Refractive surgery

Tae-im Kim, Jorge L Alió del Barrio, Mark Wilkins, Beatrice Cochener, Marcus Ang

Refractive surgery has evolved beyond laser refractive techniques over the past decade. Laser refractive surgery procedures (such as laser in-situ keratomileusis), surface ablation techniques (such as laser epithelial keratomileusis), and photorefractive keratectomy have now been established as fairly safe procedures that produce excellent visual outcomes for patients with low-to-moderate amounts of ametropia. Additionally, a broader selection of options are now available to treat a wider range of refractive errors. Small incision lenticule extraction uses a femtosecond laser to shape a refractive lenticule, which is removed through a small wound. The potential advantages of this procedure include greater tectonic strength and less dry eye. In the future, intracorneal implants could be used to treat hyperopia or presbyopia. Phakic intraocular implants and refractive lens exchange might be useful options in carefully selected patients for correcting high degrees of ametropia. Thus, physicians are now able to provide patients with the appropriate refractive corrective option based on the individual's risk–benefit profile.

Lancet 2019; 393: 2085–98

Department of Ophthalmology, The Institute of Vision Research, Yonsei University College of Medicine, Seoul, South Korea (Prof T-i Kim MD); **Cornea, Cataract and Refractive Surgery Unit, Research & Development Department VISSUM Innovation Alicante, Alicante, Spain** (J L Alió del Barrio MD); **Division of Ophthalmology, School of Medicine, Universidad Miguel Hernández, Alicante, Spain** (J L Alió del Barrio); **Department of Ophthalmology, Moorfields Eye Hospital, London, UK** (M Wilkins MD); **Department of Ophthalmology, University Hospital Morvan, Brest, France** (B Cochener MD); **Singapore Eye Research Institute, Singapore National Eye Centre, Singapore** (M Ang MBBS PhD); **and Department of Ophthalmology and Visual Science, Duke-NUS Graduate Medical School, Singapore** (M Ang)

Correspondence to: Dr Marcus Ang, Singapore National Eye Centre, 11 Third Hospital Avenue, Singapore 168751, Singapore **marcus.ang@snec.com.sg**

Introduction

Refractive error is a leading cause of reversible visual impairment worldwide, and corrective refractive surgery is one of the most frequently used ocular surgeries globally.[1–4] Myopia, also called short-sightedness, is the most common form of refractive error,[5] and its increasing prevalence around the world has made myopia a major public health issue, with billions of people estimated to be affected by this condition by 2050.[6] Although some people might consider refractive surgery a cosmetic procedure, the effect of refractive surgery on patients extends beyond spectacle independence, with the procedure leading to improved quality of life, better working ability, and improved daily working performance.[7] Furthermore, traditional laser refractive surgery has excellent visual outcomes and good safety profiles, supported by an abundant amount of scientific evidence over the past few decades.[8]

Since the previous *Lancet* Review [9] published more than a decade ago and focused specifically on laser eye surgery for refractive errors, refractive surgery has progressed beyond just corrective laser surgery. Enhancements in surgical technologies have also led to the introduction of intracorneal implants, intraocular phakic implants, and a new minimally invasive corneal refractive surgery approved by the US Food and Drug Administration (FDA). These advances have also been accompanied by improvements in imaging systems to guide better patient selection, reduced surgical complications, and optimisation of visual outcomes through customising treatments, leading to an overall improvement in safety and efficacy for patients undergoing these procedures.[8]

However, these developments also now mean that patients have a wide range of potential refractive options, which require a proper understanding of the risk–benefits and appropriate candidate selection by the surgeon. The history and development of refractive surgery, as well as preoperative clinical assessment with its outcomes and complications, were extensively described in the previous *Lancet* Review[9] on laser eye surgery. Thus, the aim of this Review is to provide an update on the rapidly evolving field of refractive surgery for physicians and surgeons, including an evidence-based summary of the outcomes and future developments. This Review encompasses updates from the previous *Lancet* Review on laser eye surgeries, but also includes developments in the latest laser refractive techniques, intracorneal implant techniques, and intraocular surgical options in refractive surgery.

For the purposes of this Review, discussion will focus on refractive errors including myopia, which occurs when parallel light rays entering the eye are focused in front of the retina, thus making distant objects blur; hyperopia, which occurs when the visual rays are focused at a theoretical point behind the retina; and astigmatism, which arises from abnormalities in curvatures of the eye (symmetrical, asymmetrical, or irregular) and leads to differential light passing through various corneal meridians (figure 1).

Although strictly not a form of ametropia, we also discuss refractive options for presbyopia, which develops in all individuals as a defect in accommodation, due to gradual thickening of the lens, loss of flexibility of the

Search strategy and selection criteria

We searched MEDLINE, Embase, and the Cochrane Library over the past 10 years using the search term "refractive surgery" and included the additional terms "laser refractive surgical procedures", "intrastromal corneal implants", and "phakic intra-ocular lenses". We excluded techniques not commonly done as primary corrections of refractive error, or that have been replaced with more efficacious techniques, such as radial keratotomy, astigmatic keratotomy, and epikeratoplasty. We selected publications with an emphasis on randomised clinical trials and original articles but did not exclude commonly referenced and highly regarded publications. We also searched the reference lists of articles identified by this search strategy and selected those that we judged relevant on the basis of the quality of data. Review articles, meta-analyses, and summary articles were included to provide readers with more details because of the limitation in scope of this Review.

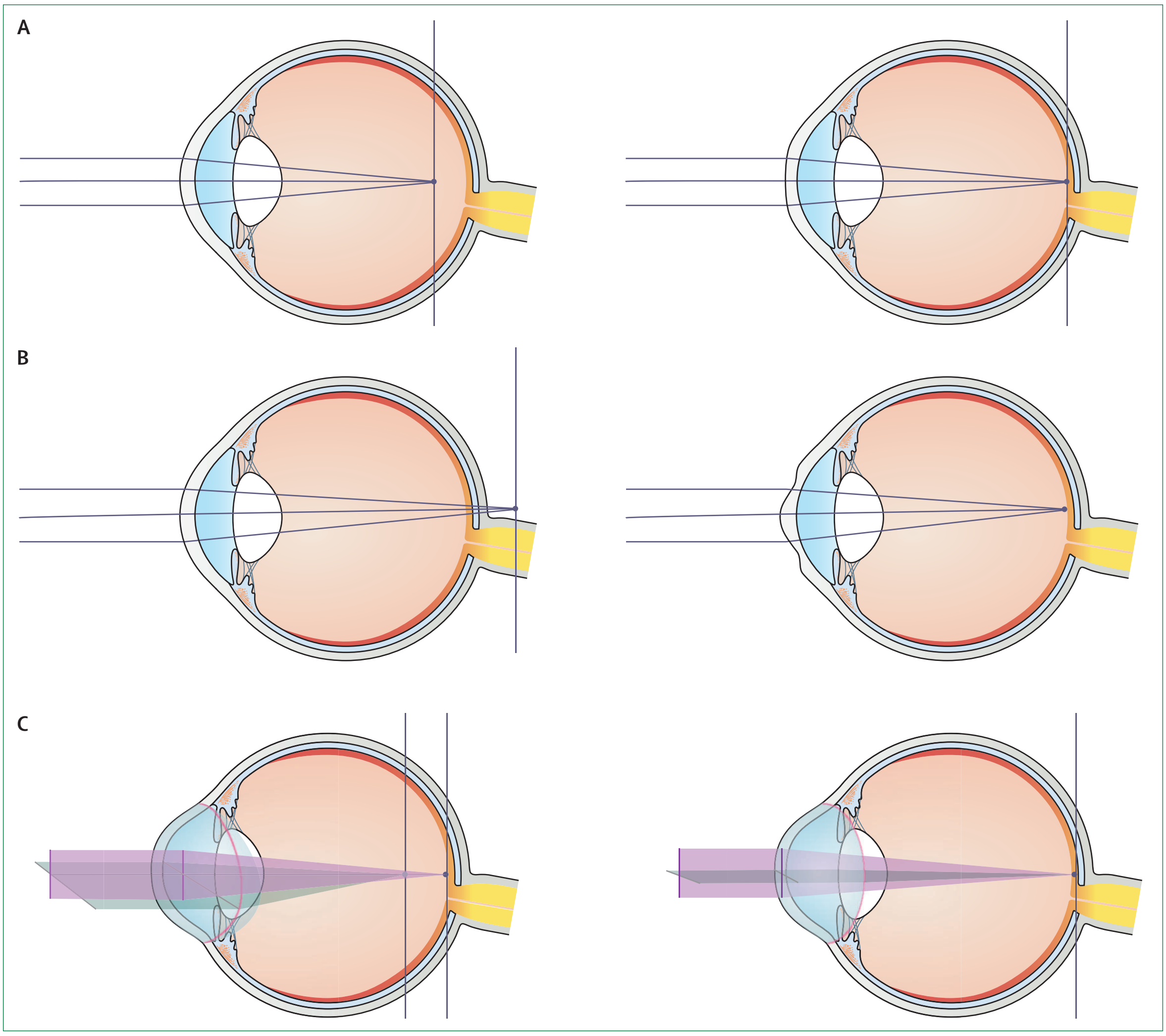

Figure 1: **Refractive errors before (left) and after (right) surgery**
(A) Refractive eye surgery corrects myopia using central ablation to flatten the corneal curvature (B) and corrects hyperopia using mid-peripheral ablation to steepen the corneal curvature. (C) Astigmatic correction restores an ellipsoid-shaped eye to its normal spherical shape by flattening a specific axis.

natural lens, and loss of the elasticity in the crystalline lens of the eye with age. This condition eventually leads to the inability to focus on near objects. A comprehensive glossary of terms has also been provided in the previous *Lancet* Review.[9]

Developments in laser refractive surgery

As the cornea is the most accessible part of the eye and provides two-thirds of the eye's refractive power, corneal surgery remains the mainstay of refractive correction. Specifically, laser refractive surgery is now widely recognised as safe and effective, yielding the most predictable results in patients with low-to-moderate amounts of refractive error.[10] A review[8] of almost 100 studies published since 2008 showed that up to 99·5% of patients who underwent laser refractive surgery met uncorrected distance visual acuity of better than 20/40 (considered spectacle independent), as many as 98·6% had refractive targets within ±1·0 dioptre, and almost 98·8% were satisfied with their outcome. Moreover, complications that could lead to visual loss, such as corneal ectasia or infection, are very rare with laser eye surgery.[11] In fact, the risk of infection after laser refractive surgery might be lower than the risk of corneal infections associated with extended contact lens use over time.[12] Corneal ablation techniques can potentially treat most refractive errors (including myopia, hyperopia, astigmatism, and presbyopia) within a given range by ablating corneal tissue into a specified shape, by use of an excimer laser.[13] Laser-assisted in-situ keratomileusis (LASIK) involves laser ablation with an excimer laser beneath a corneal flap (figure 2A). Surface ablation techniques, such as photorefractive keratectomy (PRK), involve removal of epithelium, followed by ablation of the Bowman's layer and the anterior corneal stromal tissue (figure 2B).[14] The speed and precision of laser platforms have improved substantially over the past decade, and the success of laser vision correction is highly dependent on the precision of these platforms.[15] Although LASIK corneal flaps were previously created with an oscillating microkeratome,[16] today most LASIK use a femtosecond laser rather than a blade to create the corneal flap (figure 2A). A meta-analysis[17] published in 2017 of 48 randomised trials showed that LASIK provides better predictability than other techniques. Technological improvements in the excimer laser used to ablate and reshape the cornea have also improved the accuracy of refractive treatment with customised treatments.[18] Moreover, corneal refractive surgery only using a femtosecond laser have also been developed, enabling the

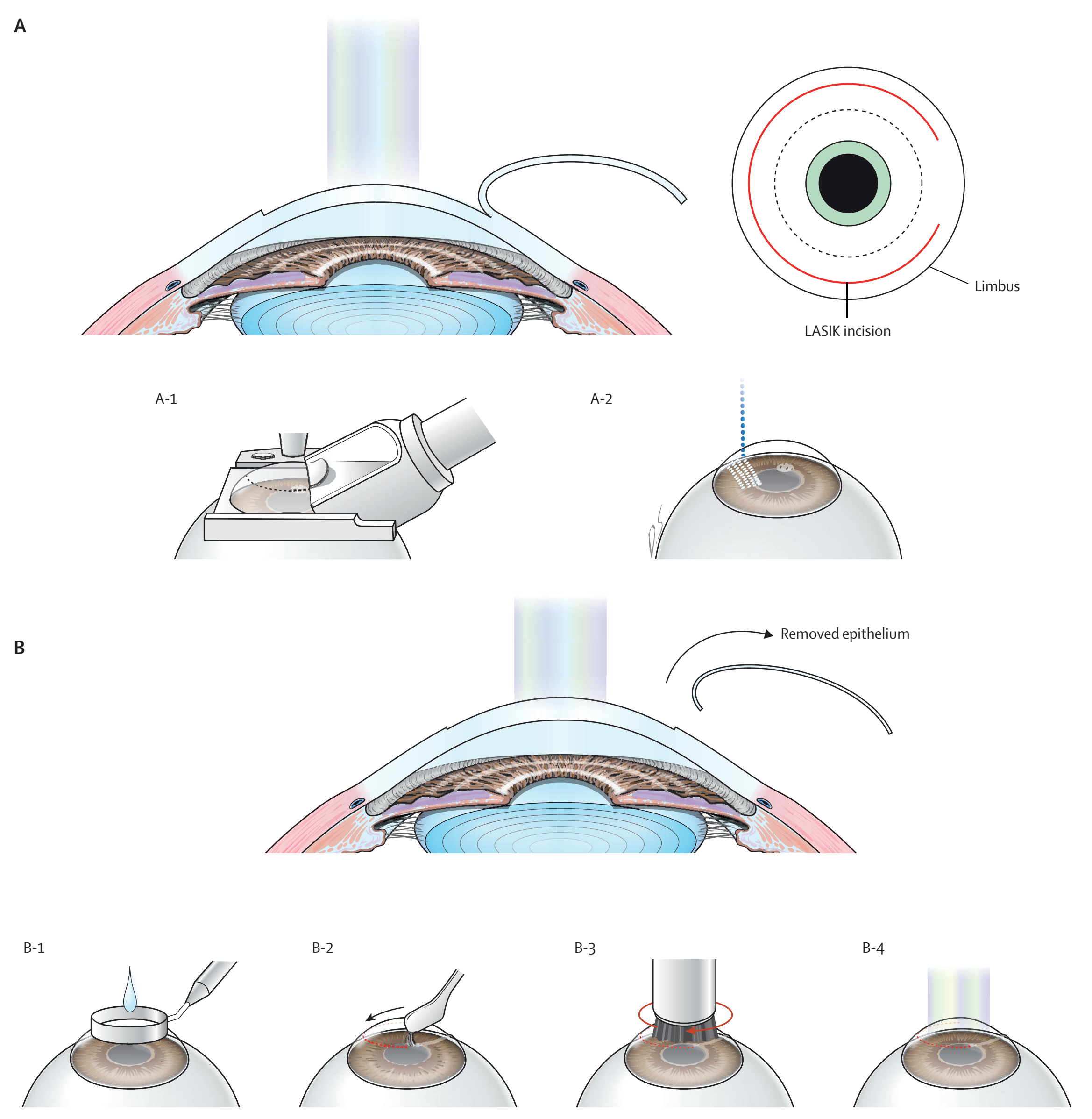

Figure 2: **Corneal refractive surgery involving laser ablation**
(A) With laser-assisted in-situ keratomileusis surgery, the corneal flap is created by cutting the corneal tissue, leaving a hinge area. (A-1) In traditional mechanical LASIK, a hand-guided, oscillating blade (known as a microkeratome) is used to create the corneal flap. (A-2) In femtosecond laser-assisted LASIK surgery, the femtosecond laser moves back and forth, emitting short, rapid bursts of laser light that create a series of minute bubbles at a predetermined depth. The mechanical or laser-created flap is then lifted, exposing the region of the cornea to be ablated. (B) With surface ablation, the epithelium is removed and the excimer laser is applied to the corneal surface. There are several methods of epithelium removal. (B-1) For laser epithelial keratomileusis surgery, the trephine is centred and pressed on to the corneal epithelium, and diluted alcohol is applied to loosen the epithelium. The thin flap of loosened epithelium is detached before an excimer laser reshapes the cornea to correct refractive errors. (B-2) With photorefractive keratectomy (PRK), a blunt blade is used to scrape the epithelium. (B-3) An Amoils brush can also be used to assist epithelium removal. (B-4) With transepithelial PRK, a laser profile of a PTK and laser treatment for refractive correction are performed in one step. LASIK=laser-assisted in situ keratomileusis. PRK=photorefractive keratectomy. PTK=phototherapeutic keratectomy.

shaping and surgical removal of the intracorneal lenticule to achieve the desired refractive correction.[19]

LASIK

See Online for video 1

LASIK is a commonly used laser corneal refractive surgery technique (video 1). Creation of the corneal flap facilitates early visual recovery, less discomfort, and reduced stromal inflammation, as well as a reduced risk of corneal haze induction.[20,21] Early postoperative patient satisfaction is high after LASIK, but candidates for this procedure need to be selected cautiously, with proper topographic assessment to reduce the risk of post-operative corneal ectasia and clinical examination for pre-existing dry eye. This procedure can induce a weakening of corneal biomechanical strength and worsen dry eye.[22] The introduction of the femtosecond laser for LASIK flap creation has reduced intra-operative, flap-related complications.[23] This improvement results from customising the flap edge by minimally distorting the cornea during cutting to produce a more regular flap cut.[24] Use of the femtosecond laser for LASIK flap creation could also improve surgical outcomes, reduce complications, and yield better biomechanical stability.[25] Additionally, LASIK provides faster visual recovery, and is less painful than surface ablation. Furthermore, long-term visual results associated with LASIK are generally excellent, with similar outcomes to surface ablation.[26]

Surface ablation laser surgery

Surface ablation has become more popular over the past few years because of the improved safety of this surgery, especially in patients with high myopia and thin corneas.[27] Surface ablation uses an excimer laser to expose and remove the corneal stroma after removing the corneal epithelium. Following this, the epithelium is allowed to regenerate on top of the ablated corneal bed through wound healing.[18] Unlike LASIK, surface ablation does not create a flap (that could be susceptible to damage), and potentially results in a biomechanically stronger cornea as a result of the relatively thicker post-procedural stromal bed.[28] However, this procedure also ablates the Bowman's layer, and the keratocyte-rich anterior corneal stroma, causing a wound healing process that can affect the refractive correction, induce scarring, and cause permanent haze formation.[29] Regeneration of the epithelium and ocular surface healing takes time, during which patients might experience pain and visual fluctuations.[30] Surface ablation techniques include PRK, in which the corneal epithelium is mechanically scraped off,[31] and laser epithelial keratomileusis, in which 20% alcohol is applied to displace the corneal epithelium.[32] Preservation of the detached epithelial sheet was previously thought to reduce pain and the inflammatory response. However, exposure to high concentrations of alcohol might affect the viability of the detached epithelial sheet.[33] The corneal epithelium can also be mechanically removed by a motorised brush,[34] or removed directly by excimer laser ablation, such as transepithelial PRK.[35] The advantage of transepithelial PRK is that the epithelial layer removal and cornea reshaping is done at the same time as the excimer laser ablation, but might need to be adjusted for the corneal epithelial thickness. In general, ocular discomfort, epithelial recovery time, and visual results do not vary greatly among these different epithelial removal techniques.[17,36] The application of low-dose topical mitomycin-C (ranging from 0·02% to 0·04%) has been shown to be beneficial in reducing subepithelial fibrosis.[37,38] Although the long-term predictability of surface ablation is similar to LASIK, myopic regression, and corneal haze can be more common after surface ablation.[39]

Wavefront-guided excimer laser surgery

Despite possible side effects and rare complications, both LASIK and surface ablation techniques produce excellent visual outcomes for correcting most low-to-moderate levels of refractive error, including myopia, hyperopia, and astigmatism, which are considered so-called lower-order aberrations.[10,11] However, visual symptoms such as halos, glare, and starbursts are sometimes reported despite good refractive results and are caused by so-called higher-order aberrations.[40–42] It is also possible to reduce these visual symptoms by use of wavefront technology. Advances in technologies to reduce these aberrations include wavefront-optimised treatments that preserve the original spherical aberration of the cornea[43,44] and customised wavefront-guided treatments,[45] which are designed to minimise surgically induced higher-order aberrations, or compensate for pre-existing higher-order aberrations in the treated eye.[46–48] However, optimised ablations could still increase higher-order aberrations and wavefront-guided treatments might not eliminate residual higher-order aberrations.[43,49] Both treatments induce minimal spherical aberration but have variable effects on other higher-order aberrations.[49,50] Further customisation of treatments could be achieved with corneal topography-guided laser ablation.[51] This procedure is most useful when the refractive error of the patient's eye matches their corneal topography. For example, most of the aberration is produced by the cornea.[52] Currently, excimer lasers with active eye tracking systems to compensate for cyclotorsion and micro-saccadic eye movements, are already considered common standards of care for such treatments.[53]

Presbyopic laser correction

Presbyopia is the gradual loss of the ability of the eye to focus on near objects as a person ages because of thickening and loss of flexibility of the crystalline lens, which is required for adapting to changes in the desired focal distance. A possible refractive strategy in carefully selected patients to overcome presbyopia is monovision, in which one eye is focused for distance, while the non-dominant eye is focused for near vision.[54] However, monovision requires a substantial period of adaptation,

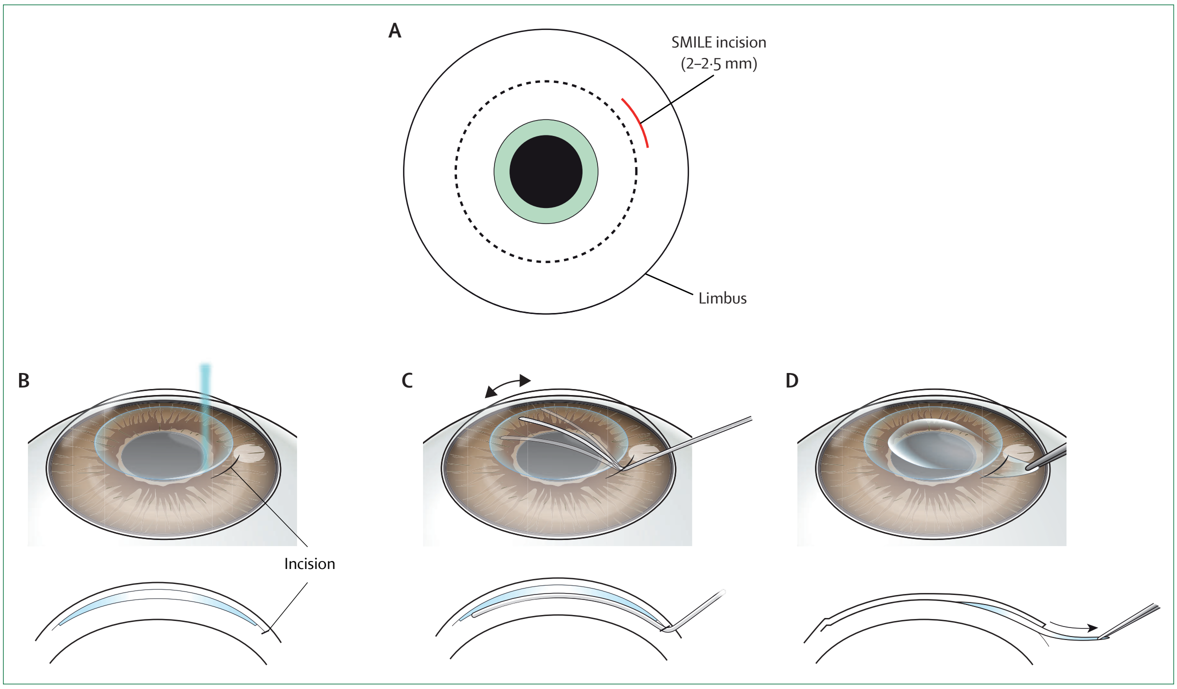

Figure 3: **Small incision lenticule extraction (SMILE)**
SMILE removes the same tissue that is eliminated by excimer laser ablation by creating an intracorneal lenticule that is extracted through a smaller corneal incision and without creating a flap. (A) With SMILE, a 2·0–2·5-mm incision is generated using a femtosecond laser for lenticule extraction. (B) This laser creates the intrastromal lenticule within the cornea and a small incision at the side. (C) A round-tip spatula is inserted through the incision to dissect the disc-shaped lenticule beneath the cap without touching the corneal surface. (D) The dissected lenticule is pulled out through the incision. SMILE=small-incision lenticule extraction.

and could lead to a reduction in stereopsis.[54] Conversely, presbyopic laser correction attempts to overcome these age-related changes by creating a multifocal, or monofocal, cornea in both eyes. Corneal multifocality can be generated with a hyper-positive central or mid-peripheral corneal zone for near vision.[55–57] A combination of inducing a spherical aberration to enhance the depth of field and micro-monovision has also been tried with so-called laser-blended vision.[58,59] It is important to counsel patients that presbyopic laser correction replaces the dynamic process of accommodation with a static modification of the corneal surface; therefore, this treatment cannot provide clear vision at all distances. Early outcomes have shown that this procedure is associated with a relatively high rate of patient satisfaction (76% to 78%) and a high degree of spectacle independence (72% to 93%).[60–62] However, issues with long-term stability, loss of distance vision, and a limited compensation for the progressive nature of presbyopia, limit the adoption of this treatment.[56,63]

Refractive lenticule extraction

After the introduction of the femtosecond laser for corneal refractive surgery,[64] refractive lenticule extraction was introduced as a novel form of so-called flapless laser eye surgery. Instead of corneal ablation, a lenticule of the desired correction is shaped within the cornea and extracted through a much smaller corneal incision (figure 3A).[19,65] Surgical techniques have evolved, from femtosecond lenticule extraction, pseudo small-incision lenticule extraction, and now to the most commonly done, small-incision lenticule extraction (SMILE), which has been approved by the FDA for the treatment of myopia and astigmatism (video 2; figure 3B–D).[19]

See Online for video 2

The potential advantages of SMILE over LASIK include less iatrogenic dry eye,[66–68] lower laser energy requirements,[69] fewer induced higher-order aberrations,[70] reduced corneal inflammation and keratocyte damage,[71,72] and lower suction intraocular pressure during the femtosecond laser procedure.[73] However, most studies report a slower recovery of visual acuity after SMILE when compared with LASIK.[74] Nonetheless, most published results suggest that SMILE is relatively safe, effective, and yields predictable outcomes for treating patients with moderate (<–5·0 dioptres) myopia and modest (<–2·0 dioptres) amounts of astigmatism,[75] with postoperative visual outcomes similar to femtosecond LASIK.[76] Perhaps more importantly, patient-reported experience, postoperative symptoms, and vision-related quality of life have been found to be similar between SMILE and LASIK.[77–79]

However, SMILE surgery is technically more challenging than LASIK because it involves manual lamellar dissection within the cornea, followed by smooth lenticule extraction (figure 3B). As such, there is a steeper surgeon learning curve, which could lead

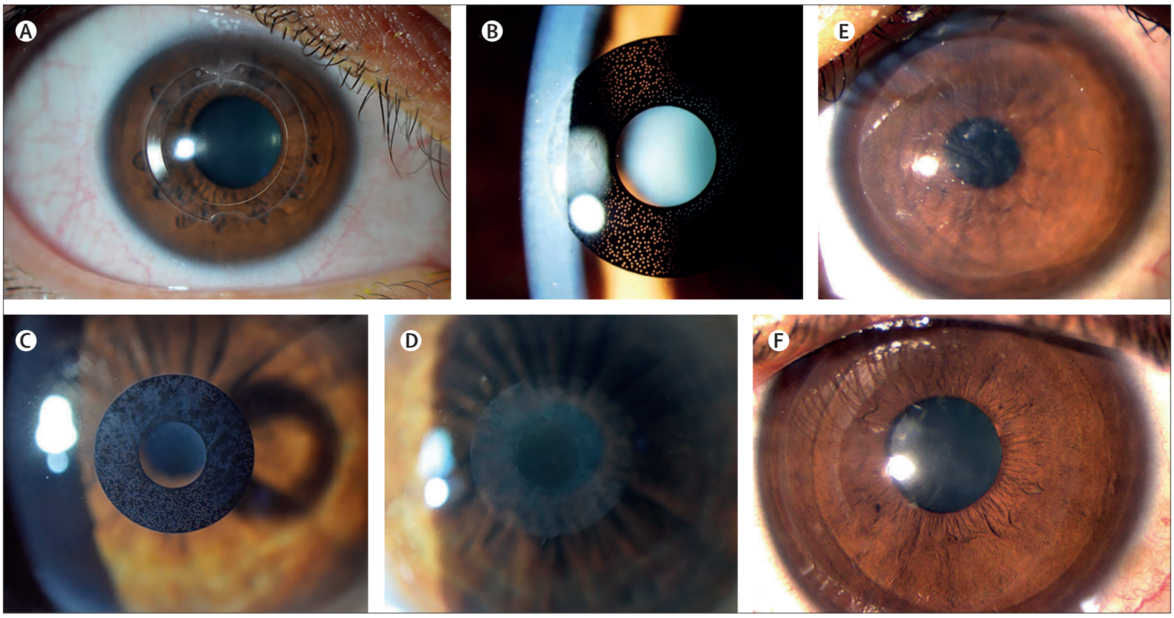

Figure 4: **Examples of intracorneal implants for refractive correction**
(A) Intracorneal ring implanted in a patient with keratoconus; Kamra inlay (B–D). (B) The peripheral microperforations allow corneal nutrition in slit lamp picture 3 months postoperatively, (C) and the progressive moderate haze associated with visual loss 4 years after implantation. (D) The inlay was removed due to a progressive induced corneal haze associated with visual loss, remaining a doughnut-shaped central corneal scar; corneal stroma enhancement with a decellularised corneal stroma lenticule in a patient with advanced keratoconus. (E) Slit lamp pictures 1 week (F) and 3 months after surgery (note the complete transparency recovery).

to unsuccessful lenticule removal, retention of corneal lenticule fragments, iatrogenic stromal scarring, and interface irregularities—all of which can lead to inferior visual outcomes.[80,81] This aspect of the procedure could explain why results produced from early reports of SMILE are highly surgeon-dependent and were shown to vary widely.[82] For example, in one trial,[83] SMILE was reported to be inferior to topography-guided LASIK in terms of visual outcomes; results were also inferior to those from most other published studies.[84] Further nomogram adjustments, software enhancements with eye tracking, or cyclotorsion compensation might improve the outcomes of SMILE, with future developments for hyperopia treatments and optimisation of femtosecond laser energy to reduce aberrations.[82]

Complications of laser refractive surgery

Laser refractive corneal surgery is a common procedure with a low complication rate.[39] However, as it is an elective surgical procedure for improving the quality of life by restoring uncorrected visual acuity, any adverse events might substantially affect patient satisfaction. Unsatisfactory outcome is often reported by patients who experience an increased glare, halos, residual refractive error, irregular astigmatism, or corneal scarring.[85] Dry eye is one of the most common side-effects and is induced by decreased tear production due to corneal nerve damage and inflammation. Fortunately, dry eye is usually temporary and can be effectively treated with lubricating eye drops or other measures. However pre-existing dry eye can be further aggravated without proper management.[86] Therefore, accurate preoperative evaluation and adequate postoperative management are crucial. Flap-related complications include flap displacement, diffuse lamellar keratitis,[87] and epithelial ingrowth,[88] all of which can be treated with topical eyedrops or, in some rare cases, a flap re-lift to treat the complication. Rarely, the procedure can weaken the biomechanical strength of the cornea, leading to corneal ectasia.[89] Thus, SMILE has some advantages, including no corneal flap, and it can retain better corneal biomechanical stability.[80] Many studies have compared and reported the change in corneal biomechanical strength after intrastromal flapless procedures and flap lifting procedures.[90–92] However, the biomechanical effects varied widely across studies and individuals.[93] Nonetheless, preoperative evaluation of eyes at risk of ectasia is key to preventing this complication, while early intervention with collagen cross-linking, intracorneal implants, or even corneal transplantation, might be required in some patients with severe postoperative ectasia.[94]

Intracorneal implants for myopia or astigmatism

The concept of refractive correction is essentially opposite to laser ablation surgery, where the refractive shift is achieved in a controlled manner by additive procedures (the introduction of different types of corneal implants inside the corneal stroma) instead of ablative procedures (in which tissue is removed from the stroma).[95] This concept was first described in 1964 as keratophakia, where an allogenic lenticule was placed at the interface of a free corneal cap and the stromal bed to treat hyperopia.[96] Although use of keratophakia was abandoned because of the technical difficulty of this procedure and the unpredictability of refractive results it yields, this procedure led to the development of synthetic corneal implants, known as inlays. Early corneal inlays (made of polymethylmethacrylate [PMMA] or polysulfone) were associated with corneal thinning or melting, and implant extrusion due to disruption of nutrient flow into the surrounding corneal stroma.[97,98] This crucial limitation was partially overcome with the development of intracorneal ring segments, new synthetic inlays with perforated designs, and new hydrogel biomaterials permitting the exchange of nutrients, such as glucose and oxygen within the corneal stroma.[97,99,100]

Intracorneal rings were first implanted by Reynolds in 1978.[101] Intracorneal rings are made of inert and biocompatible synthetic materials that are implanted deep into the stroma to modify the corneal curvature. This insertion makes the corneal shape more regular and reduces the refractive error (figure 4A).[102] Despite the success and wide application of intracorneal ring segments for correcting refractive errors during the 1980s and early 1990s, they were eventually surmounted by the success of corneal excimer laser surgery. The absence of refractive and visual predictability, and the risk of reducing best-corrected vision, caused intracorneal ring segments to be largely abandoned as a refractive solution, but intracorneal ring segments still serve a function in reducing astigmatism in selected eyes with keratoconus.

Corneal inlays for presbyopia

There are three types of presbyopia corneal inlays.[103] First, corneal reshaping inlays, which reshape the anterior corneal curvature to produce a multifocal cornea (Raindrop, ReVision Optics, Lake Forest, CA, USA; no longer in business). Second, refractive inlays, which are a modification on the refractive index of the cornea using a bifocal optic (Flexivue, Presbia, Netherlands; Icolens, Neoptics, Hünenberg, Switzerland). Third, small aperture inlays, which improve the depth of focus (Kamra, Acufocus, Irvine, CA, USA). Presbyopia inlays are always implanted in the non-dominant eye, within a corneal pocket or under a stromal flap (the pocket is usually preferred because it might decrease the incidence of dry eye),[98] and they should be centred on the first Purkinje reflex (the patient's visual axis). The Raindrop implant was discontinued in January, 2018, owing to relative inferiority in unaided and best-corrected visual acuity, and the inlay induced late scarring due to device-stimulated wound healing response.[98,104–106] Thus, the Kamra remains virtually the only available presbyopia inlay. The Kamra has a central 1·6 mm aperture and 8400 microperforations (5–11 μm in diameter) in the peripheral opaque ring to allow nutritional flow through the cornea (figure 4B);[103,104,107] it improves near vision by blocking the peripheral unfocused rays of light.[104,107]

Vukich and colleagues[108] reported the largest Kamra series in a prospective, multicentre clinical trial in which this inlay was implanted in the non-dominant eye of 507 patients with emmetropic presbyopia (with a 3-year follow-up). The study reported an average 3·3-line improvement in unaided near visual acuity, 1·0-line improvement in UIVA, and 0·4-line reduction in UDVA on the implanted eye, while no loss in binocular distance vision was observed. 8·7% of eyes required inlay removal, with dissatisfaction with the visual outcome reported to be the most common reason for removal. Other reported complications included glare, halos, night vision problems, and inlay-related central corneal haze (figure 4C).[109–111] An almost complete restoration of the visual function was reported in 6 (60%) out of 10 patients who had undergone explantation, although 8 (80%) of 10 patients reported the occurrence of mild haze, and occasionally more prominent scarring (figure 4D).[112] Despite more than a decade of studying intracorneal inlays as an effective option for presbyopia management, they have still not gained full popularity among refractive surgeons. This lack of popularity is due to the frequent problems of centration, biological intolerance, and optical performance, which could lead to a relatively high explantation rate over time, secondary to late complications, such as corneal stromal opacities, late hyperopic shift, or inadequate visual performance.

Intraocular implants for refractive correction

The potential advantages of intraocular refractive procedures include faster visual recovery, with a more stable postoperative refractive outcome, better visual quality, a wider range of refractive corrections, and a broader range of treatable ametropia. Intraocular refractive procedures are usually done in patients who have contraindications to traditional laser refractive surgery, or who have refractive errors that are unsuccessfully treated by traditional laser refractive surgery, such as extremely high myopia or hyperopia.[113] There are two types of intraocular refractive procedures: phakic intraocular lens implantation (figure 5A, B) and refractive lens exchange—ie, clear lens extraction with posterior chamber intraocular lens implantation (figure 5C, D).

Phakic intraocular lens implantation

Phakic intraocular lens implantation involves placing an intraocular lens inside the eye to augment the function of the crystalline lens, without any manipulation of the lens itself. This procedure can be a safe and effective technique to correct high degrees of refractive error, especially high myopia, in which other refractive surgery techniques are deemed unsafe.[115]

The main advantage of phakic intraocular lens implants is that the crystalline lens is retained, which can provide better visual outcomes, retaining natural accommodation in younger patients, and have fewer posterior segment complications, such as retinal detachment.[113] However, careful patient selection is required for phakic intraocular lens implantation because other complications, such as glaucoma, cataract formation, and inflammation, can occur.[114]

Phakic lenses can be either placed in the anterior or in the posterior chamber, and might require placement of a peripheral iridotomy to avoid the risk of pupillary block leading to raised intraocular pressure and angle closure glaucoma. Phakic intraocular lens implants can generally be placed in the posterior chamber or the anterior chamber of the eye (figure 5).

Posterior chamber phakic intraocular lenses are injected into the eye through a 3 mm corneo-limbal incision, placed in between the iris and the crystalline lens with the haptic zone resting in the ciliary sulcus (figure 5A). The lens remains vaulted to prevent it from resting against the crystalline lens. Implantable collamer lenses (STAAR Surgical, Monrovia, CA, USA) are FDA approved and are the most popular phakic intraocular lens worldwide because of the ease of implantation and safety profile.[116] Implantable collamer lenses can correct up to 18 dioptres of myopia and 6 dioptres of astigmatism. The latest model of implantable collamer lenses, called V4c (not FDA approved), incorporates a tiny hole in the middle of the lens to prevent aqueous flow blockage, meaning peripheral iridotomy is no longer required.[116] A large, multicentre, observational study[116] of implantable collamer lenses with a 1-year follow-up showed high efficacy, with 62 (97%) of 64 patients achieving uncorrected distance vision of 20/20. Furthermore, 60 (94%) of 64 patients were within the target refraction with excellent safety profile: only two lenses had to be exchanged because of inadequate sizing, and mild glare was reported in only 1 (3·1%) out of 64 eyes.[117] Although older posterior chamber phakic lenses were associated with a low risk of cataract development,[116] newer implantable collamer lens models are not associated with requirement for secondary cataract surgery.[118] New posterior chamber phakic intraocular lens models (none of them FDA approved) have now reached the market, such us intraocular posterior chamber lenses (Care Group, Gujarat, India) and eyecryl phakic intraocular lenses (Biotech Vision Care, Ahmedabad, India). Both of these lenses are hydrophilic acrylic intraocular lenses that offer a broader dioptre range than implantable collamer lenses. However, the efficacy and safety of these lenses have not been proven, and there is insufficient evidence to support their use.[119]

Since angle-supported lenses (a form of lens where the haptics sit in the angle, between the cornea and iris) were discontinued and their use abandoned because of excessive endothelial cell loss and other complications, such as glaucoma.[120] Iris-fixated lenses (a form of lens that is clipped to the iris) are the only anterior chamber phakic intraocular lenses currently available (figure 5B).[120] Foldable iris claw lenses (Artiflex, Ophtec, Groningen, Netherlands), can correct up to 14·5 dioptres of myopia, and can be implanted through a 3 mm corneo-limbal incision. Non-foldable iris claw lenses (Artisan, Ophtec, Groningen, Netherlands) require a larger 5·5 mm incision, but they can correct up to 23·5 dioptres of myopia and 7·5 dioptres of astigmatism.[121] For the fixation of both iris claw lenses, the iris is enclosed between the claw haptics of the intraocular lens, allowing the lens to remain in position without the use of sutures. Long-term data have demonstrated the efficacy, stability, and predictability of these lenses.[122] Although these lenses have a low risk for cataract formation, the risk for endothelial cell loss has been reported.[123] However, if the

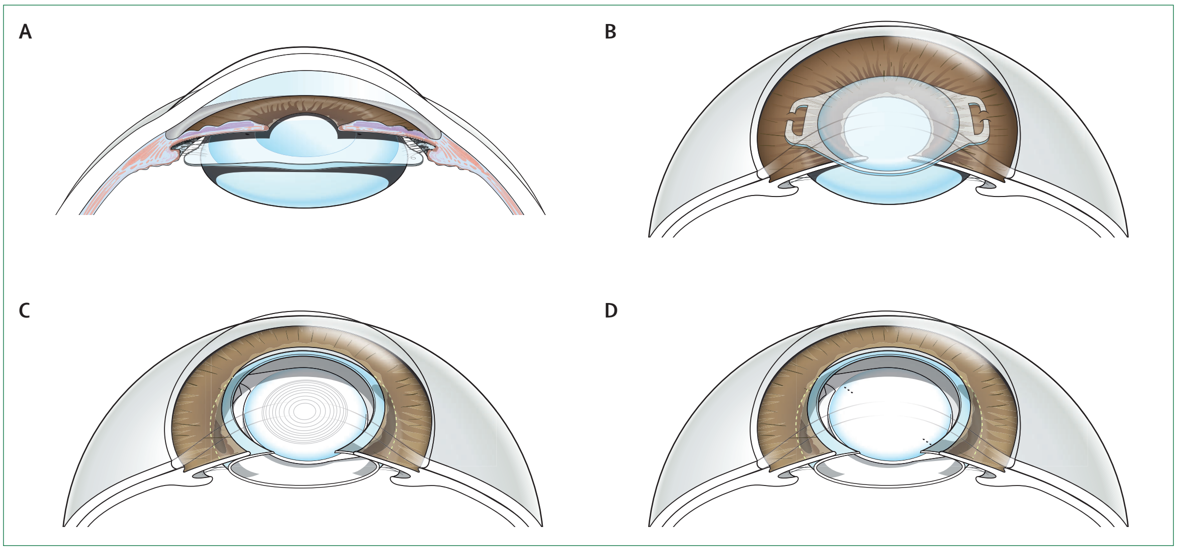

Figure 5: **Correction of refractive errors with intraocular lens implantation**
(A) Posterior chamber lens is implanted to correct refractive errors in phakic condition. (B) Also, iris claw lens is fixated to the iris in phakic condition. (C) After crystalline lens extraction, multifocal IOL is implanted inside capsular bag to provide refractive correction with bilocality or trilocality. (D) A toric IOL can correct astigmatism when it is inserted in capsular bag and aligned with predetermined an axis. IOL=intraocular lens.

	Brief description of method	Most common refractive errors treated	Surgical technique	Advantages	Disadvantages
Surface ablation (including PRK, LASEK)	Surface ablation of corneal tissue after removal of the epithelium	Myopia, hyperopia, astigmatism	Laser removes tissue by multiple-pulse photoablation to change the shape of the cornea then epithelial healing follows in a few days	Technically easy to perform, flapless, and a good option for thinner corneas to reduce risk of ectasia	Less patient comfort during recovery, longer visual recovery, prolonged tissue remodelling, risk of corneal haze or opacity
LASIK	Creating corneal flap and corneal ablation of the tissue underneath the flap, with repositioning of the flap to end the procedure	Myopia, hyperopia, astigmatism, presbyopia	Flap made by a femtosecond laser or a handheld device then flap placed back on top of laser photoablated corneal stroma	Fast recovery with minimal tissue reaction and minimal discomfort	Possible flap-related complications, corneal related complications (such as infection, scarring, and ecatasia) are rare
SMILE	Femtosecond laser cut and extraction of refractive lenticule through a small incision	Myopia, astigmatism (hyperopia under evaluation)	Femtosecond laser creates a lenticule within the cornea. Lamellar dissection and removal of the lenticule through a 2·2 mm corneal incision	Less induced dry eye, flapless, preserved structure of front corneal tissue, minimal inflammation and discomfort	Could be more technically challenging, complications include incomplete lenticule extraction
Phakic lens implantation	Insertion of intraocular lens in the presence of the natural crystalline lens	Myopia, astigmatism	Implantation of intraocular lens between iris and crystalline lens or fixation of lens with iris enclaved	Intraocular surgery without involving corneal disruption, small wound, fast recovery	Risk of endophthalmitis, iatrogenic damage including cataract formation or elevation of intraocular pressure, loss of endothelial cells
Refractive lens exchange	Removal of crystalline lens and implantation of posterior chamber IOL	Myopia, hyperopia, astigmatism, presbyopia	Crystalline lens removal followed by replacement with an intraocular lens placed in the capsular bag with resultant refractive correction	Correction for high refractive error, effective for presbyopia correction	Risk of endophthalmitis, controversial for pure refractive correction, balanced against other risks (such as retinal detachment)

PRK=photorefractive keratectomy. LASEK=laser sub-epithelial keratomileusis. LASIK=laser-assisted in-situ keratomileusis. SMILE=small incision lenticule extraction. IOL=Intraocular lens.

***Table:* Summary of common refractive surgical options**

anatomical inclusion criteria for these lenses is strictly met, the extent of endothelial cell loss is similar to physiological loss, supported by long-term data.[124]

Another advantage of phakic intraocular lenses is that they are useful for the treatment of high degrees of hyperopia (up to 10 dioptres for implantable collamer lenses and 12 dioptres for Artisan lenses). However, careful selection of patients is required because hyperopic patients often have shallower anterior chamber depths and narrower angles, which can predispose these patients to a higher risk of complications. Although under investigation, no phakic intraocular lens has been proven to be safe and effective for the management of presbyopia. Nonetheless, effective and safe alternatives for the management of moderate and high ametropia are available but require close annual follow-up and could require phakic intraocular lens explantation if complications develop, or if cataracts develop naturally with age.[121]

Refractive lens exchange

Refractive lens exchange, also known as clear lens extraction, involves the removal of the crystalline lens before cataracts have developed, followed by insertion of an artificial lens into a capsular bag that either replaces, or augments, the refractive ability of the original crystalline lens.[125] This procedure can be done in selected patients in whom corneal laser surgery is not possible—for example, in patients with abnormal or thin corneas, or patients for whom corneal surgery cannot achieve the desired refractive outcome compared with implanting a posterior chamber intraocular lens.[126] Refractive lens exchange is controversial because the risks of intraocular lens surgery (0·2–4·5%), except the risk of posterior capsular opacification,[127,128] are higher than the risks associated with corneal refractive surgery (0·02–0·98%) from LASIK.[10,129] Furthermore, in refractive lens exchange, the side-effect of infection after intraocular surgery (ie, endophthalmitis) is more severe than with corneal infections.[130] Moreover, refractive lens exchange may have a higher risk of complications than conventional cataract surgery if the patients are younger or more highly myopic.[131] For example, because patients undergoing cataract surgery are generally older, the risk of retinal detachment is lower (0·99%),[132] compared with a person with high myopia (9·21% in people with myopia more than 6·0 dioptres) or a younger patient (3·64% in 40–54 years old).[132] Nonetheless, with the advances in surgical technology leading to better refractive outcomes, fast visual recovery, and fewer postoperative complications (about 0·02%–0·05% of patients report an infection),[133–135] the improved risk–benefit ratio of refractive lens exchange has led to this practice being done more commonly in carefully selected patients.[136] The major advantage of refractive lens exchange is that all forms of refractive error can be treated based on the design of the intraocular lens. For example, presbyopia can be treated using multifocal intraocular lens implants (figure 5C) and myopia, hyperopia, and astigmatism can be treated using a monofocal lens, or monofocal toric posterior chamber intraocular lens, after refractive lens exchange (figure 5D). In general, evidence supports the use of multifocal posterior chamber intraocular lens implants because they enable most patients to achieve good near and far vision,[137] whereas monofocal toric (astigmatism correcting) posterior chamber intraocular lens implants are able to achieve good distance vision, with a reduced need for spectacles.[138] In general, refractive lens exchange is usually only used in older patients with presbyopia, and for patients with high amounts of ametropia not amenable to other refractive surgical techniques. It is also important that the patients understand the risk–benefit ratio of achieving spectacle independence.[126]

Future developments in refractive surgery

The field of refractive surgery is rapidly evolving and cannot be comprehensively described in this Review. The latest advances include the improved efficacy of laser technologies, safer surgical implants, and the incorporation of imaging systems into surgical practices that have improved precision. Improvements in the application of the femtosecond laser could increase the efficacy of new forms of refractive lenticule extraction, create customised intracorneal stromal pockets for corneal implants, and even allow for customised capsulotomy for special posterior chamber intraocular lens implants during refractive lens exchange procedures.[139] Advances in preoperative and intraoperative optical coherence tomography imaging could also improve surgical planning and accuracy of incisions, or placement of implants.[140] Corneal collagen cross-linking involves the use of riboflavin, combined with a controlled protocol of ultraviolet light exposure, to form collagen bonds within the cornea. These collagen bonds can reduce the risk of corneal ectasia in eyes undergoing laser refractive surgery.[141–143] Customised treatments (for instance, the combining of corneal collagen cross-linking with laser ablation surgeries) can improve the safety profile in eyes with thinner corneas in the future.[144] The advent of SMILE has also enabled the corneal lenticule (which is removed during surgery) to be stored and used as an allogenic cornea inlay for the treatment of presbyopia,[145] hyperopia,[146,147] and corneal ectatic diseases, such as keratoconus (figure 4E).[148,149] These biological inlays can offer advantages over commercial synthetic inlays in regard to biocompatibility, while decellularisation of these lenticules potentially further increases risks of immunogenic rejection.[148,150,151–153] Indeed, preliminary clinical results in humans show excellent biocompatibility, safety, and long-term transparency maintenance of these implants in vivo (figure 4F).[145–149]

Conclusion

Refractive surgery, in the form of laser corneal procedures, is now established as a safe and effective treatment for refractive error. Moreover, refractive surgery is also associated with excellent visual outcomes, improvement in quality of life, and high patient satisfaction.[154] Rapid advances in technology and innovation have increased the range of refractive surgical options available to patients. The minimally invasive so-called flapless SMILE procedure is gradually establishing similar efficacy, predictability, and safety compared with current first line treatments of LASIK and laser surface ablation. Advances in imaging and preoperative assessments have allowed customised laser ablation to further improve not only visual acuity, but also better visual quality. Moreover, substantial improvements in the efficacy, speed, and safety profile of intraocular surgery has disrupted the traditional risk–benefit considerations associated with intraocular phakic implants and refractive lens exchange. With these emerging trends, it is important for ophthalmologists and physicians to be aware of the advantages and disadvantages of each refractive surgery weighed against optical corrective options (summarised in table), while emphasising the necessity for careful and appropriate patient selection.

Contributors

All authors contributed to the overall concept, literature search, analysis and interpretation of the literature, writing of the manuscript, and designing of tables and figures.

Declaration of interests

BC is a consultant for Carl-Zeiss, Thea, Alcon, Shire, Cutting Edge, SIfi, Physiol, Dompé, J&J Vision, and Santen; none of which directly related to the topics discussed inthis manuscript. TK is an advisory board member of HOYA Surgical Optics. MA, JL A B, and MW declare no competing interests.

Acknowledgments

We thank Medical Illustration & Design, a part of the Medical Research Support Services of Yonsei University College of Medicine, for all artistic support related to this work.

References

1 Lou L, Yao C, Jin Y, Perez V, Ye J. Global patterns in health burden of uncorrected refractive error. *Invest Ophthalmol Vis Sci* 2016; **57:** 6271–77.

2 Fricke TR, Holden BA, Wilson DA, et al. Global cost of correcting vision impairment from uncorrected refractive error. *Bull World Health Organ* 2012; **90:** 728–38.

3 Ferraz FH, Corrente JE, Opromolla P, Schellini SA. Influence of uncorrected refractive error and unmet refractive error on visual impairment in a Brazilian population. *BMC Ophthalmol* 2014; **14:** 84.

4 Naidoo KS, Leasher J, Bourne RR, et al. Global vision impairment and blindness due to uncorrected refractive error, 1990–2010. *Optom Vis Sci* 2016; **93:** 227–34.

5 Morgan IG, Ohno-Matsui K, Saw SM. Myopia. *Lancet* 2012; **379:** 1739–48.

6 Holden BA, Fricke TR, Wilson DA, et al. Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050. *Ophthalmol* 2016; **123:** 1036–42.

7 Sugar A, Hood CT, Mian SI. Patient-reported outcomes following LASIK: quality of life in the PROWL studies. *JAMA* 2017; **317:** 204–05.

8 Sandoval HP, Donnenfeld ED, Kohnen T, et al. Modern laser in situ keratomileusis outcomes. *J Cataract Refract Surg* 2016; **42:** 1224–34.

9 Sakimoto T, Rosenblatt MI, Azar DT. Laser eye surgery for refractive errors. *Lancet* 2006; **367:** 1432–47.

10 Sugar A, Rapuano CJ, Culbertson WW, et al. Laser in situ keratomileusis for myopia and astigmatism: safety and efficacy: a report by the American Academy of Ophthalmology. *Ophthalmol* 2002; **109:** 175–87.

11 Varley GA, Huang D, Rapuano CJ, et al. LASIK for hyperopia, hyperopic astigmatism, and mixed astigmatism: a report by the American Academy of Ophthalmology. *Ophthalmol* 2004; **111:** 1604–17.

12 Masters J, Kocak M, Waite A. Risk for microbial keratitis: comparative metaanalysis of contact lens wearers and post-laser in situ keratomileusis patients. *J Cataract Refract Surg* 2017; **43:** 67–73.

13 Kanellopoulos AJ, Pallikaris IG, Donnenfeld ED, Detorakis S, Koufala K, Perry HD. Comparison of corneal sensation following photorefractive keratectomy and laser in situ keratomileusis. *J Cataract Refract Surg* 1997; **23:** 34–38.

14 Amm M, Wetzel W, Winter M, Uthoff D, Duncker GI. Histopathological comparison of photorefractive keratectomy and laser in situ keratomileusis in rabbits. *J Refract Surg* 1996; **12:** 758–66.

15 Barsam A, Allan BD. Excimer laser refractive surgery versus phakic intraocular lenses for the correction of moderate to high myopia. *Cochrane Database Syst Rev* 2014; **6:** CD007679.

16 Shemesh G, Dotan G, Lipshitz I. Predictability of corneal flap thickness in laser in situ keratomileusis using three different microkeratomes. *J Refract Surg* 2002; **18**: S347–51.

17 Wen D, McAlinden C, Flitcroft I, et al. Postoperative efficacy, predictability, safety, and visual quality of laser corneal refractive surgery: a network meta-analysis. *Am J Ophthalmol* 2017; **178:** 65–78.

18 Munnerlyn CR, Koons SJ, Marshall J. Photorefractive keratectomy: a technique for laser refractive surgery. *J Cataract Refract Surg* 1988; **14:** 46–52.

19 Ang M, Mehta JS, Chan C, Htoon HM, Koh JC, Tan DT. Refractive lenticule extraction: transition and comparison of 3 surgical techniques. *J Cataract Refract Surg* 2014; **40:** 1415–24.

20 Hersh PS, Brint SF, Maloney RK, et al. Photorefractive keratectomy versus laser in situ keratomileusis for moderate to high myopia. A randomized prospective study. *Ophthalmol* 1998; **105:** 1512–22.

21 Pallikaris IG, Siganos DS. Excimer laser in situ keratomileusis and photorefractive keratectomy for correction of high myopia. *J Refract Corneal Surg* 1994; **10:** 498–510.

22 Chan C, Ang M, Saad A, et al. Validation of an objective scoring system for forme fruste keratoconus detection and post-LASIK ectasia risk assessment in Asian eyes. *Cornea* 2015; **34:** 996–1004.

23 Stonecipher K, Ignacio TS, Stonecipher M. Advances in refractive surgery: microkeratome and femtosecond laser flap creation in relation to safety, efficacy, predictability, and biomechanical stability. *Curr Opin Ophthalmol* 2006; **17:** 368–72.

24 Ahn H, Kim JK, Kim CK, et al. Comparison of laser in situ keratomileusis flaps created by 3 femtosecond lasers and a microkeratome. *J Cataract Refract Surg* 2011; **37:** 349–57.

25 Hashmani S, Hashmani N, Rajani H, et al. Comparison of visual acuity, refractive outcomes, and satisfaction between LASIK performed with a microkeratome and a femto laser. *Clin Ophthalmol* 2017; **11:** 1009–14.

26 Kuryan J, Cheema A, Chuck RS. Laser-assisted subepithelial keratectomy (LASEK) versus laser-assisted in-situ keratomileusis (LASIK) for correcting myopia. *Cochrane Database Syst Rev* 2017; **2:** CD011080.

27 Vestergaard AH. Past and present of corneal refractive surgery: a retrospective study of long-term results after photorefractive keratectomy and a prospective study of refractive lenticule extraction. *Acta ophthalmol* 2014; **92:** 1–21.

28 Sanchez P, Moutsouris K, Pandolfi A. Biomechanical and optical behavior of human corneas before and after photorefractive keratectomy. *J Cataract Refract Surg* 2014; **40:** 905–17.

29 Wachtlin J, Langenbeck K, Schrunder S, Zhang EP, Hoffmann F. Immunohistology of corneal wound healing after photorefractive keratectomy and laser in situ keratomileusis. *J Refract Surg* 1999; **15:** 451–58.

30 Faktorovich EG, Melwani K. Efficacy and safety of pain relief medications after photorefractive keratectomy: review of prospective randomized trials. *J Cataract Refract Surg* 2014; **40:** 1716–30.

31 McDonald MB, Kaufman HE, Frantz JM, Shofner S, Salmeron B, Klyce SD. Excimer laser ablation in a human eye. Case report. *Arch Ophthalmol* 1989; **107:** 641–42.

32 Azar DT, Ang RT, Lee JB, et al. Laser subepithelial keratomileusis: electron microscopy and visual outcomes of flap photorefractive keratectomy. *Curr Opin Ophthalmol* 2001; **12:** 323–28.

33 Chen CC, Chang JH, Lee JB, Javier J, Azar DT. Human corneal epithelial cell viability and morphology after dilute alcohol exposure. *Invest Ophthalmol Vis Sci* 2002; **43:** 2593–602.

34 Amoils SP. Photorefractive keratectomy using a scanning-slit laser, rotary epithelial brush, and chilled balanced salt solution. *J Cataract Refract Surg* 2000; **26:** 1596–604.

35 Fadlallah A, Fahed D, Khalil K, et al. Transepithelial photorefractive keratectomy: clinical results. *J Cataract Refract Surg* 2011; **37:** 1852–57.

36 Antonios R, Abdul Fattah M, Arba Mosquera S, Abiad BH, Sleiman K, Awwad ST. Single-step transepithelial versus alcohol-assisted photorefractive keratectomy in the treatment of high myopia: a comparative evaluation over 12 months. *Br J Ophthalmol* 2017; **101:** 1106–12.

37 Kim TI, Pak JH, Lee SY, Tchah H. Mitomycin C-induced reduction of keratocytes and fibroblasts after photorefractive keratectomy. *Invest Ophthalmol Vis Sci* 2004; **45:** 2978–84.

38 Lee DH, Chung HS, Jeon YC, Boo SD, Yoon YD, Kim JG. Photorefractive keratectomy with intraoperative mitomycin-C application. *J Cataract Refract Surg* 2005; **31:** 2293–98.

39 Na KS, Chung SH, Kim JK, Jang EJ, Lee NR, Joo CK. Comparison of LASIK and surface ablation by using propensity score analysis: a multicenter study in Korea. *Invest Ophthalmol Vis Sci* 2012; **53:** 7116–21.

40 Buhren J, Pesudovs K, Martin T, Strenger A, Yoon G, Kohnen T. Comparison of optical quality metrics to predict subjective quality of vision after laser in situ keratomileusis. *J Cataract Refract Surg* 2009; **35:** 846–55.

41 Drum BA. Aberration analyses needed for FDA evaluation of safety and effectiveness of wavefront-guided refractive surgical devices. *J Refract Surg* 2003; **19:** S588–91.

42 Pesudovs K. Wavefront aberration outcomes of LASIK for high myopia and high hyperopia. *J Refract Surg* 2005; **21:** S508–12.

43 Myrowitz EH, Chuck RS. A comparison of wavefront-optimized and wavefront-guided ablations. *Curr Opin Ophthalmol* 2009; **20:** 247–50.

44 He L, Manche EE. Contralateral eye-to-eye comparison of wavefront-guided and wavefront-optimized photorefractive keratectomy: a randomized clinical trial. *JAMA Ophthalmol* 2015; **133:** 51–59.

45 MacRae S, Schwiegerling J, Snyder RW. Customized and low spherical aberration corneal ablation design. *J Refract Surg* 1999; **15:** S246–48.

46 Phusitphoykai N, Tungsiripat T, Siriboonkoom J, Vongthongsri A. Comparison of conventional versus wavefront-guided laser in situ keratomileusis in the same patient. *J Refract Surg* 2003; **19:** S217–20.

47 Schallhorn SC, Tanzer DJ, Kaupp SE, Brown M, Malady SE. Comparison of night driving performance after wavefront-guided and conventional LASIK for moderate myopia. *Ophthalmol* 2009; **116:** 702–09.

48 Kim TI, Yang SJ, Tchah H. Bilateral comparison of wavefront-guided versus conventional laser in situ keratomileusis with Bausch and Lomb Zyoptix. *J Refract Surg* 2004; **20:** 432–38.

49 Jun I, Kang DS, Tan J, et al. Comparison of clinical outcomes between wavefront-optimized versus corneal wavefront-guided transepithelial photorefractive keratectomy for myopic astigmatism. *J Cataract Refract Surg* 2017; **43:** 174–82.

50 Lee WS, Manche EE. Comparison of simulated keratometric changes following wavefront-guided and wavefront-optimized myopic laser-assisted in situ keratomileusis. *Clin Ophthalmol* 2018; **12:** 613–19.

51 Moshirfar M, Shah TJ, Skanchy DF, Linn SH, Kang P, Durrie DS. Comparison and analysis of FDA reported visual outcomes of the three latest platforms for LASIK: wavefront guided Visx iDesign, topography guided WaveLight Allegro Contoura, and topography guided Nidek EC-5000 CATz. *Clin Ophthalmol* 2017; **11:** 135–47.

52 Schallhorn SC, Farjo AA, Huang D, et al. Wavefront-guided LASIK for the correction of primary myopia and astigmatism a report by the American Academy of Ophthalmology. *Ophthalmology* 2008; **115:** 1249–61.

53 Smadja D, Reggiani-Mello G, Santhiago MR, Krueger RR. Wavefront ablation profiles in refractive surgery: description, results, and limitations. *J Refract Surg* 2012; **28:** 224–32.
54 Mahrous A, Ciralsky JB, Lai EC. Revisiting monovision for presbyopia. *Curr Opin Ophthalmol* 2018; **29:** 313–17.
55 Pinelli R, Ortiz D, Simonetto A, Bacchi C, Sala E, Alio JL. Correction of presbyopia in hyperopia with a center-distance, paracentral-near technique using the Technolas 217z platform. *J Refract Surg* 2008; **24:** 494–500.
56 Alio JL, Chaubard JJ, Caliz A, Sala E, Patel S. Correction of presbyopia by technovision central multifocal LASIK (presbyLASIK). *J Refract Surg* 2006; **22:** 453–60.
57 Uthoff D, Polzl M, Hepper D, Holland D. A new method of cornea modulation with excimer laser for simultaneous correction of presbyopia and ametropia. *Graefes Arch Clin Exp Ophthalmol* 2012; **250:** 1649–61.
58 Reinstein DZ, Archer TJ, Gobbe M. LASIK for Myopic Astigmatism and Presbyopia Using Non-Linear Aspheric Micro-Monovision with the Carl Zeiss Meditec MEL 80 Platform. *J Refract Surg* 2011; **27:** 23–37.
59 Reinstein DZ, Carp GI, Archer TJ, Gobbe M. LASIK for presbyopia correction in emmetropic patients using aspheric ablation profiles and a micro-monovision protocol with the Carl Zeiss Meditec MEL 80 and VisuMax. *J Refract Surg* 2012; **28:** 531–41.
60 Epstein RL, Gurgos MA. Presbyopia treatment by monocular peripheral presbyLASIK. *J Refract Surg* 2009; **25:** 516–23.
61 Ryan A, O'Keefe M. Corneal approach to hyperopic presbyopia treatment: six-month outcomes of a new multifocal excimer laser in situ keratomileusis procedure. *J Cataract Refract Surg* 2013; **39:** 1226–33.
62 Luger MH, Ewering T, Arba-Mosquera S. One-year experience in presbyopia correction with biaspheric multifocal central presbyopia laser in situ keratomileusis. *Cornea* 2013; **32:** 644–52.
63 Baudu P, Penin F, Arba Mosquera S. Uncorrected binocular performance after biaspheric ablation profile for presbyopic corneal treatment using AMARIS with the PresbyMAX module. *Am J Ophthalmol* 2013; **155:** 636–47.
64 Ang M, Mehta JS, Rosman M, et al. Visual outcomes comparison of 2 femtosecond laser platforms for laser in situ keratomileusis. *J Cataract Refract Surg* 2013; **39:** 1647–52.
65 Ang M, Tan D, Mehta JS. Small incision lenticule extraction (SMILE) versus laser in-situ keratomileusis (LASIK): study protocol for a randomized, non-inferiority trial. *Trials* 2012; **13:** 75.
66 Vestergaard AH, Grauslund J, Ivarsen AR, Hjortdal JO. Efficacy, safety, predictability, contrast sensitivity, and aberrations after femtosecond laser lenticule extraction. *J Cataract Refract Surg* 2014; **40:** 403–11.
67 Sekundo W, Gertnere J, Bertelmann T, Solomatin I. One-year refractive results, contrast sensitivity, high-order aberrations and complications after myopic small-incision lenticule extraction (ReLEx SMILE). *Graefes Arch Clin Exp Ophthalmol* 2014; **252:** 837–43.
68 Moshirfar M, McCaughey MV, Reinstein DZ, Shah R, Santiago-Caban L, Fenzl CR. Small-incision lenticule extraction. *J Cataract Refract Surg* 2015; **41:** 652–65.
69 Riau AK, Angunawela RI, Chaurasia SS, Lee WS, Tan DT, Mehta JS. Early corneal wound healing and inflammatory responses after refractive lenticule extraction (ReLEx). *Invest Ophthalmol Vis Sci* 2011; **52:** 6213–21.
70 Ganesh S, Gupta R. Comparison of visual and refractive outcomes following femtosecond laser- assisted lasik with smile in patients with myopia or myopic astigmatism. *J Refract Surg* 2014; **30:** 590–96.
71 Dong Z, Zhou X, Wu J, et al. Small incision lenticule extraction (SMILE) and femtosecond laser LASIK: comparison of corneal wound healing and inflammation. *Br J Ophthalmol* 2014; **98:** 263–69.
72 Liu YC, Teo EP, Lwin NC, Yam GH, Mehta JS. Early corneal wound healing and inflammatory responses after SMILE: comparison of the effects of different refractive corrections and surgical experiences. *J Refract Surg* 2016; **32:** 346–53.
73 Ang M, Chaurasia SS, Angunawela RI, et al. Femtosecond lenticule extraction (FLEx): clinical results, interface evaluation, and intraocular pressure variation. *Invest Ophthalmol Vis Sci* 2012; **53:** 1414–21.
74 Ji YW, Kim M, Kang DSY, et al. Lower laser energy levels lead to better visual recovery after small-incision lenticule extraction: prospective randomized clinical trial. *Am J Ophthalmol* 2017; **179:** 159–70.
75 Shen Z, Shi K, Yu Y, Yu X, Lin Y, Yao K. Small incision lenticule extraction (SMILE) versus femtosecond laser-assisted in situ keratomileusis (FS-LASIK) for myopia: a systematic review and meta-analysis. *PLoS One* 2016; **11:** e0158176.
76 Zhang Y, Shen Q, Jia Y, Zhou D, Zhou J. Clinical Outcomes of SMILE and FS-LASIK used to treat myopia: a meta-analysis. *J Refract Surg* 2016; **32:** 256–65.
77 Ang M, Ho H, Fenwick E, et al. Vision-related quality of life and visual outcomes after small-incision lenticule extraction and laser in situ keratomileusis. *J Cataract Refract Surg* 2015; **41:** 2136–44.
78 Ang M, Farook M, Htoon HM, Tan D, Mehta JS. Simulated night vision after small-incision lenticule extraction. *J Cataract Refract Surg* 2016; **42:** 1173–80.
79 Damgaard IB, Ang M, Farook M, Htoon HM, Mehta JS. Intraoperative patient experience and postoperative visual quality after SMILE and LASIK in a randomized, paired-eye, controlled study. *J Refract Surg* 2018; **34:** 92–99.
80 Krueger RR, Meister CS. A review of small incision lenticule extraction complications. *Curr opin ophthalmol* 2018; **29:** 292–98.
81 Titiyal JS, Kaur M, Rathi A, Falera R, Chaniyara M, Sharma N. Learning curve of small incision lenticule extraction: challenges and complications. *Cornea* 2017; **36:** 1377–82.
82 Damgaard IB, Ang M, Mahmoud AM, Farook M, Roberts CJ, Mehta JS. Functional optical zone and centration following SMILE and LASIK: a prospective, randomized, contralateral eye study. *J Refract Surg* 2019; **35:** 230–37.
83 Kanellopoulos AJ. Topography-guided LASIK versus small incision lenticule extraction (SMILE) for myopia and myopic astigmatism: a randomized, prospective, contralateral eye study. *J Refract Surg* 2017; **33:** 306–12.
84 Kanellopoulos AJ. Topography-Guided LASIK versus small incision lenticule extraction: long-term refractive and quality of vision outcomes. *Ophthalmol* 2018; **125:** 1658–59.
85 Zhao LQ, Wei RL, Cheng JW, Li Y, Cai JP, Ma XY. Meta-analysis: clinical outcomes of laser-assisted subepithelial keratectomy and photorefractive keratectomy in myopia. *Ophthalmol* 2010; **117:** 1912–22.
86 Wallerstein A, Jackson WB, Chambers J, Moezzi AM, Lin H, Simmons PA. Management of post-LASIK dry eye: a multicenter randomized comparison of a new multi-ingredient artificial tear to carboxymethylcellulose. *Clin Ophthalmol* 2018; **12:** 839–48.
87 Segev F, Mimouni M, Sela T, Munzer G, Kaiserman I. Risk factors for sporadic diffuse lamellar keratitis after microkeratome laser-assisted in situ keratomileusis: a retrospective large database analysis. *Cornea* 2018; **37:** 1124–29.
88 Yesilirmak N, Chhadva P, Cabot F, Galor A, Yoo SH. Post-laser in situ keratomileusis epithelial ingrowth: treatment, recurrence, and long-term results. *Cornea* 2018; **37:** 1517–21.
89 Bohac M, Koncarevic M, Pasalic A, et al. Incidence and clinical characteristics of post LASIK ectasia: a review of over 30 000 LASIK Cases. *Semin Ophthalmol* 2018; **33:** 869–77.
90 Francis M, Khamar P, Shetty R, et al. In vivo prediction of air-puff induced corneal deformation using LASIK, SMILE, and PRK finite element simulations. *Invest Ophthalmol Vis Sci* 2018; **59:** 5320–28.
91 Spiru B, Kling S, Hafezi F, Sekundo W. Biomechanical properties of human cornea tested by two-dimensional extensiometry ex vivo in fellow eyes: femtosecond laser-assisted LASIK versus SMILE. *J Refract Surg* 2018; **34:** 419–23.
92 Kanellopoulos AJ. Comparison of corneal biomechanics after myopic small-incision lenticule extraction compared to LASIK: an ex vivo study. *Clin Ophthalmol* 2018; **12:** 237–45.
93 Seven I, Vahdati A, Pedersen IB, et al. Contralateral eye comparison of SMILE and flap-based corneal refractive surgery: computational analysis of biomechanical impact. *J Refract Surg* 2017; **33:** 444–53.
94 Giri P, Azar DT. Risk profiles of ectasia after keratorefractive surgery. *Curr Opin Ophthalmol* 2017; **28:** 337–42.
95 Barraquer JI. Modification of refraction by means of intracorneal inclusions. *Int Ophthalmol Clin* 1966; **6:** 53–78.
96 Barraquer JI. Keratophakia. *Trans Ophthalmol Soc UK* 1972; **92:** 499–516.

97 Garza EB, Gomez S, Chayet A, Dishler J. One-year safety and efficacy results of a hydrogel inlay to improve near vision in patients with emmetropic presbyopia. *J Refract Surg* 2013; **29:** 166–72.
98 Malandrini A, Martone G, Menabuoni L, et al. Bifocal refractive corneal inlay implantation to improve near vision in emmetropic presbyopic patients. *J Cataract Refract Surg* 2015; **41:** 1962–72.
99 Yilmaz OF, Bayraktar S, Agca A, Yilmaz B, McDonald MB, van de Pol C. Intracorneal inlay for the surgical correction of presbyopia. *J Cataract Refract Surg* 2008; **34:** 1921–27.
100 Mulet ME, Alio JL, Knorz MC. Hydrogel intracorneal inlays for the correction of hyperopia: outcomes and complications after 5 years of follow-up. *Ophthalmol* 2009; **116:** 1455–60.
101 Burris TE. Intrastromal corneal ring technology: results and indications. *Curr Opin Ophthalmol* 1998; **9:** 9–14.
102 Vega-Estrada A, Alio JL. The use of intracorneal ring segments in keratoconus. *Eye Vis (Lond)* 2016; **3:** 8.
103 Lindstrom RL, Macrae SM, Pepose JS, Hoopes PC Sr. Corneal inlays for presbyopia correction. *Curr Opin Ophthalmol* 2013; **24:** 281–87.
104 Konstantopoulos A, Mehta JS. Surgical compensation of presbyopia with corneal inlays. *Expert Rev Med Devices* 2015; **12:** 341–52.
105 Limnopoulou AN, Bouzoukis DI, Kymionis GD, et al. Visual outcomes and safety of a refractive corneal inlay for presbyopia using femtosecond laser. *J Refract Surg* 2013; **29:** 12–18.
106 Baily C, Kohnen T, O'Keefe M. Preloaded refractive-addition corneal inlay to compensate for presbyopia implanted using a femtosecond laser: one-year visual outcomes and safety. *J Cataract Refract Surg* 2014; **40:** 1341–48.
107 Arlt E, Krall E, Moussa S, Grabner G, Dexl A. Implantable inlay devices for presbyopia: the evidence to date. *Clin Ophthalmol* 2015; **9:** 129–37.
108 Vukich JA, Durrie DS, Pepose JS, Thompson V, van de Pol C, Lin L. Evaluation of the small-aperture intracorneal inlay: three-year results from the cohort of the U.S. Food and Drug Administration clinical trial. *J Cataract Refract Surg* 2018; **44:** 541–56.
109 Seyeddain O, Hohensinn M, Riha W, et al. Small-aperture corneal inlay for the correction of presbyopia: 3-year follow-up. *J Cataract Refract Surg* 2012; **38:** 35–45.
110 Igras E, O'Caoimh R, O'Brien P, Power W. Long-term results of combined LASIK and monocular small-aperture corneal inlay implantation. *J Refract Surg* 2016; **32:** 379–84.
111 Huseynova T, Kanamori T, Waring GO 4th, Tomita M. Outcomes of small aperture corneal inlay implantation in patients with pseudophakia. *J Refract Surg* 2014; **30:** 110–16.
112 Alio JL, Abbouda A, Huseynli S, Knorz MC, Homs ME, Durrie DS. Removability of a small aperture intracorneal inlay for presbyopia correction. *J Refract Surg* 2013; **29:** 550–56.
113 Nanavaty MA, Daya SM. Refractive lens exchange versus phakic intraocular lenses. *Curr Opin Ophthalmol* 2012; **23:** 54–61.
114 Pop M, Payette Y. Refractive lens exchange versus iris-claw Artisan phakic intraocular lens for hyperopia. *J Refract Surg* 2004; **20:** 20–24.
115 Huang D, Schallhorn SC, Sugar A, et al. Phakic intraocular lens implantation for the correction of myopia: a report by the American Academy of Ophthalmology. *Ophthalmol* 2009; **116:** 2244–58.
116 Packer M. Meta-analysis and review: effectiveness, safety, and central port design of the intraocular collamer lens. *Clin Ophthalmol* 2016; **10:** 1059–77.
117 Kamiya K, Shimizu K, Igarashi A, et al. Posterior chamber phakic intraocular lens implantation: comparative, multicentre study in 351 eyes with low-to-moderate or high myopia. *Br J Ophthalmol* 2018; **102:** 177–81.
118 Alfonso JF, Lisa C, Fernandez-Vega L, Almanzar D, Perez-Vives C, Montes-Mico R. Prevalence of cataract after collagen copolymer phakic intraocular lens implantation for myopia, hyperopia, and astigmatism. *J Cataract Refract Surg* 2015; **41:** 800–05.
119 Yasa D, Urdem U, Agca A, et al. Early results with a new posterior chamber phakic intraocular lens in patients with high myopia. *J Ophthalmol* 2018; **2018**: 1329874.
120 Guell JL, Morral M, Kook D, Kohnen T. Phakic intraocular lenses part 1: historical overview, current models, selection criteria, and surgical techniques. *J Cataract Refract Surg* 2010; **36:** 1976–93.
121 Kohnen T, Kook D, Morral M, Guell JL. Phakic intraocular lenses: part 2: results and complications. *J Cataract Refract Surg* 2010; **36:** 2168–94.
122 Tahzib NG, Nuijts RM, Wu WY, Budo CJ. Long-term study of Artisan phakic intraocular lens implantation for the correction of moderate to high myopia: ten-year follow-up results. *Ophthalmology* 2007; **114:** 1133–42.
123 Jonker SMR, Berendschot T, Ronden AE, Saelens IEY, Bauer NJC, Nuijts R. Long-term endothelial cell loss in patients with artisan myopia and artisan toric phakic intraocular lenses: 5- and 10-year results. *Ophthalmol* 2018; **125:** 486–94.
124 Morral M, Guell JL, El Husseiny MA, Elies D, Gris O, Manero F. Paired-eye comparison of corneal endothelial cell counts after unilateral iris-claw phakic intraocular lens implantation. *J Cataract Refract Surg* 2016; **42:** 117–26.
125 Alio JL, Grzybowski A, El Aswad A, Romaniuk D. Refractive lens exchange. *Surv Ophthalmol* 2014; **59:** 579–98.
126 Alio JL, Grzybowski A, Romaniuk D. Refractive lens exchange in modern practice: when and when not to do it? *Eye Vis (Lond)* 2014; **1:** 10.
127 Hashemian H, Mirshahi R, Khodaparast M, Jabbarvand M. Post-cataract surgery endophthalmitis: brief literature review. *J Curr Ophthalmol* 2016; **28:** 101–05.
128 Schallhorn SC, Schallhorn JM, Pelouskova M, et al. Refractive lens exchange in younger and older presbyopes: comparison of complication rates, 3 months clinical and patient-reported outcomes. *Clin Ophthalmol* 2017; **11:** 1569–81.
129 Chua D, Htoon HM, Lim L, et al. Eighteen-year prospective audit of LASIK outcomes for myopia in 53 731 eyes. *Br J Ophthalmol* 2018; published online Oct 24. DOI:10.1136/bjophthalmol-2018-312587.
130 Liu YC, Wilkins M, Kim T, Malyugin B, Mehta JS. Cataracts. *Lancet* 2017; **390:** 600–12.
131 Westin O, Koskela T, Behndig A. Epidemiology and outcomes in refractive lens exchange surgery. *Acta Ophthalmol* 2015; **93:** 41–45.
132 Daien V, Le Pape A, Heve D, Carriere I, Villain M. Incidence, risk factors, and impact of age on retinal detachment after cataract surgery in France: a national population study. *Ophthalmol* 2015; **122:** 2179–85.
133 Creuzot-Garcher C, Benzenine E, Mariet AS, et al. Incidence of acute postoperative endophthalmitis after cataract surgery: a nationwide study in France from 2005 to 2014. *Ophthalmol* 2016; **123:** 1414–20.
134 Jabbarvand M, Hashemian H, Khodaparast M, Jouhari M, Tabatabaei A, Rezaei S. Endophthalmitis occurring after cataract surgery: outcomes of more than 480 000 cataract surgeries, epidemiologic features, and risk factors. *Ophthalmol* 2016; **123:** 295–301.
135 Behndig A, Montan P, Stenevi U, Kugelberg M, Lundstrom M. One million cataract surgeries: swedish national cataract register 1992-2009. *J Cataract Refract Surg* 2011; **37:** 1539–45.
136 Jaycock P, Johnston RL, Taylor H, et al. The Cataract National Dataset electronic multi-centre audit of 55 567 operations: updating benchmark standards of care in the United Kingdom and internationally. *Eye (Lond)* 2009; **23:** 38–49.
137 Rosen E, Alio JL, Dick HB, Dell S, Slade S. Efficacy and safety of multifocal intraocular lenses following cataract and refractive lens exchange: metaanalysis of peer-reviewed publications. *J Cataract Refract Surg* 2016; **42:** 310–28.
138 Kessel L, Andresen J, Tendal B, Erngaard D, Flesner P, Hjortdal J. Toric intraocular lenses in the correction of astigmatism during cataract surgery: a systematic review and meta-analysis. *Ophthalmol* 2016; **123:** 275–86.
139 Ewe SY, Abell RG, Vote BJ. Femtosecond laser-assisted versus phacoemulsification for cataract extraction and intraocular lens implantation: clinical outcomes review. *Curr Opin Ophthalmol* 2018; **29:** 54–60.
140 Ang M, Baskaran M, Werkmeister RM, et al. Anterior segment optical coherence tomography. *Prog Retin Eye Res* 2018; **66:** 132–56.
141 Kanellopoulos AJ, Asimellis G. Combined laser in situ keratomileusis and prophylactic high-fluence corneal collagen crosslinking for high myopia: two-year safety and efficacy. *J Cataract Refract Surg* 2015; **41:** 1426–33.
142 Tomita M, Yoshida Y, Yamamoto Y, Mita M, Waring GT. In vivo confocal laser microscopy of morphologic changes after simultaneous LASIK and accelerated collagen crosslinking for myopia: one-year results. *J Cataract Refract Surg* 2014; **40:** 981–90.

143 Cheema AS, Mozayan A, Channa P. Corneal collagen crosslinking in refractive surgery. *Curr Opin Ophthalmol* 2012; **23:** 251–56.
144 Elling M, Kersten-Gomez I, Dick HB. Photorefractive intrastromal corneal crosslinking for the treatment of myopic refractive errors: six-month interim findings. *J Cataract Refract Surg* 2017; **43:** 789–95.
145 Jacob S, Kumar DA, Agarwal A, Agarwal A, Aravind R, Saijimol AI. Preliminary evidence of successful near vision enhancement with a new technique: presbyopic allogenic refractive lenticule (PEARL) corneal inlay using a SMILE lenticule. *J Refract Surg* 2017; **33:** 224–29.
146 Li M, Li M, Sun L, Ni K, Zhou X. Predictive formula for refraction of autologous lenticule implantation for hyperopia correction. *J Refract Surg* 2017; **33:** 827–33.
147 Pradhan KR, Reinstein DZ, Carp GI, Archer TJ, Gobbe M, Gurung R. Femtosecond laser-assisted keyhole endokeratophakia: correction of hyperopia by implantation of an allogeneic lenticule obtained by SMILE from a myopic donor. *J Refract Surg* 2013; **29:** 777–82.
148 Alio Del Barrio JL, El Zarif M, Azaar A, et al. Corneal stroma enhancement with decellularized stromal laminas with or without stem cell recellularization for advanced keratoconus. *Am J Ophthalmol* 2018; **186:** 47–58.
149 Mastropasqua L, Nubile M, Salgari N, Mastropasqua R. Femtosecond laser-assisted stromal lenticule addition keratoplasty for the treatment of advanced keratoconus: a preliminary study. *J Refract Surg* 2018; **34:** 36–44.
150 Alio del Barrio JL, Chiesa M, Garagorri N, et al. Acellular human corneal matrix sheets seeded with human adipose-derived mesenchymal stem cells integrate functionally in an experimental animal model. *Exp Eye Res* 2015; **132:** 91–100.
151 Liu YC, Teo EPW, Ang HP, et al. Biological corneal inlay for presbyopia derived from small incision lenticule extraction (SMILE). *Sci Rep* 2018; **8:** 1831.
152 Liu R, Zhao J, Xu Y, et al. Femtosecond laser-assisted corneal small incision allogenic intrastromal lenticule implantation in monkeys: a pilot study. *Invest Ophthalmol Vis Sci* 2015; **56:** 3715–20.
153 Damgaard IB, Ivarsen A, Hjortdal J. Biological lenticule implantation for correction of hyperopia: an ex vivo study in human corneas. *J Refract Surg* 2018; **34:** 245–52.
154 Solomon KD, Fernandez de Castro LE, Sandoval HP, et al. LASIK world literature review: quality of life and patient satisfaction. *Ophthalmology* 2009; **116:** 691–701.