used rigid anterior chamber model.

SETTING: Fundación Oftamológica Los Andes, Santiago, Chile.

METHODS: The distal end of a phacoemulsification handpiece was placed inside a compliant artificial anterior chamber. Digital recordings of chamber pressure, chamber volume, inflow, and outflow were performed during occlusion break of the phacoemulsification tip. The occlusion break profile of 2 different consoles was compared.

RESULTS: Occlusion break while using a rigid anterior chamber model produced a simultaneous increase of chamber inflow and outflow. In the rigid chamber model, pressure decreased sharply, reaching negative pressure values. Alternatively, with the collapsible chamber model, a delay was observed in the inflow that occurs to compensate the outflow surge. Also, the chamber pressure drop was smaller in magnitude, never undershooting below atmospheric pressure into negative values. Using 500 mm Hg as vacuum limit, the Infiniti System (Alcon) performed better that the Legacy (Alcon), showing an 18% reduction in peak volume variation.

CONCLUSIONS: The collapsible anterior chamber model provides a more realistic representation of the postocclusion surge events that occur in the real eye during cataract surgery. Peak volume fluctuation (mL), half volume recovery time(s), and volume fluctuation integral value (mL × s) are proposed as realistic indicators to characterize the postocclusion surge performance. These indicators show that the Infiniti System has a better postocclusion surge behavior than the Legacy System.

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Postocclusion surge producing anterior chamber instability is an undesirable phenomenon that occurs after occlusion break during phacoemulsification. Consequences are anterior chamber shallowing and complications such as posterior capsule rupture and vitreous loss.

The introduction of low-compliance tubing, aspiration bypass systems, modified phaco needles, and other measures have helped reduce the magnitude of postocclusion surge, allowing surgeons to safely increase the vacuum levels used during phacoemulsification. However, the recent introduction of phaco consoles with extended vacuum capabilities has renewed concerns about occlusion break behavior under this new scenario.

Adequate postocclusion surge characterization in a controlled setting is necessary to compare present phacoemulsification console performance and any strategies to be developed in the future.

Pressure changes in rigid anterior chamber models have been considered equivalent to what occurs in vivo. In these models, a transient negative pressure drop occurs after occlusion break, and this magnitude has been used as an indicator of postocclusion surge.[1]

The real eye is not a rigid chamber; instead, it possesses compliance that allows the walls of the anterior chamber to collapse when the internal pressure drops. This collapse represents a volume shift and should be measured in volume units.

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MATERIALS AND METHODS

A phacoemulsification fluidics laboratory was prepared to simulate postocclusion surge conditions mimicking the behavior of the anterior chamber of the eye during real surgery. The main portion, hosting the distal end of the phaco handpiece, was composed of a rigid chamber that could be connected optionally through a stopcock to a collapsible test chamber. This setting allowed the comparison of the behaviors of a rigid and of a collapsible chamber during postocclusion break conditions (Figures 1 and 2).

A computer-controlled solenoid (MD0626, Mechetronics Ltd.) was used to drive a rubber plunger to obstruct and clear the distal end opening of a phaco needle, simulating the occlusion break conditions that occur during surgery.

Pressure transducers (NovaSensor 1210-030D3L) were used to record pressure fluctuations inside the artificial anterior chamber as well as inside the aspiration line. Sensors were calibrated to read 0 at atmospheric pressure. Differential readings were taken from 2 pressure sensors connected by a low-resistance segment inserted in the aspiration line to conform a flowmeter configuration used to derive relative outflow data.

A volume sensor (Figure 3) was devised to record the artificial anterior chamber volume fluctuations occurring during occlusion break. This volume sensor used a high-sensitivity pressure transducer (NovaSensor 1210-005D3L) to make a pressure reading known to be proportional to the height of a water column in direct connection with the fluid chamber surrounding the immersed collapsible artificial anterior chamber.[2] Pressure exerted by the small water column used to make the volume fluctuation recordings was irrelevant when compared with the pressure present at the infusion line and did not affect the readings.

In certain experiments, flowmeters were installed in the irrigation and in the aspiration line to provide inflow and outflow rate measurements and their time relationship. These flowmeters provided semiquantitative surge magnitude information but accurately displayed surge timing information.

A data-processing system with input/output capabilities was built around a Borland Delphi programming language interfacing through the parallel port LPT2 of an IBM PC computer with an analog-digital converter (TLC1542C, Texas Instruments). The system allowed simultaneous recording of the readings of all sensors with a sample rate of 50 Hz. The program provided the signals to automate the operation of the solenoid controlling the occlusion and release process to coordinate with the data-capture process. Display of the data and measurements was performed digitally at PC level.

To validate the physical properties of the artificial anterior chamber, the compliance curves of the collapsible artificial anterior chamber and of enucleated pig eyes were compared using an experimental setup.

Experiments were performed using 1.1 mm flared ABS tips. Two phacoemulsification consoles were compared (Alcon Infiniti and Alcon Legacy 20000 with Advantec software and MaxVac cartridge) using a constant water column height of 78 cm. Aspiration flow rate was set to 60 mL/min, and vacuum limit was set

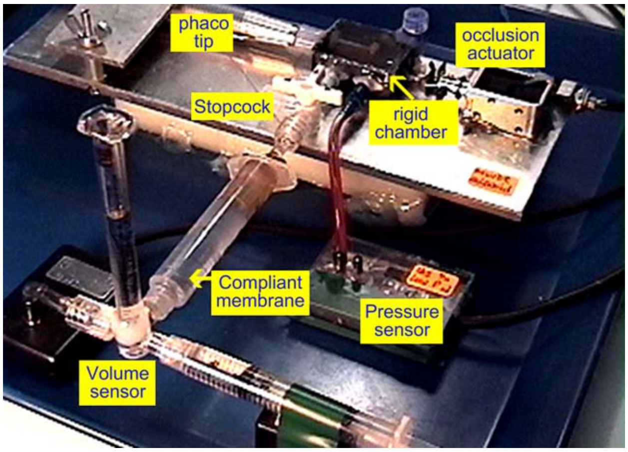

Figure 2. Phacoemulsification fluidics laboratory setup.

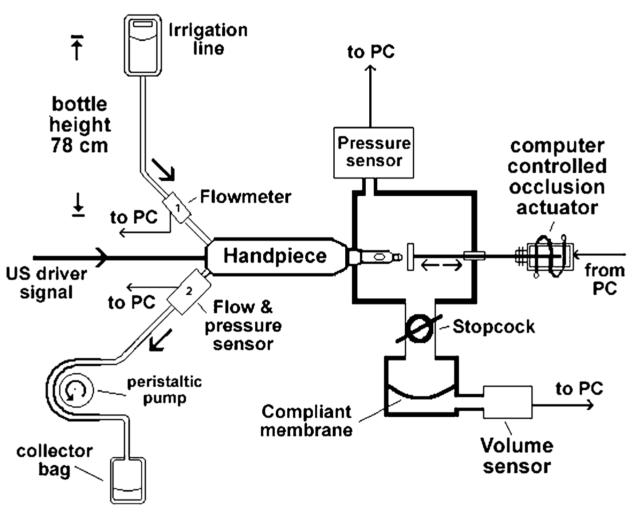

Figure 1. Anterior chamber model. A selector valve allows the use of a rigid chamber or a collapsible anterior chamber model. Pressure and volume changes were recorded using a personal computer, which also controlled an occlusion actuator.

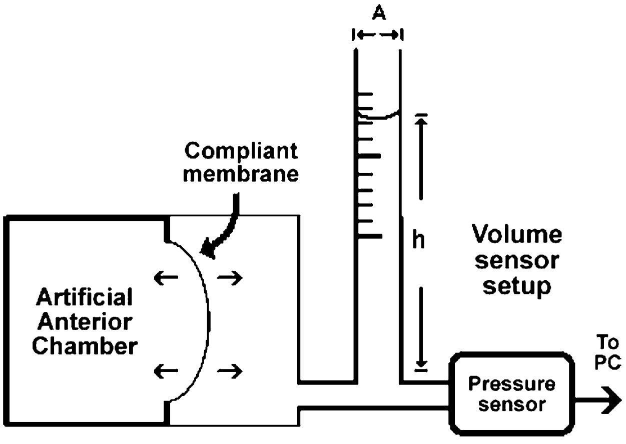

Figure 3. Volume sensor array shows a compliant membrane. Measuring the pressure produced by the water column allowed determination of the volume variation inside the collapsible chamber (h = column height; A = cross-sectional area).

depending on the experiment. Special care was taken to ensure proper fluid filling of all compartments, checking that no bubbles that could alter compliance were present anywhere in the system.

RESULTS

The compliance curve obtained from the artificial collapsible anterior chamber was equivalent to the 1 obtained from an enucleated pig eye (Figure 4). Both showed a similar behavior in the range of infusion line pressures used clinically and in the experiments. In the upper range of positive pressures (5 to 80 cm H_2O), both showed a similarly constant, relatively small compliance, depicted by the almost flat curves. The slope of these segments (using the square minimum method for linear regression) was 2.9 mL/cm H_2O for the artificial chamber and 3.2 mL/cm H_2O for the pig eye. Also, the artificial compliant chamber behaved in a similar way to in the pig eye when the internal pressure was less than 5 cm H_2O, both showing an abrupt change in compliance. In this range of intraocular pressure (IOP), small decrements produced a significant volume shift, corresponding to the chamber's collapse. These results provide strong evidence that the artificial collapsible anterior chamber had similar compliance characteristics to those in a real eye, validating the experimental model.

The fluidic behavior was compared during postocclusion surge of the Legacy and Infiniti phacoemulsification units using a rigid and a collapsible anterior chamber model with different vacuum limit settings. A typical data recording is shown in Figure 5. The left half (Figure 5, *A*) represents the data obtained using a rigid chamber, whereas the right half (Figure 5, *B*) shows the events when the collapsible chamber was used. The top tracing depicts the aspiration line vacuum. The second tracing corresponds to chamber volume fluctuation. The third tracing illustrates outflow rate in relative units, and the bottom tracing shows the pressure inside the artificial anterior chamber.

When the tip is not occluded, the vacuum is near 0 because the open line does not allow vacuum to build up in the aspiration line. As soon as the plunger occludes the phaco tip, vacuum increases until it reaches the preset limit value. When the occlusion breaks, aspiration line vacuum decreases, approaching atmospheric pressure.

When the tip is occluded, the artificial anterior chamber pressure reflects the pressure produced by the water column height in the irrigation line as the system is almost in static equilibrium (small influence of aspiration bypass system if present).

Rigid Chamber Model Results

The straight horizontal line observed in the volume fluctuation tracing (Figure 5, *A*) during the postocclusion surge in the rigid chamber model shows that volume fluctuations are not allowed in this model. When occlusion breaks in this model, chamber pressure decreased sharply below atmospheric pressure and later recovered to the positive steady-state pressure of the open system. Immediately after the occlusion break, there was a transient increase in the aspiration line outflow that doubled the flow rate observed once the steady-state conditions were restored.

Compliant Chamber Model Results

Postocclusion surge events using the collapsible chamber (Figure 5, *B*) showed a different behavior. The negative

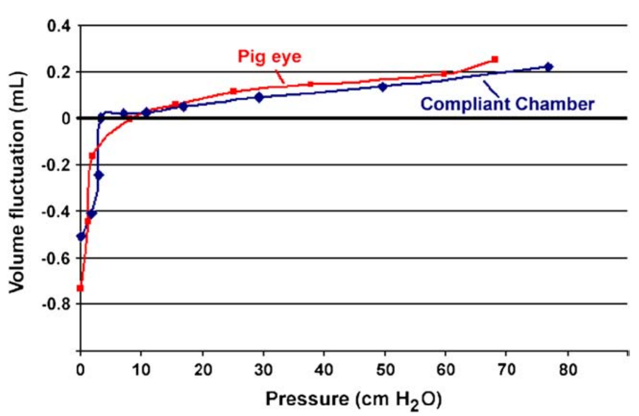

Figure 4. Artificial collapsible anterior chamber and pig eye compliance curves. Both show a high compliance in the lower internal pressure range and a relatively small compliance in the upper pressure range connected by an abrupt transition zone.

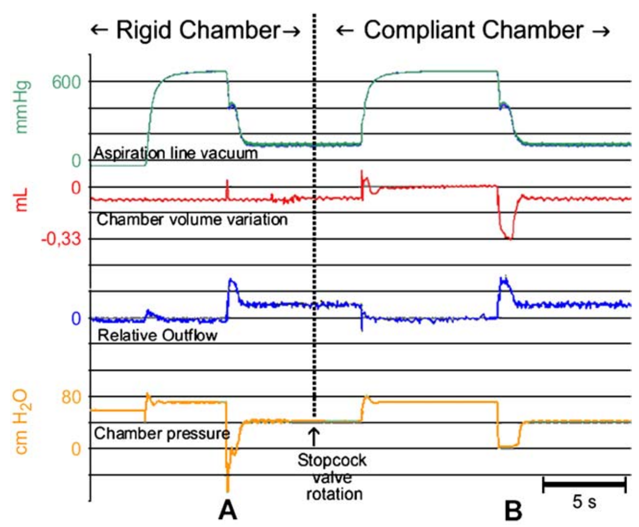

Figure 5. Sample of recorded data from an Alcon Infiniti with a vacuum limit setting of 670 mm Hg. Rotation of the selector valve converts the noncompliant chamber (*A*) into a compliant chamber (*B*).

pressure shift observed inside the artificial anterior chamber when occlusion was released did not follow a spike pattern, without going below atmospheric pressure. Duration of the volume surge was slightly longer under this modality.

A volume fluctuation was recorded after occlusion break, mainly consisting of a transient reduction in artificial anterior chamber volume. Anterior chamber volume recovered to preocclusion break values after a short interval.

Inflow rate and outflow rate recordings using the rigid chamber (Figure 6, *A*) showed that immediately after the occlusion breaks, there was a simultaneous increase in outflow and in inflow of the same magnitude. Recordings using the collapsible chamber (Figure 6, *B*) showed a delay between the increment in outflow and in inflow, the inflow coming later. This delay was related to the collapsible anterior chamber providing the outflow volume and then being refilled by the inflow line.

There is no current consensus about how postocclusion surge should be measured. Measuring the absolute chamber pressure shift or the absolute chamber volume shift does not fully address the complex relationships that exist between these magnitudes and their time course. For this reason, a novel method to better characterize the postocclusion surge phenomenon is proposed.

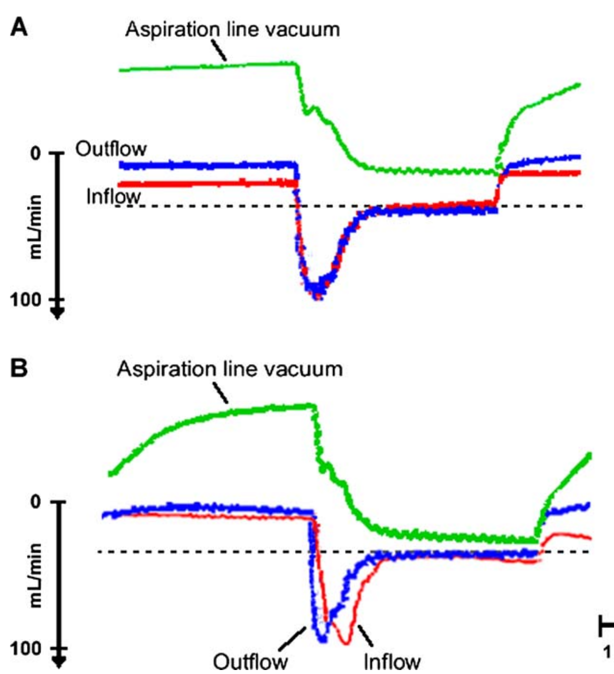

Figure 6. Outflow and inflow offset during postocclusion surge in a rigid chamber (*A*) and in a collapsible chamber (*B*). In the collapsible chamber, outflow increases before inflow, implying a transient chamber collapse. Dotted line reflects the steady-state flow rate.

Volume fluctuation is better described in terms of the peak volume fluctuation, using the volume of the chamber before the postocclusion surge as a reference. It reflects the maximum volume change that occurs after occlusion breaks and is measured in volume units (mL). Volume fluctuation integral (expressed in mL $\times$ s) was defined as the area enclosed within the volume fluctuation curve during postocclusion surge and the line joining the points at which postocclusion surge begins and the point at which volume regains its steady-state value. This line represents the path the volume curve would follow if postocclusion surge did not exist with a smooth transition occurring between preocclusion and postocclusion break steady-state conditions. Half-volume recovery time value was proposed, considering the difficulty in determining the precise moment at which the postocclusion surge volume fluctuation ends. It is defined as the time elapsed between the beginning of the postocclusion surge and the point at which half of the volume has recovered to the final steady-state value (Figure 7). This appears to be an improved way to measure postocclusion surge volume shift duration.

The chamber pressure fluctuations (Figure 8) were analyzed in a similar way. Zero pressure is equal to atmospheric pressure. Peak pressure reflects the minimum pressure reached during postocclusion surge, "absolute pressure fluctuation" describes the pressure difference between the peak pressure and the value before the postocclusion surge, both values measured in pressure units (cm H_2O). Pressure fluctuation integral (expressed in cm $H_2O \times s$) reflects the area enclosed within the pressure curve and a line joining the preocclusion and the postocclusion surge pressure values.

Measurements were made using Alcon's Legacy 20000 and Infiniti Vision System (Table 1 and Figure 9). A preset vacuum limit of 500 mm Hg was used to compare their performance. Also, a vacuum limit of 670 mm Hg was used in

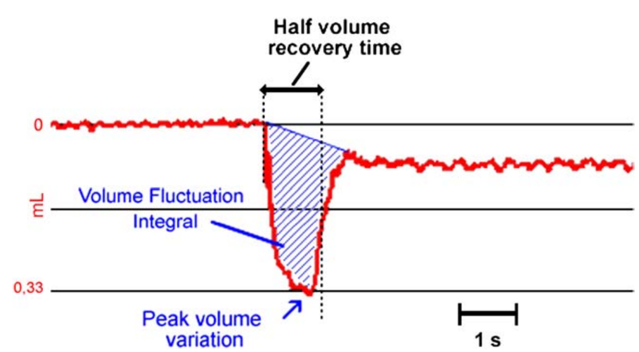

Figure 7. Volume fluctuation in a collapsible anterior chamber. Half volume recovery time uses the midpoint between the peak volume variation and the postrecovery volume reading.

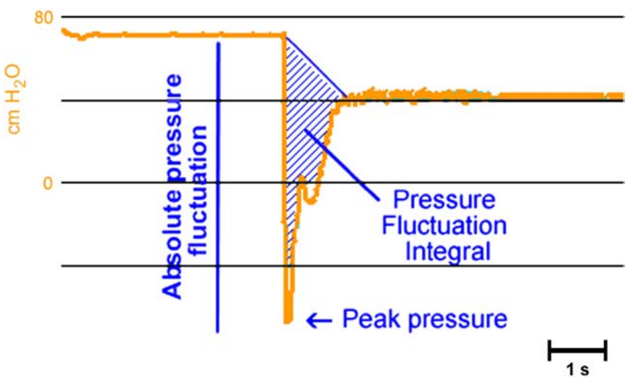

Figure 8. Pressure fluctuation characterization during the surge. Pressure fluctuation integral is expressed in cm H_2O × seconds.

the Infiniti to depict its profile with this higher vacuum not reachable with the Legacy.

The Infiniti showed an 18% reduction in peak volume variation, a 22% reduction in half-volume recovery time, and a 13% reduction in the volume-fluctuation integral when compared with the Legacy. The Infiniti values for the integrated pressure variation associated with these volume changes were reduced in 32% compared with the Legacy.

The Infiniti showed an 11% reduction in absolute pressure fluctuation and a 27% reduction in pressure fluctuation integral with respect to the Legacy when using the rigid chamber with the same parameters.

DISCUSSION

The eye is a compliant chamber capable of changing its volume when the pressure of its content varies. Eye compliance can be better understood as the change in eye volume per unit change in IOP. In the case of the eye, compliance is not a linear phenomenon. The relatively nondistensible eye walls composed by the sclera and cornea determine that when a pressure increment occurs in a range above atmospheric pressure (positive pressure), a small increment in eye volume is observed. This behavior is explained by limited choroidal cushion compressibility and by the scleral rigidity index.

However, when a pressure reduction occurs in a range near atmospheric pressure, a significant reduction in eye volume is observed related to inward displacement of the eye walls. This phenomenon is responsible for the most severe postocclusion surge events, particularly anterior chamber shallowing and corneal collapse. These concepts are illustrated in the compliance curves shown in Figure 4.

Previous studies have addressed the postocclusion surge phenomenon, focusing on pressure shifts[3,4] and not taking into consideration that the main events that occur are related to volume shifts owing to the collapsible nature of the real eye. There is a dissociation between the nature of the phenomena (volume shifts) and the methods previously used to characterize the postocclusion surge (pressure shifts).

A rigid chamber, by definition, has no compliance when operating in a liquid, bubble-free environment. Although a rigid chamber model may be used to characterize the fluidic behavior of phacoemulsification equipment, the results using this approach cannot be used to accurately predict the postocclusion surge behavior in a collapsible chamber such as the real eye. Figure 5 shows that the chamber pressure profiles are completely different when using a rigid chamber (Figure 5, *A*) than when using a compliant chamber (Figure 5, *B*). The main difference is that pressure inside the compliant eye chamber, in this setting, will never

Table 1. Postocclusion surge characterization.

	Maximum Vacuum Preset Values		
	Legacy	Infiniti	
Parameter	500 mm Hg	500 mm Hg	670 mm Hg
Rigid chamber			
Peak pressure (cm H_2O)	−44.5	−31.5	−71.5
Absolute pressure fluctuation (cm H_2O)	117.1	104.7	143.6
Pressure-fluctuation integral (cm H_2O × s)	51.2	37.6	86.3
Compliant chamber			
Peak pressure (cm H_2O)	3.4	7.9	2.3
Absolute pressure fluctuation (cm H_2O)	69.2	64.7	69.2
Pressure-fluctuation integral (cm H_2O × s)	47.4	32.1	89.7
Peak volume fluctuation (mL)	−0.17	−0.14	−0.34
Volume-fluctuation integral (mL × s)	−0.08	−0.07	−0.36
Half-volume recovery time (s)	0.60	0.47	1.18

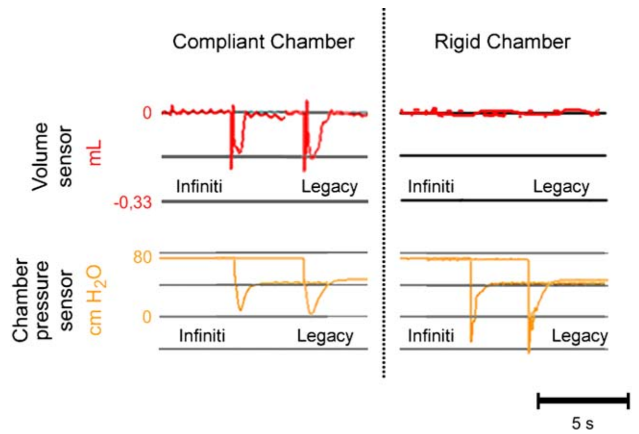

Figure 9. Comparison of Alcon Legacy and Infiniti postocclusion surge responses using 500 mm Hg as vacuum limit setting.

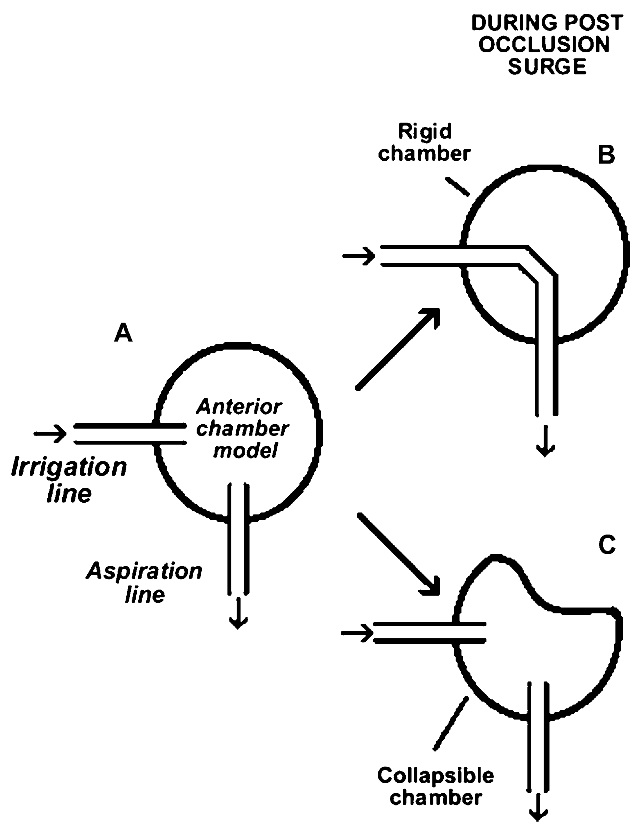

Figure 10. Functional models of postocclusion surge (*A*). A different postocclusion surge response is observed when a rigid chamber model (*B*) or a collapsible chamber model (*C*) is used.

become negative during a surge as long as the eye can keep collapsing.

We propose the use of a compliant anterior chamber model in which volume and pressure changes are recorded to characterize the postocclusion surge response of a particular setting. We also introduce novel measurement methodologies to describe the surge that consider the volume shift and the time course of volume fluctuation. A better representation of the postocclusion surge was achieved using peak volume fluctuation, volume fluctuation integral, pressure fluctuation integral, and half-volume recovery time.

The delay observed between the outflow and the inflow during the postocclusion surge is a direct consequence of the compliant chamber (Figure 6, *B*). After the occlusion breaks, vacuum in the aspiration line is first compensated with volume provided by the collapsible chamber and later restored by inflow from the irrigation line. Anterior chamber pressure remains steady at atmospheric pressure (Figure 5, *B*), while the chamber walls transiently collapse to provide fluid to compensate for the surge (Figure 10, *C*). The pressure change in a compliant chamber condition, such as our setting and in the real eye, will never reach values below atmospheric pressure during the surge event.

When a rigid anterior chamber model is used, there is no delay between the outflow and the inflow (Figure 6, *A*), and the chamber pressure shows a pressure undershoot below atmospheric pressure during the surge event before recovering to the steady state (Figure 5, *A*). The absence of a collapsible component determines that the vacuum inside the aspiration line is transmitted to the irrigation line after the occlusion breaks. This explains the negative pressure spike and also the simultaneous nature of the outflow and inflow fluctuations observed in the noncollapsible chamber model. When measuring the postocclusion surge in a rigid anterior chamber, the pressure inside the tubing is being evaluated. It is as if the eye did not exist, and it is the same as having a rigid tube connecting the inflow and outflow tubings (Figure 10, *B*).

It must be considered that the postocclusion surge response as evaluated in this study has been made in a controlled environment starting at a preset level of vacuum. During real surgery, occlusion is transient and intermittent, creating surges of different magnitudes proportional to the vacuum level present at the point of occlusion break. Also, occlusion may break at different speeds leading to different surge levels for a similar vacuum level. Although all these conditions may be mimicked in our experimental setup, it is expected that these responses will vary in a proportional amount with respect to the results exposed above.

Volume fluctuation characterization as detailed in this study should help better understand the postocclusion surge response of different phacoemulsification equipment in an environment closely resembling real-eye conditions. It also improves our comprehension of the surge phenomenon and can help us in the design of better surge-handling strategies. The availability of improved surge-canceling methodologies allows safe use of higher vacuum levels in the removal of the lens, consequently reducing the required levels of ultrasonic power.

Although it may seem that currently available surge-handling methodologies would suffice, it should be considered that the recent introduction of consoles with expanded vacuum capabilities and large-diameter aspiration probes such as waterjet-based techniques will reissue postocclusion surge considerations.

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