Eye (2018) 32, 204–209

www.nature.com/eye

CAMBRIDGE OPHTHALMOLOGICAL SYMPOSIUM

Fluidics and rheology in phaco surgery: what matters and what is the hype?

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Abstract

Rheology can be defined as the study of materials flow behaviour under applied deformation forces (stresses). Inside the eye during cataract surgery, transient or reversible deformation (elasticity) and permanent or irreversible deformation (flow) can both apply. Although the fluidics of modern phaco machines is an important part of this talk, there are a number of issues relating to flow and fluids in the eye during cataract surgery, which are unrelated to the machine, which can hinder or help the operating surgeon in removing a cataract. In addition, coping with the numerous complications, which can occur in the eye at the time of surgery, relies on an understanding of how fluidics and rheology can help to control the pressurised eye and bring the surgery to a successful conclusion.

Eye (2018) **32,** 204–209; doi:10.1038/eye.2017.299; published online 19 January 2018

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Received: 25 October 2017
Accepted: 29 October 2017
Published online:
19 January 2018

Introduction

The concepts of and some of the laws applying to flow are beautifully and mathematically described in Newton's Principia[1] (recently republished after a successful Kickstarter campaign) and relate in the main to so-called Newtonian flow (in a fluid such as water), wherein the viscosity of the fluid does not change in relation to its shear rate. The flow rate of such fluids are proportional to the fourth power of the radius of the vessel they travel in (Pousseille's formula) and so small changes in vessel diameter can produce large changes in the flow rate. This can be relevant to the anticipation and management of post-occlusion surge experienced in some phaco machines.

Viscoelastics (ophthalmic viscoelastic devices)

These are pseudoplastic substances whose use in the eye have transformed the facility and safety of intraocular surgery. They help to provide space in the anterior segment, protection for the endothelium and move and support tissues such as the iris as well as helping with haemostasis. Their key property is pseudoplasticity which means that their viscosity changes with flow (non-Newtonian property). This enables what is a thick solution to be injected along a narrow cannula into the eye where, once static again resumes a stiff supportive mass. They can broadly be divided into dispersive and cohesive types, which relates to how the molecules act in relation to one another. Dispersives break apart easily thus tending to be able to remain *in situ* against the endothelium when fluid is flowing around the anterior chamber, whereas cohesives tend to stick together which means they tend to wash out in one mass and stay put less easily. Ophthalmic viscoelastic devices (OVDs) are formed from repeating units of *N*-acetyl glucosamine and hyaluronic acid and these repeating units form long chains. It is the length and folding of these long chains into a tertiary structure which give each particular molecular-weight variant its individual properties. An indication of a particular viscoelastic's pseudoplastic properties can be given by the pseudoplasticity index. This ratio of the viscosity of a substance when standing still (zero flow) over the viscosity when moving at a set rate and as an indication of the differing natures of these substances the pseudoplasticity index for Helon GV (Greater Viscosity), which has a molecular weight of 1.4%, 5×10^6 daltons is 10 000 whereas that for HPMC is 28 illustrating the fact that HPMC does not exhibit very useful pseudoplasticity.

A new class of OVDs was created when AMO introduced Healon 5 (sodium hyaluronate 2.3%, 4×10^6 daltons), which is a pseudodispersive, ultra-viscous cohesive. This is known as a viscoadaptive and behaves as a very cohesive viscoelastic to pressurize and create space, but can provide the protection of dispersives. It has both properties of viscoelastics, by being a substance that changes its behavior at different flow rates. The lower the flow rate, the more viscous and cohesive it becomes. The higher the flow rate, the more dispersive the viscoelastic is allowing for better protection of the corneal endothelial cells from injury during phacoemulsification.

One of the problems caused by viscoelastics at the beginning of the sculpting phase of phacoemulsification, is that the phaco tip can become blocked with visco-elastic as the needle is moved across the anterior chamber. If the majority of viscoelastic is flushed out of the eye during hydrodissection, then this will not happen, but if some OVD remains in the eye before sculpting starts then the vibrations of the needle will tend to push structures away and no effective sculpting takes place as the tip is blocked. This is important as it is possible to cause a phaco burn during this phase if it is not noticed that no flow is occurring into the needle tip. Allowing aspiration to occur for a few seconds before starting to phaco (sculpt) will usually avoid this potential complication.

Fluidics during phacoemulsification surgery

The basic set-up for fluid flow into the eye during phacoemulsification is shown in Figure 1. Modern phaco machines have either a Peristaltic or a Venturi pump driving the aspiration of fluid out of the eye. This fluid is replaced by fluid contained (usually) in an infusion bottle and inflow must equal or exceed outflow for the anterior chamber to be maintained. Bottle fluid running out and excess pump speed (aspiration rate) are two common causes of anterior chamber collapse.

In the static situation when the phaco tip is in the eye and no flow is occurring (foot position 1) then for every 15 cm of bottle height above the patient's eye level, 11 mm Hg intraocular pressure (IOP) will be generated. It is easy to calculate that at a bottle height of 1 meter above the eye an IOP of ~70 mm Hg will be generated and this should be borne in mind in eyes which are high risk of visual wipe-out as this is around the closing pressure of the central retinal artery. In foot position 2 with no tip occlusion, the same bottle height produces a lower IOP because of aspiration, so it is safer in such eyes to ensure aspiration is active when the phaco probe is in the anterior chamber as soon as possible after insertion.

In the early machines, another of the problems that the operating surgeon had to deal with was post-occlusion surge, which was a collapsing anterior chamber following phaco tip blockage, followed by sudden clearing of the blockage (usually by fragmenting the piece of lens material causing tip occlusion). As the tip cleared, the soft, compliant tubing would collapse and then re-expand causing a surge in flow out of the eye resulting in anterior chamber collapse—often onto the vibrating phaco needle. As flow in the tubing is proportional to the fourth power of the radius of the tubing (Pousseille's Law) small changes in tubing diameter caused large volume changes in the anterior chamber.

A number of mechanisms have been developed to prevent this including the use of non-compliant (stiff, non-collapsible) tubing, and others are summarised in Table 1.

The use of non-compliant tubing has meant that increased pump speeds can be used allowing faster flow rates in peristaltic machines and thus the differences between the two pump types in terms of flow control is now very little. Indeed, in a modern peristaltic machine, the old idea of being able to unlink the vacuum and aspiration rates no longer really hold true. This is because in order to be able to develop a certain aspiration rate out of the eye, a negative pressure (relative vacuum) will develop in the tubing. This can be demonstrated by setting such a machine to a set aspiration rate of, say, 30 ml/minute and watching the 'achieved' flow rate as the phaco pedal is depressed into position two. Full flow rate will not be achievable without also pre-setting a higher than normal vacuum setting. In truth, this also used to happen to a degree with older machines but the internal sensors were not sensitive enough to show the actual vacuum and aspiration rates achieved and were more of a guide. In this regard, modern peristaltic pumps act more like Venturi systems in which vacuum and aspiration and not fully separable.

Fluid flow related problems during phaco surgery

Hydrodissection in eyes with a shallow AC

Iris prolapse was a common occurrence in eyes undergoing scleral section extra-capsular cataract extraction. This was because of the proximity of the iris root to the wound and a similar mechanism causing iris prolapse during corneal tunnel phacoemulsification may occur. For this reason, in eyes with a shallow AC (and often a more steeply curved peripheral cornea) should have a slightly more corneal wound which is slightly longer than usual. This will allow avoidance of fluid flow under the peripheral iris root which might prolapse the iris out of the wound (Figure 2).

Gentle, small aliquots of fluid should be used in such eyes during hydrodissection for the same reason.

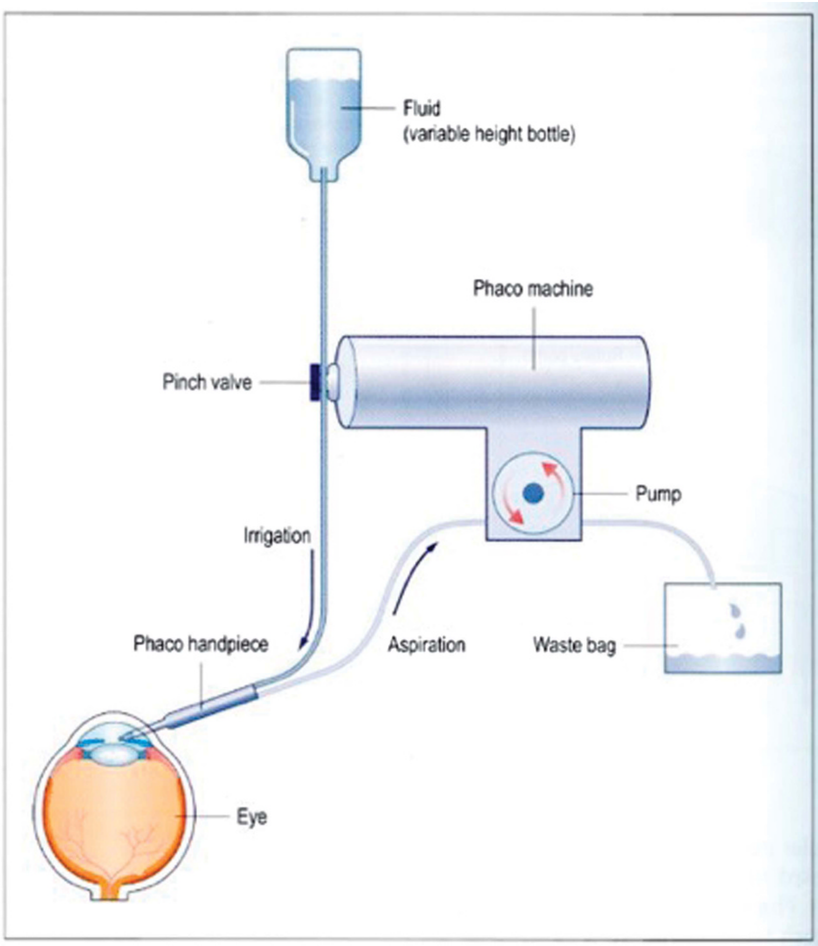

Figure 1 Diagram showing the general set up and principles of a phacoemulsification system. The pressure in the anterior chamber reaches a a fixed value dependant on the bottle height once the pinch valve opens (foot pedal position 1). In foot pedal position 2, aspiration of fluid from the eye starts as the pump is activated and then in foot pedal position three, vibration of the phaco needle commences to emulsify the cataract.

Table 1 Methods of preventing post-occlusion surge

Aspiration by-pass system	A hole in the phaco needle allows some flow to take place even when tip occlusion gas occured
Non-compliant tubing	Stiff, non-collapsible tubing allows faster pump speeds without the tubing diameter changes significantly.
In-line sensors	Detect pressure changes in the vacuum line and release fluid into the line to neutralize pressure difference or, detect when an occlusion break occurs and temporarily stop the pump.
Intelligent phaco	Used in the Alcon Infinity and Centurion machines. Detects when horizontal phaco tip is blocked and when vacuum reaches a pre-set proportion of the maximum vacuum initiates a burst of longitudinal phaco energy to clear the tip.
Bi-manual phaco	Separates inflow and outflow using separate infusion cannula and 'cold' phaco needle with no irrigation sleeve.

Reverse pupil block during phaco needle insertion (irrigation on)

This phenomenon is often observed in Myopic eyes or eyes having previously undergone vitrectomy. As the irrigation fluid enters the AC there is a sudden and significant deepening of the AC caused by reverse pupil block. This can make it difficult to reach the surface of the cataract without severely tilting the phaco probe and makes the actual phacoemulsification much more difficult. To reverse this happening the so-called Cionni manoeuvre[2] can be used. This entails simply putting a

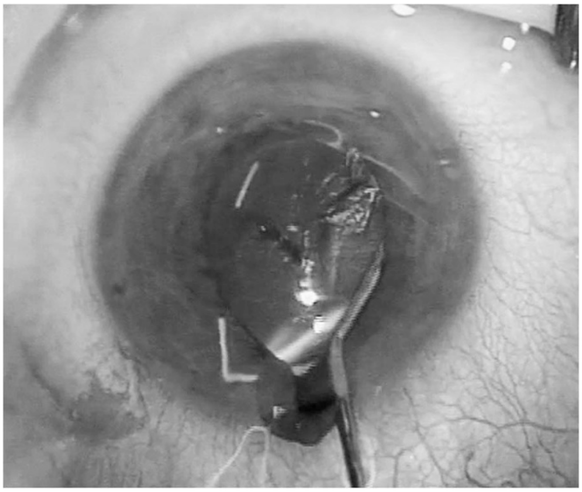

Figure 2 Iris prolapse occurring during hydrodissection in an eye with a shallow AC and a too-peripheral corneal wound.

second instrument under the edge of the iris and lifting the iris towards the cornea (anteriorly). This breaks the pupil block and the AC stays less deep until the irrigation is removed and re-introduced into the eye when the same thing can happen.

To prevent it happening in the first place the phaco needle is introduced with irrigation off and then before it is switched on, the second instrument is placed under the iris to lift it slightly anteriorly and then as the fluid is switched on, pupil block will not occur and the AC will not deepen. This technique was described by Richard Packard.[3] It needs to be repeated each time the AC is entered with irrigation fluid flowing.

Fluid loss through side port and chamber instability during last fragment removal

It has been calculated[4] that up to 67% of fluid used during phaco surgery is lost through side port leakage. Making sure that the side port is suitably sized for the second instrument used and limiting the use of the second instrument during the procedure can all help to reduce the fluid used. Importantly, removing the second instrument before the last fragment of nucleus is removed will increase chamber stability and give better protection to the posterior capsule than keeping the second instrument in the eye, which has been the traditional teaching. Although this can feel counter-intuitive, it does work and will allow safer removal of the last fragment. Keeping the second instrument in the eye leads to increased leakage and thus instability of the anterior chamber and a more mobile posterior capsule. In addition, side port leakage can cause excess fluid to accumulate on the corneal surface and reduce the clarity of the view of intraocular structures. If this is seen to occur (Figures 3a and b), then by removing the second instrument leakage stops, the AC stabilizes, and the view improves.

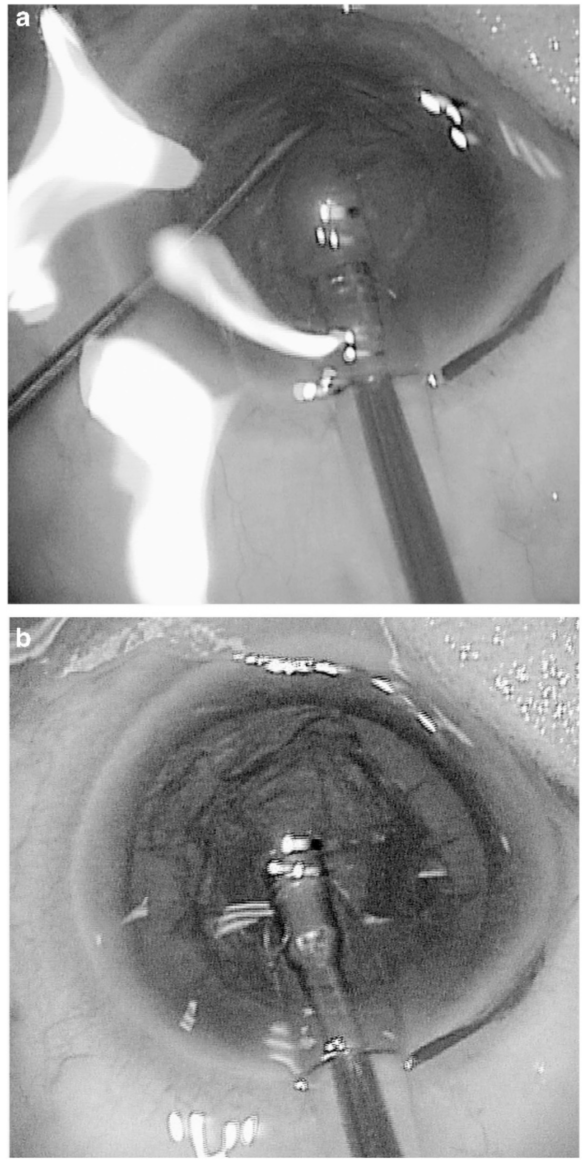

Figure 3 (a) Picture showing excess fluid flowing out of the side port during phacoemulsification. This fluid is obscuring the surgeons view of the anterior chamber. (b) Having removed the second side-port instrument the leakage stops and the view clears.

Flow issues after posterior capsule rupture

Posterior capsule rupture (PCR) with vitreous loss may be associated with a 40× increased risk of retinal detachment.[5] Most of this increased risk results from the way this acute situation is handled rather than the fact that it happens *per se*.

Avoiding vitreo-retinal traction is key and so early recognition of the event is critical. At no time should there be active phacoemulsification in the anterior segment in the presence of vitreous. The phaco tip cannot cut vitreous but it is a particularly efficient aspirator and will easily exert enough vacuum to separate the neurosensory retina from the retinal pigment epithelium (RPE). The RPE pump pressure is 0.27 mm Hg and so is easily overcome by over-zealous aspiration.

Having recognized a posterior capsular tear, the irrigation fluid should be kept on and Triamcinolone injected into the AC. This will, because of its particulate nature stick to vitreous and effectively coat its surface demonstrating its extent. This is the only way of effectively showing vitreous in the AC. Previous concerns about possible toxicity of the preserved Triamcinolone have not been borne out and indeed, there is now a non-preserved version available in the UK marketed by Farmigea (40 mg/ml). Having identified vitreous in the anterior chamber a dry vitrectomy is performed to remove it, replacing its volume with injection of viscoelastic. When this is complete, a viscoelastic BSS exchange is performed aiming to keep the posterior capsule tamponaded at all times. This prevents extension of the PC tear and also prevents movement of vitreous into the AC.

With old style vitrectors it was important to lower the bottle height when performing an anterior vitrectomy as the co-axial vitrector would often force more vitreous out of the eye (Figure 4). Modern vitrectomy probes are used through a side port with separate irrigation and this means that anterior vitrectomy is carried out in a closed system meaning that the irrigation bottle height can be maintained as there will be no flow until aspiration is started after the vitreous cutter is initiated (Figure 5).

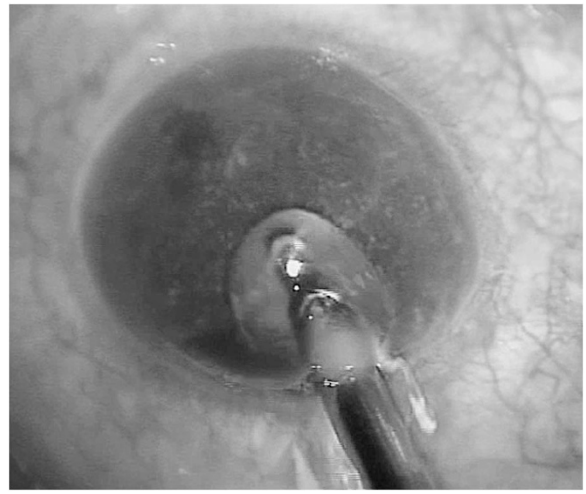

Figure 4 Old style co-axial vitrector used through main wound after vitreous loss. The uncontrolled anterior chamber allows much leakage and enables flow of more vitreous out of the eye.

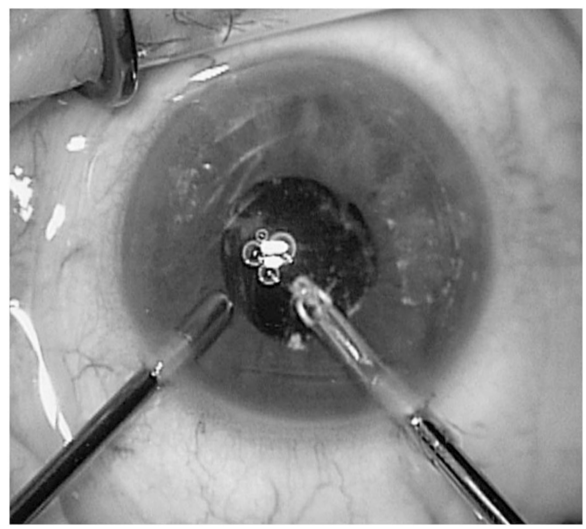

Figure 5 Modern bi-manual anterior vitrectomy. The anterior chamber is stable and no flow occurs out of the eye except through the vitreous cutter.

Suprachoroidal hemorrhage

This feared complication tends to cause a sudden hardening of the eye during the later stages of phacoemilsification. Usually, once the nucleus is removed, the AC refuses to deepen when the irrigation/aspiration (I/A) is inserted into the anterior chamber. Often viscoelsatic is used in an attempt to deepen the chamber but to no avail. It all flows out as rapidly as it is put in. If a SCH is suspected, then the eye should be closed and left undisturbed to allow the hemorrhage to tamponade itself. A week later the eye can be re-operated and the operation completed safely using a bimanual I/A, which helps to maintain a stable AC. Confirmation of a small SCH can be made with the indirect Ophthalmoscope during the operation and confirmed later with B-scan ultrasound. If the operating surgeon fails to recognise the early signs, then the hemorrhage will extend and will produce a poor outcome. A reversal of the normal flow patterns is the essential sign to pick up.

Summary

Understanding fluid flow in the eye and the principles of the phaco machine pump-type and its various parameters are essential for safe and effective phaco surgery. Knowledge of the nature of fluid flow and the dynamics of viscoelastics help to establish control and stability in the anterior chamber and deliver a high standard of cataract surgery outcomes.

Conflict of interest

The author declares no conflict of interest.

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