LABORATORY SCIENCE

Mechanical model of human eye compliance for volumetric occlusion break surge measurements

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Purpose: To develop a mechanical model of human eye compliance for volumetric studies.

Setting: Alcon Research, Ltd., Lake Forest, California, USA.

Design: Experimental study.

Methods: Enucleated human eyes underwent pressurization and depressurization cycles with peak intraocular pressures (IOPs) of 60 to 100 mm Hg; anterior chamber pressure and volume changes were measured. Average net volume change curves were calculated as a function of IOP for each eye. Overall mean volumes were computed from each eye's average results at pressure points extrapolated over the range of 5 to 90 mm Hg. A 2-term exponential function was fit to these results. A fluid chamber with a displaceable piston was created as a mechanical model of this equation. A laser confocal displacement meter was used to measure piston displacement. A test bed incorporated the mechanical model with a mounted phacoemulsification probe and allowed for simulated occlusion breaks. Surge volume was calculated from piston displacement.

Results: An exponential function, $V = C_1 \times \exp(C_2 \times IOP) + C_3 \times \exp(C_4 \times IOP) - V_0$, where V, the volume, was fit to the final depressurization curve obtained from 15 enucleated human eyes. The C_1 through C_4 values were −0.07141, −0.23055, −0.14972, and −0.02006, respectively. The equation was modeled using a piston system with 3 parallel springs that engaged serially. The mechanical model mimicked depressurization curves observed in human cadaver eyes.

Conclusion: The resulting mechanical compliance model measured ocular volumetric changes and thus would be helpful in characterizing the postocclusion break surge response.

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Anterior chamber stability is an essential requirement for surgical safety during phacoemulsification. It is achieved by maintaining a nearly constant anterior chamber volume throughout the various stages of the procedure. Irrigating fluid is added to the anterior chamber only as needed to replace the volume of fluid and disassembled lens fragments that are removed from the eye. Any fluid surging from an eye after an occlusion break can compromise the stability of the anterior chamber and lead to complications such as posterior capsule rupture, vitreous loss, dropped lens fragments, endophthalmitis, and cystoid macular edema.[1,2]

An occlusion event initiates when fluid flow through the tip of a phacoemulsification probe is obstructed by lens fragments, iris tissue, or an ophthalmic viscosurgical device. As a phacoemulsification pump evacuates fluid from the aspiration line, negative pressure or vacuum builds relative to atmospheric pressure and stores potential energy in the walls of the aspiration tubing and cassette as a function of their compliance; entrapped air also expands in response.[3,4] An occlusion break surge event follows when this obstructing material abruptly clears the tip. The aspiration line and cassette suddenly expand, the entrapped air collapses, and fluid is pulled from the anterior chamber faster than the irrigation supply can replenish it. On occasion, the volume

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of an occlusion break surge might be sufficient to collapse the anterior chamber and risk structural damage to the eye.[5] Accurate measurements of the surge volume for a given eye can, therefore, predict the expected chamber stability after an occlusion break for any given system and its corresponding settings.

Factors that affect surge volume include surgical system characteristics, surgeon-controlled machine settings, and eye compliance. Compliance is the change in volume associated with a corresponding change in pressure (Δ volume/Δ pressure). Its inverse is stiffness. Eye compliance is nonlinear, a factor that has to be taken into consideration when addressing occlusion break surge characteristics. Previous tests of surge volume were limited by the lack of a human eye compliance model, difficulty and complexity of setup, and limited reproducibility of results.[1]

Eye compliance was first measured by Friedenwald.[6] He described a volume–pressure relationship for the eye and proposed a constant ocular rigidity coefficient to characterize this nonlinear relationship. Other authors have since suggested alternatives to this proposed relationship.[7]

The purpose of this study was to develop a mechanical model of human eye compliance that can be used for volumetric studies of the occlusion break surge response of different phacoemulsification systems. This study shows experimental data to support a new independently derived mathematical human eye compliance model that forms the basis of a new mechanical eye model. The mechanical model enables direct surge-volume measurements after simulated occlusion breaks and standardizes surgical system comparisons. Unlike models that rely on donor eyes, which might require repeated freezing and thawing and be subject to retesting fatigue, a mechanical model provides consistent results for repeated measurements and can be used for testing over time as systems are improved. In addition, a mechanical model of human eye compliance provides the ability to clarify the impact of surgical settings on surge characteristics.

MATERIALS AND METHODS

This study was performed in a laboratory setting using human cadaver eyes. No living patients or animals were involved.

Human Eye Compliance Model

Human donor eyes with intact lenses were used to obtain compliance data. Intraocular pressure (IOP) was varied from 5 mm Hg to as high as 100 mm Hg. The setup (Figure 1) included a calibrated pressure controller (model CPC6000, Mensor) connected to the top of a 1 mL glass pipette with a 0.0016-inch ruby orifice at its junction for flow-rate control (model RB-82675-0016, Bird Precision). The glass pipette outlet was connected to a short piece of polyvinyl chloride tubing terminating at a flow sensor (model ME4PXN212, Transonic Systems, Inc.) that measured changes in volume; the flow sensor outlet was connected to a 25-gauge syringe needle. The pipette inlet, pipette outlet, and flow sensor all had intermediate stopcocks to facilitate priming of the syringe needle, flow sensor, and tubing. The pipette was primed to the height equivalent of eye level, and 2 pressure transducers (model XCL-072 transducer, Kulite Semiconductor Products, Inc.; model 1169-01-50-100 H programmable amplifier, Raetech Corp.) were mounted to either end of the pipette for verification of net-volume measurement from the flow sensor. The syringe needle of the primed system was inserted through a human donor eye's corneal limbus and into the anterior chamber while the eye rested unconstrained on a Styrofoam base. A second syringe needle with a connected pressure transducer was primed and inserted through the limbus and into the anterior chamber opposite the first needle (Figure 2).

Eye pressure was initially maintained at 5 mm Hg with the pressure controller while the fluid height in the pipette remained at eye level. Fluid flow into the eye was initiated by setting the controlled air pressure to 60 to 100 mm Hg while a digital oscilloscope (Waverunner 606Zi, Lecroy Corp.) captured changes in IOP and flow rate from the pressure transducer and flow sensor, respectively. After the eye pressure and fluid flow reached equilibrium at approximately 30 seconds, the controlled air pressure was set to 5 mm Hg. No fluid leakage from the syringe needle insertion sites was observed during testing.

Twenty-one phakic eyes from 12 donors ranging in age from 51 to 94 years (mean age 71 years) were tested on the same day they were received. Wetting drops were added between cycles to ensure proper eye hydration. Pressurization–depressurization test cycles were repeated up to 12 times per human donor eye. Data from 6 of the 21 eyes were rejected. Data were rejected from 4 eyes because air bubbles in the syringe needle at the limbus, which communicated IOP to the pressure transducer, impaired IOP measurements. Data were rejected from 1 eye because it was damaged during needle insertion. Data from another eye were mistakenly rejected along with the data from its paired eye (originally rejected because of an air bubble affecting measurement) and erroneously excluded from the final overall average. Data from the remaining 15 eyes were used for the final average eye curve-fit measurement.

For the mechanical model, a fluid chamber was created that was sealed with a thin polyethylene membrane that transmitted pressure to a piston surface (Figure 3). A confocal laser displacement sensor (model LT-9030M, Keyence Corp.) was used to measure piston displacement. The digital oscilloscope converted output voltage to volume (cm^3) using the known laser sensitivity value and known piston diameter. A spring fixture with 3 springs, which could be used to stiffen piston displacement at variable pressures, was incorporated into a test bed (Figure 4). A phacoemulsification handpiece was mounted within an acrylic block. The acrylic block formed a sealed cylindrical fluid chamber with the block's inner diameter sealing the handpiece sleeve's compressed outer diameter. In addition, the acrylic block held a lever with a sealed ball joint to form an occlusion on a phaco tip's distal end. A piece of soft natural rubber tubing fixed to the lever's end could rotate against the cutting surface of the phaco tip to establish full occlusion (Figure 5). The acrylic block had a connection to the spring fixture through stiff polyurethane tubing, and the handpiece was made to rest slightly above the spring fixture's fluid chamber to provide the head pressure necessary to offset the piston and spring mass.

RESULTS

Human Eye Compliance Model

Figure 6 shows the human eye compliance curves from the 15 of 10 donors. Pressurization and depressurization cycles were analyzed separately. To model human eye volume (V) changes due to IOP, the curve $V = C_1 \times \exp(C_2 \times IOP) + C_3 \times \exp(C_4 \times IOP) - V_0$, was fit to individual pressure cycles, where C_1, C_2, C_3, and C_4 were coefficients, and V_0 was chosen such that $V = 0$ at 7 mm Hg for each individual cycle. This 2-term exponential fit was chosen as a practical approximation of the following 2 regions observed in the test data: a highly compliant region at low IOP and a rigid nonlinear region at high IOP. Note that V_0 was chosen for