Surgical correction of refractive errors

A Brahma FRCOphth[1,2] C N J McGhee FRCS FRCOphth[1,3]

J R Soc Med 2000;**93**:118–123 SECTION OF OPHTHALMOLOGY, 11 FEBRUARY 1999

Refractive surgery refers to surgical or laser procedures performed on the eye to alter its refractive power and lessen dependence on spectacles and contact lenses.

The optical system of the eye is divided into a corneal portion and a lens portion: thus the eye is a compound optical system and the normal refracting power is approximately 64 dioptres (D). The human cornea is responsible for two-thirds of the eye's refracting power, about 43D; the remaining third is provided by the crystalline lens. The corneal and lens surfaces alter the direction of incident light rays to focus them on the retina.

In the normally sighted (emmetropic) eye, light rays from infinity are focused on the retina and this occurs when the optical system is in balance—that is, the dioptric power is equal to the length of the eye (Figure 1). Emmetropia is considered merely to be a point on the normal spectrum of refractive status which marks the transition from hyperopia (*long* sightedness) to myopia (*short* sightedness). It occurs when the length of the eyeball, the curvature of the cornea, and the power of the unaccommodated lens are all appropriate for focusing light on the retina.

In contrast, in ametropia objects are not sharply focused on the retina by an eye with relaxed accommodation. The eye is too long or short for its focusing power or too weak or strong for its length, thus the light rays cannot be brought to a sharp focus on the retina. This can be compounded by astigmatism, generally created by unequal curvature of the cornea, in which only some parts or none of the image might be focused on the retina. Myopia is corrected with a diverging (concave) lens and hyperopia with a converging (convex) lens.

Studies of ocular refraction indicate that emmetropia is not the normal refractive state; low hyperopia, of about +1.00D, is the peak in the normal distribution curve[1], and 2–3% of the population have high myopia (over −6.00D)[2].

To correct ametropia, spectacles have been used for centuries and contact lenses since the latter part of the nineteenth century. A more permanent treatment, to avoid the inconvenience of optical aids and to improve unaided vision, has been an aim of ophthalmologists and others for more than a century. Table 1 and Figure 2 indicate the variety of methods currently used to correct ametropia.

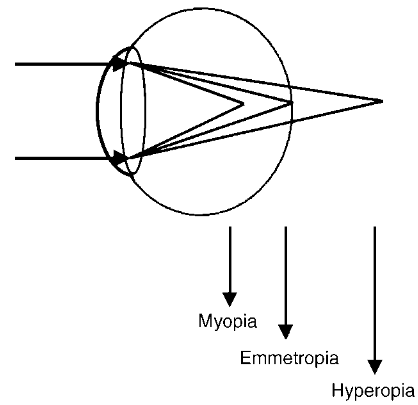

Figure 1 **Refractive error states of the eye**

Refractive errors can be corrected by surgery performed upon the two major refracting elements of the eye—the cornea and the lens. One of the most common operations performed in the UK is cataract extraction with intraocular lens (IOL) implantation and this is, in essence, a refractive surgery procedure, since it improves the optics and clarity of the refracting media. However, since the major component of the refractive power of the eye resides in the anterior surface of the cornea, alterations to the more accessible cornea will also lead to a change in the eye's refractive power.

SURGERY TO ALTER CORNEAL CURVATURE

Sato[3], in the 1930s, altered the curvature of the cornea by performing posterior radial keratotomies (RK)—incisions that cause the cornea to flatten by weakening the paracentral cornea, thus reducing its focusing power. Unfortunately, these multiple incisions on the endothelial (rear) surface of the cornea subsequently led to corneal decompensation. Not until the 1970s did anterior RK gain popularity following the work of Fyodorov and Durnev[4] in Russia. RK is a relatively low-cost procedure and does not require sophisticated technology; nonetheless, it has never gained widespread popularity in the UK. It continues to have a role in the correction of low to moderate myopia (up to −4.00D). In the Prospective Evaluation of Radial Keratotomy (PERK)[5] study, 53% of eyes achieved 'normal'

[1]Department of Ophthalmology, University of Dundee, Ninewells Hospital, Dundee DD1 9SY, Scotland, UK; [2]Manchester Royal Eye Hospital, Oxford Road, Manchester M13 9WH, UK; [3]Department of Ophthalmology, University of Auckland, New Zealand.

Correspondence to: Mr Arun Brahma, Royal Eye Hospital, Oxford Road, Manchester M13 9WH, UK

Table 1 **Refractive surgery procedures currently practised**

Site	***Procedure***	***Mechanism***
Cornea		
Myopia	Radial keratotomy	Paracentral weakening of the cornea
	Keratomileusis	Removal of central corneal stroma
	Epikeratophakia	Addition of diverging corneal tissue
	Excimer laser ablation	Removal of central corneal tissue
	Intrastromal implants	Intracorneal lens/ring
Hyperopia	Circular/hexagonal keratotomy	Central weakening of the cornea
	Keratomileusis	Weakening of the cornea and ectasia
	Epikeratophakia	Addition of central tissue
	Excimer laser ablation	Removal of mid-peripheral stroma with central steepening
	Intrastromal implants	Intracorneal lens/ring
	Keratophakia	Increase in central thickness
	Laser thermokeratoplasty	Central steepening by peripheral fibrosis
Intraocular	Clear crystalline lens extraction ± intraocular lens (for myopia and hyperopia)	
	Phakic intraocular lens (anterior/posterior chamber)	

unaided vision of 6/6 or better and 85% achieved socially adequate unaided vision of 6/12 or better, but 3% of eyes showed a reduction of best spectacle-corrected visual acuity.

Keratomileusis, or corneal 'sculpting' by removal of tissue, leads to a change in the shape and refractive power: to correct myopia, the corneal curvature is flattened and for hyperopia the curvature is steepened as illustrated in Figure 3. Barraquer[6], in 1949, conceived this operation, in which the anterior two-thirds of the cornea is resected as a disc, frozen and lathed on the posterior aspect of the disc (flattened or steepened) to alter the anterior corneal curvature before being then sutured back in place. A variation on this theme is epikeratoplasty, and Werblin and Kaufman[7] created such 'contact lenses' from donor human corneal tissue. This technique requires an eye bank to provide the tissue, which is frozen and lathed to the required anterior corneal curvature to correct either myopia or hyperopia. This corneal tissue 'contact lens' is then sutured on to the anterior surface of the recipient cornea after removal of the corneal epithelium. In the UK, this tissue

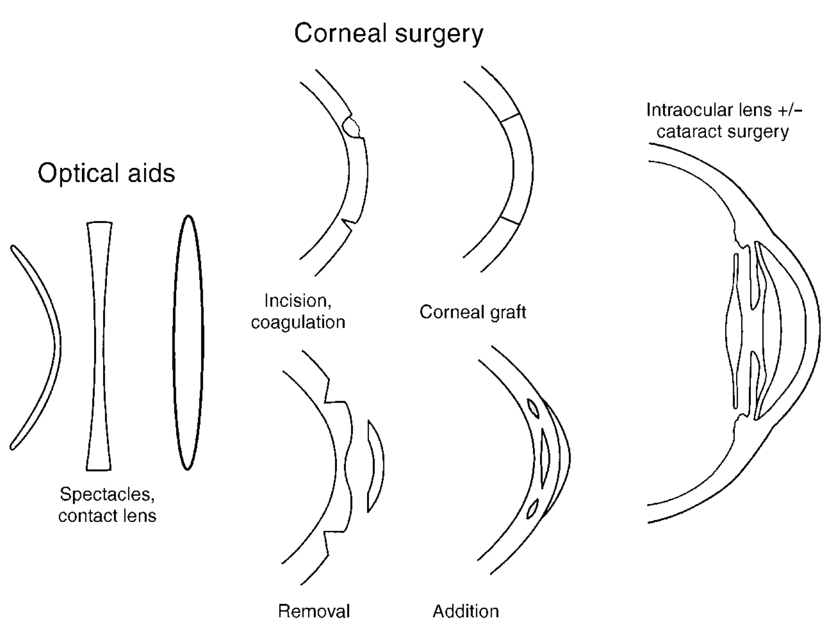

Figure 2 **Current methods to correct ametropia**

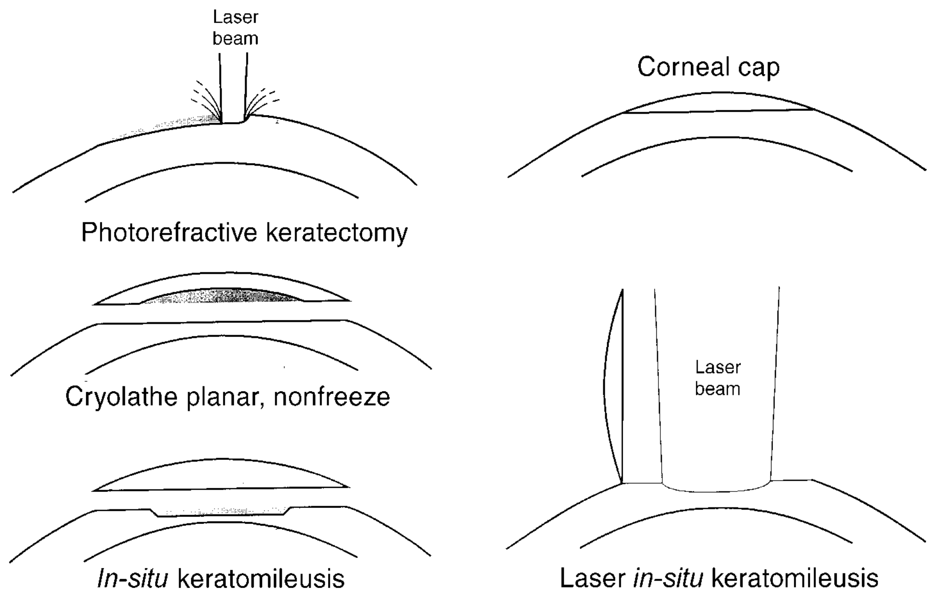

Figure 3 **Changing the anterior corneal shape**

is available from the Corneal Transplant Service Eye Bank, United Kingdom Transplant Support Services Authority. Currently, neither of these techniques is widely used.

With the advent of automated microkeratomes, a lamellar and planar (non-reflective) disc of anterior corneal tissue could be more easily resected, followed by microkeratome excision of stromal tissue from the corneal base by a second refractive cut. This flattens the curvature of the cornea and reduces its refracting power. The planar primary disc of tissue is repositioned, with or without sutures. However, this technique, termed automated lamellar keratoplasty, is constrained by the limited accuracy of the thickness and, therefore, the refractive effect of the second, mechanical cut in the corneal base[8,9].

In preference to these mechanical methods, the excimer laser has been used increasingly to reshape the anterior cornea. This method allows precise resection of submicron amounts of tissue, to correct refractive error. Laser techniques are discussed in depth in the second half of this article.

An alternative strategy is to add material to the cornea rather than remove it. The insertion of intrastromal implants of polymethylmethacrylate can alter the power of the cornea[10]. Intracorneal rings if placed in the paracentral cornea flatten the cornea, thus avoiding treatment in the visual axis. These procedures are reversible, and the availability of rings of different thickness and radius of curvature enables correction of low levels of myopic refractive error up to -4.00D[11]. Similarly, a central implant of the same refractive index as the cornea increases the central corneal thickness and power, and such techniques have been used with limited success in correcting hyperopia[12].

INTRAOCULAR REFRACTIVE SURGERY

The treatment of refractive error by clear lensectomy and implantation of an intraocular lens of the appropriate power has gained popularity as result of the success of small-incision phacoemulsification cataract surgery. This modality does not require expensive laser machines and is within the surgical capability of most ophthalmic surgeons, but its disadvantages include the loss of accommodation and the small but real hazards of retinal detachment[13] and endophthalmitis. Patients with high myopia are at greatest risk of retinal detachment: before treatment they require careful retinal examination and prophylactic treatment of suspicious lesions of the retina.

Insertion of a prosthetic lens within the eye in combination with the natural crystalline lens can effectively correct refractive error. The Baikoff angle-supported[14] and the Worst iris-supported lens[15] are two examples of such phakic lenses. Again, this technique is subject to limitations, with reports of corneal endothelial cell loss after the procedure[15]. A recent development is the precrystalline intraocular 'contact lens'. Early results are promising, but potential complications such as cataract formation and pupil-block glaucoma raise concern and the results of long-term prospective studies are eagerly awaited[16,17].

EXCIMER LASER

The public and ophthalmic interest in refractive surgical procedures has been greatly heightened over the past few years with the advent and widespread availability of the excimer laser, with its ability to precisely remove submicron amounts of corneal tissue. The first commercial excimer lasers were developed in the early 1980s to deliver laser action in the ultraviolet range (193 nm). Trokel *et al.*[18], in 1983, were the first to report the use of the excimer laser to ablate corneal tissue, and in 1988 Munnerlyn *et al.*[19] published an algorithm relating diameter and depth of ablation to the required refractive correction. Whilst Europe, Canada and most South American countries have used the excimer laser for several years free of regulation, the US Food and Drug Administration did not approve use of the excimer laser for myopic photorefractive keratectomy until 1995. Over a million treatments have now been performed worldwide.

The use of excimer lasers to alter the anterior curvature of the cornea can be divided into two techniques—surface-based photorefractive keratectomy (PRK) or photoastigmatic refractive keratectomy (PARK); and laser *in-situ* keratomileusis (LASIK). Both techniques can be used to correct myopia, hyperopia and astigmatism but to different degrees. The greatest experience has been achieved in the treatment of myopia.

Photorefractive keratectomy

In PRK, the excimer laser beam directly ablates corneal stroma, either through the epithelium or, more usually, after its manual removal, to correct the refractive error (Figure 3). The beam ablates both the superficial Bowman's membrane and the underlying stroma to the required depth. PRK remains the most popular refractive procedure in the UK and over 50 000 treatments have been performed.

With 6mm diameter ablation zones, treatment of up to −6.00D has given satisfactory results with 48–100% of patients achieving unaided visual acuity of 6/6 or better and 82–100% achieving 6/12 or better[20–23]. For higher myopia, up to −10.00D, postoperative reports[24] indicate visual acuity of 6/6 in between 25% and 40% and 6/12 or better in 89%. The loss of best spectacle-corrected visual acuity (BSCVA) of two or more Snellen lines, a significant complication, occurs in 0–4% of cases and 0.5–2% develop severe corneal haze[25,26]. For higher myopia, in excess of −10.00D, results are substantially poorer. In this group of patients, up to 15% of eyes develop significant corneal haze, 4–21% of eyes lose two or more lines of BSCVA and the retreatment rate is up to 26%[27]. In view of these results, most clinicians in the UK limit the use of PRK to below −8.00D of myopia. Several clinical trials have confirmed that PRK techniques are associated with an important risk of corneal haze and loss of BSCVA in myopic corrections greater than −10.00D; therefore, alternative techniques to correct high myopia continue to be developed.

Laser *in-situ* keratomileusis

LASIK avoids the risk of corneal scarring in the area of photoablation, keeping the epithelium and Bowman's layer intact in the visual axis. This procedure combines lamellar surgical techniques of the cornea with excimer laser photoablation of the exposed stroma (Figure 3). To date, this is the only widely utilized extraocular technique to correct high myopia.

In 1991, Pallikaris[28] developed the LASIK technique of creating a superficial nasally hinged corneal flap, which could be repositioned accurately and securely onto the cornea without sutures, the basis of current techniques. In this procedure, the laser ablation is performed on the exposed stromal surface. Concurrently, Burrato[29], echoing Barraquer's lathe technique, pioneered a technique whereby a 300 μm thick anterior lamellar corneal cap was removed and inverted beneath the excimer laser beam. Next the refractive correction (ablation) was applied to the rear of the cap, which was then repositioned and sutured into place. However, a hinged flap has several advantages over a free corneal cap[30] including a reduction in the risk of flap damage or loss, decreased risk of stromal desiccation, a reduction in interface contamination with debris and less induced astigmatism. Therefore, the free-cap technique has been abandoned.

LASIK operative procedure

The procedure is performed under topical anaesthesia. First a suction ring is applied to the globe, centred on the cornea. It fixates the cornea and provides a guide ring into which an automated microkeratome is inserted. This keratome is advanced manually or automatically across the cornea to create the nasally hinged corneal flap. Proper assembly and smooth running of the microkeratone are very important; otherwise the corneal flap may be badly damaged. Once the corneal flap of approximately 160 μm thickness is created, it is gently raised, everted and placed on the nasal aspect of the globe, exposing the underlying corneal stroma. The patient maintains fixation on an illuminated target and the excimer laser ablation (15–60 seconds) is performed. On completion of the ablation, the flap is replaced into its original anatomical position, where it adheres securely into place in 2–5 minutes. The 10–15 minute procedure is completed with instillation of a topical antibiotic.

Clinical results

In terms of final refractive and visual outcome, the LASIK procedure seems slightly superior to surface-based PRK for treatment of myopia below −7.5D. Initial reports[30–32] suggest greater benefit from LASIK correction of higher refractive errors, with fewer eyes exhibiting lost lines of BSCVA and a more predictable and stable refractive result. An additional advantage is the ability to enhance any undercorrection or regression by lifting the flap and further ablating the stromal surface up to 6 months later. Currently, many refractive surgeons still advocate the use of PRK for treatment of myopia up to −6.00D or −8.00D and reserve LASIK for myopia more than −6.00D. The upper limit of refractive error for LASIK treatment is thought to lie in the region of −12.00D to −15.00D (limited to some extent by corneal thickness), although corrections of −30.00D or greater have been reported. For prosthetic intraocular lenses the upper limit depends only on the power of lenses available.

Advantages of LASIK over PRK from the patient's point of view include the absence of postoperative pain, rapid visual rehabilitation and the possibility of prompt treatment of the fellow eye due to the early stabilization of the refraction. In LASIK, the fellow eye can be treated within 2–6 weeks rather than the 4–12 weeks required after PRK[33]. Indeed, some practitioners have advocated same-day bilateral LASIK surgery. With increasing experience of the LASIK technique, many surgeons now advocate LASIK as the procedure of choice for all levels of myopia from −1.00D to −15.00D.

Correction of hyperopia

Data on the treatment of hyperopia by LASIK are limited. Hyperopic corrections require large ablation zones, with a diameter of 8–9 mm, applied in an annular pattern to create central corneal steepening. This can be troublesome because the resultant, relatively small, central optical zone can easily be decentred, and substantial rates of under-correction and retreatment have been reported[34]. Hyperopic corrections, with both surface-based PRK and LASIK techniques, are currently regarded as investigational by the Royal College of Ophthalmologists.

Complications

Some complications associated with LASIK procedures are common to all excimer laser techniques since the same basic laser technique is used[35]. Others are predominantly related to the use of the microkeratome and the production of the corneal flap[36]. The most severe, and fortunately the rarest, of these complications is penetration of the cornea and entry into the anterior chamber, which can result in expulsion of intraocular contents. Consequently, only accredited surgeons familiar with intraocular microsurgical techniques, who have had further specific training in LASIK procedures, should consider performing this kind of surgery. Complications that can arise include perforation of the corneal flap, decentration of the laser ablation and irregular astigmatism, epithelial in-growth at the edge of the flap and interface debris.

New developments

As with all new techniques, improvements are continually being sought. These include new microkeratomes which avoid the risk of anterior chamber penetration and are easier to use. New and more efficient excimer laser delivery systems incorporating eye-tracking devices are also increasingly available.

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