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Major Advances in Cataract Surgery

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1. Introduction

Cataract is the leading cause of blindness worldwide and likely has been since at least ancient times [1]. Consequently cataract surgery is recorded to have attracted the interest of surgeons for thousands of years [2,3]. During this period physicians and scientists have tried to improve the results of cataract surgery [1]. Cataract surgery is the most frequently performed operation in the world. In this chapter the principal concepts and pathways in thinking which have driven the development of the operation forward as well as some of the causes for resistance to change are discussed.

2. The Platonic theory of vision - The operations and observations of Susruta, Celsus and Galen

The first record of cataract being surgically treated is from 600 B.C. by Susruta of India [1]. It is quite possible that cataract surgery was performed by other surgeons before him including outside India but no reliable record from them has been found. Susruta used couching wherein the cataract is surgically dislocated away from the visual axis by a surgical instrument inserted into the eye [4]. Modernday cataract surgery has moved considerably beyond couching but it is worth noting in this context that couching is still performed by 'quack' doctors and also some traditional 'healers' for example in many underdeveloped parts of Africa, in the Yemen, and in rural China. Modern couching uses a long needle-like device inserted just behind the limbus - thereby crudely clearing the visual axis for light transmission by displacing the cataract into the anterior chamber or vitreous cavity [5]. The result is fairly unpredictable and the rate of blindness is high including many years after surgery. Retained lens matter is known to elicit a potentially very marked inflammatory reaction within the eye risking intractable glaucoma while vitreous loss risks both the latter complication as well as a significantly increased risk of retinal detachment and maculopathy. Siddig and Ali studied outcomes of this 'modern' form of couching done by rural 'healers' in the Darfur region of Sudan and found that 22% of patients develop endophthalmitis, and 38% develop longterm optic nerve atrophy from glaucoma [5]. Overall in the longterm they found that 60% of patients eventually had no perception of light in the operated eye after undergoing couching. It is likely that these outcomes would have been even worse in ancient times when there was no recourse to modern antibiotics for endophthalmitis or treatments for glaucoma. Yet couching remained the norm as far as surgical management of cataract went for many centuries.

With the conquest of northern India by Alexander the Great his physician brought knowledge of couching to Alexandria in Egypt [1]. It is possible the technique was in use even before this time in Egypt. Celsus in 25 A.D. provided the earliest extant description of the couching operation [1]. However the first recorded major advance in the practice of cataract surgery was not in finding a technique to supercede couching but in assessing the visual potential of an eye being considered for cataract surgery [1]. In this context Galen's records are worth scrutiny [1,2]. Galen (died 199 A.D.) was born and trained in medicine in Pergamon in Asia Minor (in modernday Turkey). After completing additional clinical work in the main medical cities of his time, Galen moved practice to Rome where he records couching cataracts [2]. Galen noticed that before cataract surgery a visible inequality of static pupil size was of limited prognostic value as the pupil can be of normal size with even severe cataract or many other disease processes in the eye or the opposite fellow eye [1,2]. He also noted what is now called the "consensual" light reflex and he also made an association between it and visual potential in the fellow eye. He observed that if a diseased eye is occluded there will be less dilation of the fellow eye than otherwise expected, and sometimes there is none. He also noted that if positive this test may be associated with a poor visual prognosis for cataract surgery in the affected eye [2,6]. However Galen's proposed mechanism to explain this correct observation was flawed. The Platonic schematic inherited from Ancient Greece by the Romans exerted a retarding influence in this context since it proposed a "pneuma" emerging from the eye which was responsible for sight. According to Plato, whose views dominated much of Ancient Greece and Rome, light was not thought of as the stimulus for vision, but rather sight was falsely regarded as a consequence of the emission of the 'visual spirit' from the brain, optic nerve and finally the eye, passing through its pupil to the outside world [2]. On the basis of the Platonic schematic Galen therefore mistakenly proposed that the 'pneuma' was responsible for pushing the pupil aside which thereby caused the pupil's movement in the light [2]. This faulty Platonic model of vision would act as a conceptual barrier to advances in the field of vision science and ophthalmology including cataract surgery for hundreds of years to come.

3. A different perspective to visual perception by the Imams Jafar ibn Mohammad and Mohammad ibn Ali – The Platonic schematic of vision discarded

Galen's "prognostic pupillary signs" were translated and transcribed into Arabic thereby preserving them during the European Dark Ages [2]. It was in the Middle East that the Platonic schematic of visual perception would eventually be discarded leading to important advances in optics and successful clinical outcomes in ophthalmology [1,2]. These observations were original and not a rehashing of older Greek, Persian or Coptic knowledge nor was it knowledge that was, as some have rather fancifully advanced, secretly saved from being burned in the library of Alexandria [1,2,7].

The key advance made during this period of history was the fundamental observation wherein light was recognised as the stimulus for vision, a belief recorded to have first been made by the Imam Jafar ibn Mohammad (702-765 A.D.) who taught at the academy started by his father the Imam Mohammad ibn Ali in the Arabian city of Medina [1,7,8,9]. The Imam Jafar ibn Mohammad stated that for every sensory phenomenon, including sight, there was an organ (in the case of vision the eye) to perceive it, and in the case of vision the stimulus was light, and it was this which gave rise to the visual phenomena including colour vision [1,7,8]. The Imam Jafar ibn Mohammad is also recorded to have stated the concept that rays of light are emitted, reflected or transmitted by objects, and also that it is the entry of these rays of light into the eye that causes vision (as opposed to the Greco-Roman pneuma, which postulated the reverse) - he thereby undid the age-old Platonic schematic for vision which had retarded advance in vision science and ophthalmology [1,7,8]. Using a clear logical argument he correctly stated for the first recorded time what eventually became a scientific truism:

"The rays of light from different objects come to our eyes and enable us to see them. The rays of light from our eyes do not go out and fall on other objects, otherwise we could have seen them in the darkness also. We see only those objects which are luminous. If they are not luminous themselves, they must reflect the light falling upon them by some luminous object." [1,7,8]

The profundity of the above statements in the face of the Platonic schematic of vision which had dominated the scientific and medical world cannot be overestimated. The first recorded mathematical concepts in geometric optics were also proposed by the Imam Jafar ibn Mohammad on the basis of which he proved that light scatter can be explained by regarding light as rays and this scatter is the cause of unclear vision for distant objects [1,7,8]. In these contexts he stated:

"If we make a device through which all the rays of light coming from the camels grazing at a distance of 3000 Zirah [One Zirah = 40 inches] entered our eyes we would see them grazing at a distance of only 60 Zirah and all other objects would look 50 times nearer to us." [1,7,8]

He also stated that since minification of objects occurs as little light is geometrically entering the eye (a small angle object) that the opposite, magnification, would occur when more light enters the eye and the angle increases - and hence distant objects could be magnified if the rays of light from the object could be concentrated to increase the angle by suitable employment of a technical instrument [1,7,8]. This is the first description of a theory for magnifying instruments, both simple lenses as well as microscopes and telescopes, and also for key functions of the crystalline lens including accommodation. These new beliefs about optics and vision carried far and wide owing to the immense number of students of the Imam Jafar ibn Mohammad – which included eminent scientists like Jabir bin Hayan (also known in the West as 'Geber', a man universally regarded as the scientific 'father' of chemistry) [1,9]. The Imam Jafar ibn Mohammad also stated that light and time were related, that light had a motion, and, additionally, that this motion was very rapid. Light was in his opinion capable of moving objects if concentrated, an important principle that while technically unfeasible in ancient times is an important principle associated with the mechanism of lasers in the modern world [1,7,8].

4. Applications of the new model for vision to optics, clinical diagnosis and cataract surgery in the Middle East

In the 9th and 10th centuries physicians in the Middle East applied Galen's prognostic pupillary signs to decide which cataracts carried a good visual prognosis [1,2,10,11]. The influence of the new teachings on vision and optics by the Imam Jafar ibn Mohammad is once again hard to overestimate since he taught innumerable major scholars in the eighth century. Applying his teachings on vision both Ammar ibn Ali and Ibn Sina (also known as

Avicenna) are recorded to have likewise discarded Plato's theory which had been incorrectly used by Galen in their correct explanation of the pupil's movement which correctly stated that it was a light stimulus which entered the pupil from outside which drove the pupil's movement and not a visual 'pneuma' being emitted from within the eye [2,12]. Both men noted additionally the existence of a direct pupil response to light for the first time in the literature, in distinction to Galen who had noted only the consensual response [2].

The erudite German ophthalmologist and medical historian Julius Hirschberg, speaking in 1905 at the American Medical Association in California, after dedicating 5 years to the study of the field noted how great his initial surprise was at the rapid advance in the field of ophthalmology in the Middle East during the period which would have been just after the Imam Jafar ibn Mohammad proposed his correct explanation for how vision arises [13]. Hirschberg does not seem to have been familiar with the details of the works of the latter since in 1905 few works by the Imam Jafar ibn Mohammad had been translated into English or German. Consequently Hirschberg was unable to fully explain how ophthalmologists of this period in the Middle East based their clinical practice on a rejection of the older Platonic schematic of vision inherited from the Greco-Roman world, since they otherwise frequently used such sources like Galen's Ten Treatises of the Eye by Ammar ibn Ali in *Choice of Eye Diseases*. In the absence of Ancient Greek or Roman sources (which all upheld the erroneous Platonic schematic of visual perception) the origin of the new theory for vision could only have come from within this part of the world and the Imam Jafar ibn Mohammad since the latter was widely influential, had innumerable eminent students including students of science who spread across the Islamic world, and since his recorded statements exist to this day showing his thinking was logical and went unchallenged [1,7,8].

Following on from the theoretical advances of the Imam Jafar ibn Mohammad the first recorded advance in the technique of cataract surgery since couching occurred. In *Choice of Eye Diseases* written in Egypt by the Iraqi Ammar ibn Ali, who invented the hollow needle and syringe for clinical use (hence his invention of the hypodermic syringe), he describes adapting one of his hollow needles for the purpose of cataract extraction:

"Then I constructed the hollow needle, but I did not operate with it on anybody at all, before I came to Tiberias. There came a man for an operation who told me: Do as you like with me, only I cannot lie on my back. Then I operated on him with the hollow needle and extracted the cataract; and he saw immediately and did not need to lie, but slept as he liked. Only I bandaged his eye for seven days. With this needle nobody preceded me. I have done many operations with it in Egypt." [14]

Was this operation of cataract aspiration as described by Ammar ibn Ali an intracapsular cataract extraction (ICCE) wherein the posterior capsule is removed with the cataract or an extracapsular cataract extraction (ECCE) wherein the posterior capsule is left intact hence reducing significantly the risk of vitreous loss and its attendant complications? Given that the mechanism of aspiration seems to have been fairly crude by modern standards it is unlikely that the posterior capsule survived, but this is not known with certainty. It is also likely that this technique would have been used for softer cataracts for obvious reasons. What is known with certainty is that it represents the first recorded description of *extraction* of a cataract, the first major advance in ophthalmic surgery since couching.

This major technical advance in cataract surgery took place after a very prolonged period of stagnation in surgical advance in the field. It took place shortly after the Platonic schematic for vision had been discarded - and combined with the long history of couching that preceded it – it would seem unlikely to have been a coincidence. The likely reason for this is as follows. Galen, who is often referred to by Middle Eastern physicians including Ammar ibn Ali in his *Choice of Eye Diseases*, had wrongly viewed the Platonic pneuma as pushing the pupil aside as it exited the eye - hence it was proposed to account for the pupillary movement [1,2]. This theory, albeit deeply flawed, had fitted well conceptually with the couching operation - it made thematic sense that the lens likewise could be pushed out of the way, this time by a surgical instrument, in the same way the pneuma was held responsible for pushing the pupil out of the way causing it to dilate or constrict. The abandonment of this Platonic schematic for vision beginning with the Imam Jafar ibn Mohammad (8th century) was hence likely to have been a factor giving rise to the birth of new conceptual approaches to cataract surgery resulting in the aspiration of the lens as an alternative to couching, aided by the coincidental technical invention of the hypodermic syringe which was adapted for this purpose. Whether Ammar ibn Ali's cataract aspiration operation was truly the first of its kind or an inadvertent revision of a much older technique hence becomes irrelevant in this context. The Persian physician Mohammad ibn Zakariya al-Razi also described such an aspiration technique for cataract and there is a suggestion by him it may have been performed even earlier by Antyllus, a 2nd-century Greek physician though unlike Ammar ibn Ali and Mohammad ibn Zakariya al-Razi there is no original record of the operation from Antyllus himself should he have undertaken the procedure [15]. In the Middle East a knife to create a wound and oral suction were in use to assist the aspiration procedure - like sucking on a straw [15].

Building on the teachings of the Imam Jafar ibn Mohammad on geometrical optics in approximately 984 Ibn Sahl wrote a treatise entitled 'On Burning Mirrors and Lenses' laying out his understanding of how curved mirrors and lenses bent and focussed light, and on which basis Ibn Sahl has been credited with the first recorded description of what was much later called Snell's law of refraction [16]. Ibn Sahl also used this law to work out the shapes of lenses that focus light with no geometric aberrations, known as anaclastic lenses, an important fundamental advance in what would one day become an applied science of clinical optics including intraocular lens design [16]. Rashed has shown that Ibn Sahl's treatise was used in part by Abu Ali al-Hasan ibn al-Hasan ibn al-Haitham of Basra in Iraq (often called Ibn al-Haitham, also known in the West as Al Hazen) (965–1039 A.D.) in his Book of Optics which brought together much of the work up to that time, including dispersion of white light into its constituent colours [16,17]. Al-Haitham also described the geometry of the reflection of light and built the first pinhole camera showing an intra-ocular image of the outside world formed by inversion of the image passing through the cornea and lens in the pupil plane [1,9].

5. Advances in cataract extraction in Europe

The technique of cataract extraction by aspiration, though practised in the Middle East alongside couching, seems to have been performed only by a small number of surgeons such as the pioneering Ammar ibn Ali. The rate of such progress in science, medicine and surgery within the Middle East seems to have started to wither away after the 10th century and there is little evidence that the practice of cataract surgery reverted to anything more than couching once again.

It was in Europe in 1748 where cataract surgery was next extensively developed by the French ophthalmologist Jacques Daviel who used an extracapsular technique made public in 1753 [18]. Daviel incised the inferior cornea at the limbus with a myrtiform or triangular knife and enlarged the incision on both sides with a thin, blunt pointed, double-edged knife as far as was possible till the cornea became too unsupported to cleanly incise after which he completed the incision superiorly within the cornea to above the pupil with curved scissors. The anterior capsule of the lens was incised with a sharp-edged needle and with a spatula the cataractous lens loosened which he then delivered. The corneal flap was replaced without sutures and then covered with a compress to protect against disturbing the wound so as to allow it to eventually heal sufficiently so as to seal the eye. In effect this is a similar technique to modern extracapsular surgery except for significant advances in instrumentation, suturing and capsulorhexis technique.

By the late nineteenth century the ECCE operation had progressed little more save for the adoption by many European surgeons of the von Graefe knife to make the corneal section – an instrument invented by the celebrated German surgeon after whom it is named. Even as late as the end of the twentieth century some surgeons in England were still using this technique in a highly developed form employing a 'no-touch' technique (that is no contact between hands and the eye). Some surgeons took this to unusual lengths and did not even glove.

6. Intraocular lens implantation

A very major advance in cataract surgery was implantation of a lens within the eye to replace the crystalline lens removed during cataract extraction – and called 'the intraocular lens' (IOL). The theoretical benefit of this had been acknowledged ever since the first studies of the function of the lens in the Middle East from the 8th to the 10th centuries A.D. Yet it was not performed successfully till the mid-twentieth century. It has been suggested by Fechner and Fechner that Tadini, an Italian-born ophthalmologist living in the second half of the eighteenth century, is likely to have been the first European to have conceived of the possibility of intraocular correction of aphakia [19]. Running contrary to popular belief amongst many ophthalmologists a detailed literature review also suggests that the first IOL was not implanted by the English surgeon Harold Ridley in London but, as researched by Fechner and Fechner, as follows [19]. They note that Casanova recorded that Tadini possessed a box of artificial glass lenses for intraocular use - they suggest that the latter passed Tadini's idea onto Casaamata, an ophthalmic surgeon in Dresden, Germany and who is the first surgeon recorded to have implanted an intraocular lens (IOL) to correct aphakia in 1795 [19]. However being made of glass the IOL sank in the eye owing to its weight and the idea for IOL implantation did not seem to catch on till it was revisited in the twentieth century in London [19]. As a result, even into the present day patients exist who underwent bilateral cataract extractions in the age before IOL implantation was near-universal and who wear highly plus spectacle-mounted lenses which cause considerable image magnification (aphakic spectacles) including 'jack in the box' aberrations. Other problems are associated with aphakia in addition to poor visual acuity. Unless corrected by a lens there is a loss of binocular single vision following unilateral cataract extraction, and in children the outcome was even poorer not only because of amblyopia but because of the poor quality of contact lenses which were available till the fairly recent past.

The problem of post cataract extraction aphakia would be revisited by a London medical student who would change the history of ophthalmology forever – incidentally it does not seem the unknown medical student himself ever became an ophthalmologist himself. The medical student remarked in the presence of Harold Ridley, an ophthalmic surgeon in London, how theoretically the outcome of cataract surgery could be improved considerably if the lens that Ridley had extracted during a cataract operation could be replaced. Ridley seized upon this idea with practical determination. He found an inert material for an artificial lens in the form of polymethylmethacrylate (PMMA). It had already been observed by ophthalmologists that glass and plastic intraocular foreign bodies in injured aircrew during World War II did not elicit a significant inflammatory response provided the iris was not touched, so the choice of PMMA seemed a good one. In 1949 Ridley implanted the first such IOL in London and set about trying to popularise the practice. He met for many years with severe resistance from many other surgeons, some of which seems to have been likely due to an element of professional rivalry [20]. Ridley's attempts to popularise IOLs were not helped by the fact that the early surgeons performing the procedure forgot that the refractive index of PMMA was different in air and in water (and hence inside the eye) – leading to a massive miscalculation of the postoperative refraction. This however opened the door to the applied science of biometry, which would eventually spawn a large number of mathematical equations to accurately compute the target IOL power within the eye, a field which has had many contributors from both sides of the Cold War which was going on at the time including the Russian surgeon Fyodorov, and which continues to advance with equations such as the SRK-T, Hoffer Q and Holladay 2 which are currently the most widely used formulae to calculate the IOL power. Ridley and another British surgeon Peter Choyce co-founded the International Intraocular Implant Club in 1966, an organisation which was in large part responsible for the gradual acceptance of artificial lens implantation [20]. Nevertheless for these and related reasons IOL implantation took a long time to became standard spreading slowly and haphazardly to different parts of the world. Subsequent design modifications have considerably improved the lens design.

Above all the vogue for newer methods of cataract extraction would drive the development of newer IOLs. A drawback of the PMMA lenses is that they were rigid and could not be folded. Initially this did not seem to matter as the early IOLs were anterior chamber (AC) IOLs such as iris clip-on lenses. However clinical experience in their use would prove to surgeons that AC IOLs had many problems, many of which have not even yet been fully resolved, including corneal decompensation from corneal endothelial loss, uveitis and hyphaema. By the 1990s with the beginning of the widespread popularity of phacoemulsification newer IOLs made of acrylic and silicone would become popular since they could be folded to take advantage of the much smaller wound offered by phacoemulsification, and being flexible they could also more readily be placed within the capsular bag or even ciliary sulcus should the latter lack support rather than in the anterior chamber. Once the technique of phacoemulsification eventually became routine these lenses also thereby came into routine use. IOLs made of PMMA did not cause much posterior capsule opacity (PCO) when placed in the capsular bag as the rigid lens had a sharp edge and was also more adherent to the posterior capsule preventing migration of cells responsible for PCO. The newer IOL materials of silicone and acrylic induced more PCO, which temporarily slowed down their acceptance by some units, though fortunately this was countered in the 1980s by the increasing use of pulsed Neodymium:Ytrrium, Aluminium, Garnet (Nd:YAG) laser used in the Q-switched mode for posterior capsulotomy

- obviating the need for an invasive procedure such as posterior capsulectomy to deal with the PCO.

Since the 1990s injectable foldable IOLs have become more and more popular. These are deployed within the eye from within a cartridge inserted into the eye instead of manually using forceps. They however require familiarity with the exact specific mechanism of insertion including loading the IOL to be used safely and the ease, safety and reliability varies a great deal between different manufacturers.

7. Advances in cataract extraction – ECCE and ICCE

There was little advance in the actual technique of cataract extraction for a long period of time - the extracapsular technique popularised by Daviel in the late eighteenth century remained – except that the von Graefe knife came to be used by many European surgeons for making the corneal section. Instead of a spatula as used by Daviel in the twentieth century 'needling' was frequently the method employed to remove the cataract, which involved making a corneal incision and scraping the cataract out with (ideally) an intact posterior capsule, a technique used in children till the late twentieth century.

In the twentieth century advances in surgical cryotherapy permitted an application to cataract surgery with what came to be called 'intracapsular cataract extraction' (ICCE). In 1962 Dr Charles Kelman devised a modern version of the cryoprobe, a freezing instrument for the extraction of cataracts within their capsules (and also later applied by him for sealing retinal breaks). In ICCE, after making an incision into the eye similar to the large incision used in traditional extracapsular surgery, a cryoprobe is inserted into the eye which because of the extremely cold temperature it 'freezes' anything it comes into contact with – in this case it is made to stick to the anterior capsule and the entire lens with its anterior and posterior capsules are extracted 'en bloc'. A modification was administration of intracameral zonulolysins to facilitate this process by dissolving the zonules, and also liquid nitrogen could be applied to the anterior capsule to enhance the stickiness of the adhesion. Vitreous loss was common and de Wecker's scissors evolved to excise vitreous – a technique now almost replaced by anterior vitrectomy. Owing to vitreous loss being fairly common the risk of retinal detachment was much higher than more modern techniques of cataract extraction, and the corneal incision was also much larger. ICCE is still extremely rarely used to extract a hypermobile lens by some surgeons, though a posterior pars plana approach to remove the cataract using phacoemulsification may be preferred by many faced with this situation. Since there is no capsular bag left after ICCE the only option for IOL implantation is an anterior chamber design.

Both traditional ECCE and ICCE were used by different surgeons in different institutions till the 1980s. Advances in the ability to perform posterior chamber IOL implantation, and the gradual introduction of operating microscopes during the 1970s offering better intraocular visibility and ability to safely place multiple corneal sutures, led to modifications in key steps of the old ECCE operation. The modernday ECCE operation consequently comprises extraction of the crystalline lens using a can-opener capsulorhexis and controlled irrigation to dislocate the lens into the anterior chamber with the modern irrigating vectis instrument from where the lens is delivered and after anticipated IOL implantation 'in the bag' closure of the corneal section using several 10-0 sutures. This operation is still recommended in cases where phacoemulsification is not safe such as some cases of loss of the anterior capsular edge during capsulorhexis, or if phacoemulsification is impractical such as in some eye camps in developing countries. An advance in the field of ECCE has been 'small incision' ECCE using a scleral tunnel to perform the operation. This avoids the need for sutures and permits increased recuperation time and higher volume surgery since it does not require suturing of the section.

It is also worth noting that rehabilitation from older forms of cataract surgery (whether ECCE or ICCE) which pre-date the widespread use of the operating microscope (a 1970s development) was very prolonged as corneal suturing could not be safely performed in anything but a most rudimentary fashion without the magnification and stereopsis afforded by the operating microscope. Furthermore corneal suturing materials were crude – 10-0 sutures were not available- and at best a single silk suture could be temporarily placed to seal a corneal wound by the 1960s. In the 1950s and before even this was not possible. Patients would consequently have to lie with their heads sand-bagged flat on their backs for weeks in hospital while the incision into the eye healed sufficiently for them to be allowed to move. Indeed this was a familiar sight to those who visited eye wards in the 1950s in many countries from the United Kingdom to India.

8. Dr Charles Kelman and the age of phacoemulsification

The revolutionary introduction by Dr Charles Kelman of New York of the phacoemulsification technique ('phaco') in 1967 had at least three main implications. First it would eventually permit surgeons to reduce the morbidity from cataract surgery considerably as it allowed access to the cataract using a much smaller incision than ECCE or ICCE. In the early years of the procedure this meant that recovery would be much faster as patients would not have to lie sandbagged for weeks. However even with modern ophthalmic surgical suturing techniques phaco offers great advantages in terms of reducing the risk of endophthalmitis and refractive problems associated with larger wounds. Second the development of phaco spurred on interest in foldable IOLs as discussed above. Third it permitted very high volume cataract surgery to be performed as a day case – indeed it thereby had major ramifications for the expansion of day case surgery in the overall field of surgery.

The principal clinical advantage of phaco is consequent to the small wound size afforded by the ultrasound-emitting tip of a handpiece used by the surgeon to cut the cataract inside the eye - this is the core feature of the technique. The cut fragments of the crystalline lens are removed from the eye by holes for vacuum and aspiration which are built into the phaco handpiece. These parameters can all be adjusted by the surgeon. Modern phaco machines employ a titanium or steel tip inserted via a main incision typically less than 3.0 mm and emitting ultrasonic frequency of 40,000 Hz thereby emulsifying the lens material. A second instrument inserted via a much smaller side port augments the surgeon's ability to manually crack or chop the nucleus into smaller fragments alongside use of ultrasound to emulsify the lens. In a throwback to the distant past aspiration is still used in virtually all modern cataract surgery. After all 'hard' parts of the cataract have been removed a dual irrigation-aspiration (I-A) instrument or a bimanual I-A system is used to aspirate the remaining peripheral cortical material. In very soft cataracts the entire procedure can be done using aspiration obviating the need for ultrasound altogether.

The phaco handpiece can be inserted into the eye through a much smaller incision than for ECCE or ICCE. Typical modern wounds for phaco are 2 to 3 mm wide (and can in the latest microincisions be less than 2 mm in width) The small incision size used in

phacoemulsification permits the option of "sutureless" wound closure in contrast to ECCE which utilises a larger wound (10-12mm) requiring stitching; further, although sutureless ECCE via a scleral tunnel may be used the incision is still larger than for phaco.
The early phaco operations were complicated by very significant corneal endothelial loss creating resistance to the use of the technique since visual outcomes from ECCE were, despite the prolonged period of recuperation, nevertheless good in the longterm. Kelman himself noted that there was a period when after pioneering ‘phaco’ he was banned from operating altogether at the hospital in New York where he had done the first operation. Kelman persisted in improving his technique. With persistence in improving his technique Kelman was able to obviate complications of early phaco operations such as significant corneal endothelial damage. By the mid-1990s the operation he pioneered in 1967 had come to be the most widely used method for cataract extraction in the developed world. In addition to showing the sometimes very long period required for acceptance of a fundamentally good surgical technique (such as IOL implantation) the prolonged time course for the acceptance of phaco also underlines the very long learning curve to the operation. This is owing to the number of complex steps being performed, some simultaneously, in a very limited physical space within the anterior chamber – a learning curve which is probably longer than that of any other operation in the book of surgery and which took intraocular surgery into a new level of technical skill. Simply put no other operation takes many hundreds of independent procedures to become confident at it, and the operation is sometimes wrongly dismissed as minor or easy to perform based upon misleading impressions arising from the often high turnover in expert hands and the implications for revenue generation and payment.

9. Phaco-refractive surgery

Recuperation has been much faster with phaco than with ECCE surgery - astigmatism and other wound-related complications like pain and infection are all reduced. But it has also allowed refractive modification of the cornea in a more predictable manner. Once the risk of corneal decompensation was reduced phaco was found to leave a less damaged corneal surface than the large wound of ECCE of ICCE surgery, a surface that was much closer to the ideal optical sphere of textbooks on physiological optics. This of course meant surgeons could manipulate the cornea more predictably – the era of phaco-refractive surgery burgeoned in the 1990s.
A wide variety of methods were devised to deal with corneal astigmatism at the same time as phaco. This began with modifying wound construction – ‘on-axis’ corneal incisions flattened the steep meridian; temporal corneal sections could reduce the astigmatic effect of an incision compared with other incisions; phaco wound incisions further from the visual axis were noted to have less effect on astigmatism just as with other corneal sections. Later coupled limbal relaxing incisions were popularised by some surgeons, which can now be planned using biometry inputted into a computer algorithm, though the refractive effect diminishes with time. Finally toric IOL design provided the definitive solution to astigmatism allowing surgeons to make safe triplanar wounds to reduce the risk of endophthalmitis and simultaneously reduce postoperative astigmatism.
Alongside modifications to the cornea, the other ocular refracting surface of the lens was also subject to further manipulation in terms of IOL design in addition to toric IOLs. Monofocal IOLs were supplemented with a variety of new generic IOL designs which could

compensate in theory for the loss of accommodation with cataract extraction – accommodative (i.e. pseudo-accommodative) and multifocal IOLs. These designs of IOLs could be combined within a toric IOL design to also address the issue of astigmatism. However apart from toric design the other generic modifications to IOL design remain somewhat controversial, with at present only multifocals gaining reasonable popularity, though with a risk of glare and reduction in contrast sensitivity. For those myopes wishing to avoid spectacles for reading the option of monovision is still favoured by many surgeons, leaving one eye myopic enough to read with (typically about -1.5D to -1.75D) and the other emmetropic for distance and intermediate vision.

'Intracor' refractive laser treatment has very recently offered the option of reducing presbyopia without cataract extraction and IOL implantation by modifying the corneal thickness centrally, but its only niche should it become more widely used would be as a neo-adjunctive therapy for presbyopia prior to eventual cataract surgery with IOL implantation as the patient ages and develops significant lenticular opacity. Corneal refractive surgery with LASIK (Laser-Assisted in Situ Keratomileusis), LASEK (Laser Epithelial Keratomileusis) and PRK (photorefractive keratectomy) can help patients with high order aberrations following cataract surgery in whom the aberrations can be identified using wavefront technology.

10. Fluidics and adjuncts to phacoemulsification

The most recent innovations have sought to extent Kelman's principal success in using phaco to use bimanual instrumentation separating the phaco tip (cum aspirator) from irrigation and to make the wound smaller and smaller – sub-2mm wounds are now feasible and have given rise to smaller bimanual instruments and readily insertable IOLs.

Alongside these major advances other developments have included modifications to the original phaco machine fluidics. The older peristaltic pumps notoriously suffered the risk of occlusion (suction) breaks during the procedure. Venturi pumps overcame this problem. Further hybrid-like pumps using elements from both basic designs have been developed. The field has come full circle in fact in the past decade with many pumps employing a superior peristaltic design with more rigid tubing to prevent the infamous occlusion breaks which risked tearing the posterior capsule in earlier designs. By far the biggest advantage of all these advances has been the maintenance of a much more stable anterior chamber than with earlier machines dating to the 1990s.

More evolved phaco tip design has come to be used over the past couple of decades with the general abandonment of the old-fashioned Kelman tip and also the successful development of phaco tips that can vibrate not only in continuous mode but in burst and pulse modes. The latter modes enable more efficient removal of lens fragments and reduce the risk of corneal burns from the high frequency ultrasound tip of the phaco handpiece, a complication which has consequently significantly reduced in frequency. Adjunctive techniques include the development of capsule tension rings, dyes to optimise visibility, ophthalmic viscosurgical devices, sharp disposable knives and advances in microbiology especially the use of pre-operative povidone iodine and antibiotics administered intracamerally or subconjunctivally which significantly reduce the risk of endophthalmitis. These are just a selection of the more significant advances in cataract surgery which have accompanied the phaco revolution over the past 3 decades. Awareness and understanding of the effects of phacoemulsification on the retina have given rise to peri-operative drugs such as intracameral or subconjunctival or peribulbar steroids and topical non-steroidal anti-inflammatory agents (NSAIDs) to reduce the risk of macular oedema in select patients. Yellow-tinted IOLs have been employed to reduce the potentially hazardous effect of blue light on the macula, an area of research that has become topical once again more recently owing to the discovery of blue light sensitive inner retinal photoreceptors involved in circadian rhythms, the pupil light reflex and perception of light [21].

Finally phacoemulsification has permitted the field of ophthalmic anaesthesia to change massively during the past 30 years. The eye is the most sensitive structure in the body and is associated with a number of specialised techniques of anaesthesia to permit surgery on the organ. Early phacoemulsification operations were all done under general anaesthesia where this was feasible, and carried the risks of a general anaesthetic. Regional anaesthetic blocks could also be employed. Retrobulbar injections with their higher risks of potentially very serious local and systemic complications such as globe perforation and cardiorespiratory depression have moreoless fallen out of use in favour of the less risky peribulbar injections. In many countries during the 21st century newer soft-needle techniques such as sub-Tenon's local anaesthesia displaced other needle-based techniques as the standard technique to administer regional anaesthesia in cataract surgery (and this has been extended from cataract surgery to many other intraocular operations). Owing to the small corneal wound size used in phacoemulsification the possibility of topical anaesthesia has been found to be feasible, ideally supplemented with intracameral anaesthesia, and is a viable option for anaesthesia in selected patients.

11. Laser cataract surgery

Most base modifications to the fundamental phacoemulsification ultrasound technique have come and gone or simply not caught on. Aqualase is essentially defunct after a brief flurry of interest - it employed a water jet in place of ultrasound. Torsional ultrasound is a newer development which is still being used in some phaco machines – it reduces the amount of phaco power expended during most operations. While the latter can work well for dense cataracts and the former for softer cataracts phaco has been able to cope well with all densities of cataract leading to its great versatility as the preferred technique for cataract extraction in most situations.

The only significant promise of a major advance beyond phacoemulsification is at present femtosecond laser which cuts the cataract using a laser after a corneal section and anterior capsulorhexis have been made (the latter can also be made by the laser). This leaves only extraction of the cataract to the surgeon after which the soft lens matter may be aspirated, IOL inserted under a viscoelastic which is aspirated and the wound closed. The longer term outcomes of this technique are in the process of evaluation [22]. Femtosecond cataract surgery may come to occupy a niche within the overall field of cataract surgery, even though the procedure is at present slow to perform on a high volume basis generally requiring two operating theatres – one for the laser and one for the surgery.

12. Conclusion - The future

Whether femtosecond laser cataract surgery replaces or gains a niche alongside phacoemulsification and extracapsular cataract extraction is unknown. However it is interesting to note that the full femtosecond technique, which is the most recent technique in cataract surgery, requires utilisation of all the theoretical and practical advances described at the start of this chapter which were made in the 8th to 10th centuries. These are the rejection of the Platonic schematic for vision, understanding of the function of the crystalline lens, the theory of lasers including their ability to disrupt matter, and the extraction of cataract by aspiration. It is always risky predicting the future, but it is a fair guess that the major advances in cataract surgery in the future, should they occur, will likely proceed along similar conceptual pathways.

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