Excimer laser treatment of corneal surface pathology: a laboratory and clinical study

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Abstract
The argon fluoride excimer laser emits radiation in the far ultraviolet part of the electromagnetic spectrum (193 nm). Each photon has high individual energy. Exposure of materials or tissues with peak absorption around 193 nm results in removal of surface layers (photoablation) with extremely high precision and minimal damage to non-irradiated areas. This precision is confirmed in a series of experiments on cadaver eyes and the treatment of 25 eyes with anterior corneal disease (follow-up 6 to 30 months). Multiple zone excimer laser superficial keratectomy is considered the treatment of choice for rough, painful corneal surfaces. All patients in this group were pain-free postoperatively. Where good visual potential exists, ablation of a single axial zone is recommended and results in improved visual acuity and reduction of glare. A hyperopic shift was noted in this group.

The potential of excimer lasers in ophthalmic surgery was first suggested in 1983 following their successful industrial application in etching highly precise patterns into plastics. A distinct advantage of argon fluoride excimer laser radiation (193 nm) is that there is no significant damage beyond exposed areas. Ultrastructural examination of corneal excisions in animal models confirmed that these could be produced with a very high degree of accuracy and control. Damage to adjacent unexposed tissue was limited to 300 nm beyond the boundary of the zone of ablation. In non-perforating excisions of varying depths endothelial damage was noted only when the base of the excision was within 40 μm of Descemet’s membrane, which is similar to but less extensive than diamond knife incisions. Furthermore, excisions can be controlled precisely, in terms of uniformity along the length of a single cut, reproducibility between cuts, and in anticipated cut depth (accuracy ± 3%, diamond knife incisions ± 12%). The first clinical application was therefore the correction of astigmatism with T-cut excisions.

The nature of corneal damage induced by excimer radiation at 193 nm is unique, because it results from an extremely high photon energy and high peak power. At this wavelength each photon has an energy of 6-4 electron volts, and, as this exceeds the binding voltage of carbon-carbon bonds, a single absorbed photon may lead to bond breakdown. Ultraviolet radiation in this spectral domain does not propagate well in air, and at any biological interface the photons are virtually all absorbed within a few microns of the surface. Thus, with each laser pulse a layer of tissue only a few molecules thick will be ablated from the surface. Tissue damage induced by other clinical lasers is achieved by concentrating laser energy into a focused point. However, the excimer laser beam has a large cross sectional area, and since every photon in the beam has the potential to produce tissue change the entire cross section can be utilised. The 1 cm by 2 cm rectangular profile is adjusted by cylindrical quartz lenses, and the resultant square beam profile becomes circular by passing the emergent beam through an aperture. This facility to photoablate large areas of cornea permits selective removal of tissue to induce a refractive change (photorefractive keratectomy – PRK).

For PRK and superficial keratectomy to become accepted in clinical practice an understanding of the nature and quality of wound healing is essential. Complete epithelial wound healing is necessary to re-establish the outer osmotic barrier of the cornea and optical brilliance. Studies have been undertaken to assess latency of wound healing, epithelial migration and adhesion properties, and the presence or absence of hyperplasia. Stromal wound healing has been examined in relation to loss or disturbance of transparency, keratocyte infiltration, and scar formation. Endothelium has been assessed in relation to potential cell loss or long-term population changes. Finally the putative mutagenic effects of ultraviolet radiation on the cornea have been assessed by both unscheduled DNA repair and tissue culture, coupled with enzyme poisoning techniques. None of these studies has highlighted areas of concern that would preclude the beginning of clinical trials with the excimer laser. The aim of this study was to determine whether the laser could be used for wide area ablations to remove opacities and produce an optically smooth surface. Since photoablation occurs across the entire area exposed, with repeated pulses the original surface contour will be reproduced in the base of the ablated disc. It was necessary therefore to devise a means of smooth-
ing an uneven surface. The simplest method of achieving this was to apply a liquid with approxi-
mately the same ablation properties as the cornea. The surface tension of the liquid would ensure that any surface irregularities would be negated. If irregularities in the corneal surface had a different ablation rate from that of the surrounding tissue—for example, the calcium deposits in band keratopathy—it would be necessary to shield underlying tissue with a liquid while the crystalline peaks underwent ablation.

This paper describes the use of the excimer laser for the production of large-area, optically smooth corneal surfaces in the laboratory and in the clinic.

Materials and methods
After ethical committee approval all clinical trials were carried out in the Department of Ophthalmology at St Thomas’s Hospital, London. A Summit Technology UV200 excimer laser was used with spectral emission at 193 nm. The pulse energy resulted in a radiant exposure of 180 mJ/cm²; the pulse frequency was fixed at 10 Hz and tissue removed per pulse was 0.24 μm. The beam configuration was circular in cross section, and a number of fixed beam diameters were used between 1 and 4 mm.

Excimer Laser Pattern Ablation in Cadaver Eyes
(1) The aim of this experiment was to create an irregular surface in cadaver corneas and then to determine whether the excimer laser could smooth these irregular surfaces. Donor eyes were used within 16 hours of death and secured in a Tudor Thomas stand. Ocular rigidity was maintained by injecting normal saline into the vitreous through the pars plana. After removal of the epithelium with a hockey end blade the globe was placed directly beneath the laser aperture and the helium-neon aiming beams focused on the centre of the cornea. An area of stroma was masked by placing a piece of bent wire on the corneal surface in the path of the beam. Fifty pulses of laser energy were then directed on to the partially occluded corneal surface with a 3 mm diameter beam. This resulted in excavation of the stromal surface in areas not shielded by the wire. In areas beneath the wire, ridges of original tissue remained.

The next objective was to remove the induced pattern with the laser to restore a smooth surface across the entire ablated zone. The wire was removed and the excavated areas ‘masked’ with 1% or 2% hydroxypropylmethylcellulose (HPMC) or polyvinyl alcohol to prevent their further ablation. These tear substitutes have a high water content and were assumed to have similar ablation rates to corneal stroma.

(2) In this experiment the excimer laser was used to create a cylindrical excavation 1 mm in diameter and 100 μm deep. The beam diameter was then increased to 3 mm, the ablated cylinder filled with 1% HPMC, and the surrounding stromal surface carefully dried. Ablation of the stroma was continued until the surrounding stroma had been ablated to the same depth as the original cylinder. In practice this process was monitored by changes in tissue fluorescence to be described in the results.

Excimer Laser Smoothing of Surgical Lamellar Keratotomy Beds
This experiment was designed to assess the potential of the excimer laser in combination with masking agents to smooth irregular corneal surfaces. A series of surgical lamellar keratectomies was performed on donor eyes. The initial incision was made with a disposable 6 mm trephine, and the lamellar dissection was done with a steel blade and Pauflke’s knives, beginning at the base of the trephine cut. HPMC was applied to the keratectomy base and its amount and distribution adjusted, while multiple overlapping ablation zones were produced until the base was smooth.

Histopathology
After laser exposure a 5 mm penetrating incision into the posterior globe was made and the eyes were immersed in fixative. The initial fixative used was 2.5% glutaraldehyde buffered in 1 M sodium cacodylate with 10 g/l calcium chloride at a final pH of 7.4. After 24 hours the corneas were prepared for light microscopy (LM) and electron microscopy (EM). Those for scanning EM were postfixed overnight in 2% osmium tetroxide buffered in 0.1 M sodium cacodylate, dehydrated through a series of ascending concentrations of acetone, and critical-point dried. Dried samples were sputter-coated with a 30 nm layer of gold before examination in a Hitachi 520 scanning electron microscope (SEM). For transmission electron microscopy (TEM) specimens were postfixed for only one hour in the osmium tetroxide solution described above, dehydrated in alcohol, and then embedded in Araldite (CY212) via epoxypropane. Sections were cut at 1 μm on glass knives for LM and on diamond knives for EM and mounted on 200 mesh copper grids, stained with uranyl acetate and lead citrate before examination in an AEI 801 transmission electron microscope.

Treatment of Band Keratopathy and Allied Superficial Pathologies
Twenty-five patients underwent excimer laser superficial keratotomy to remove band kerato-
pathy or to smooth roughened corneal surfaces arising from other pathology (see tables). Amethocaine 1% was instilled, a speculum inserted, and the patient taught to fixate the centre of a ring of fibreoptic lights located around the laser aperture. A beam diameter was selected to match the areas to be treated, and in some cases the size of the beam was reselected at different stages in the procedure. The effects of photobleaching were assessed with the integral binocular operating microscope positioned alongside the laser aperture. Once steady fixation was achieved, the masking liquid was applied to the corneal surface and photobleaching started. During the process the surgeon could vary the
site of ablation by making small movements of
the patient's head. After the procedure, which
lasted about 15 minutes, a mydriatic (homatra-
pine 2% eye drops) and antibiotic (chloram-
phenicol 1% eye ointment) were instilled and the
eye padded for 24 hours. Follow-up was daily for
the first week, weekly for one month, three
monthly for two further visits, and then six
monthly. For the first month chloramphenicol
0-5% eye drops were used four times a day.

The surface characteristics of selected patients
were examined and recorded with a prototype
photokeratoscope. In addition, while it was
impossible in most cases to comment on the
preoperative status of the corneal endothelium
owing to superficial opacification, it was
examined postoperatively at intervals via
specular reflection with the slit-lamp. Refraction
was carried out where possible.

Although the morphology of band kerato-
pathy varies, we subdivided the patients into two
broad categories. The first had rough, craggy
deposits with varying degrees of discomfort, the
second, smooth even deposits with little or no
discomfort.

Two treatment regimens were undertaken.
Either a single 4 mm diameter zone or a series of
partially overlapping 4 mm diameter zones was
ablated. The single area technique was most
commonly used for smooth bands which caused
impaired vision and glare and the multiple zone
technique for rough, painful bands. The noise
associated with laser pulses (10 Hz) was demon-
strated to the patients prior to the procedure, and
they were warned to expect a faint smell of
burning during treatment (see below).

Results

EXCIMER LASER PATTERN ABLATION IN CADAVER
EYES

(1) The bar relief pattern produced on the cornea
by shielding the underlying stroma by bent wire
was best demonstrated by SEM (Figs 1A, 2A). The
smoothness of the ablated surface was
comparable to Bowman’s layer on the non-
ablated ridges, and the stromal architecture was
obscured by a continuous membrane-like struc-
ture. The ridges, noted to have smooth perpen-
dicular walls, were successfully ablated to pro-
duce a homogeneous, optically smooth surface
(Fig 1B). In some specimens the ablation to
produce the pattern and the subsequent smooth-
ing ablation were not coincident. This resulted in
a small peripheral annulus in which the ridges
could still be seen (Figs 1B, 2B).

The most suitable masking liquid was 1%
HPMC, since it was easy to apply and remove
and filled the deivilities between surface irregu-
larities. HPMC fluoresced a bright blue when
irradiated and corneal stroma a dark blue-black.
There was thus a clear indication of the three
dimensional geometry of stroma undergoing
ablation. When 1% HPMC flooded the surface,
an even bright blue fluorescence was noted
across the entire target area with each pulse. As
the masking agent was ablated, corneal stromal
irregularities projected through the surface of
the HPMC and were ablated, as dark blue,
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almost black, 'islands' within the bright blue HPM C fluorescence. As ablation proceeded, so the pattern and surrounding masking agent were removed until a common depth was reached, at which point HPMC once again spread throughout the 3 mm zone, indicated by homogeneous bright blue fluorescence. Further ablation beyond the original depth of 10–12 μm removed the little remaining HPMC, and the entire area appeared dark-blue-black, with each pulse confirming that the pattern had been completely removed. If further pulses were applied, then the 3 mm zone of ablation was uniformly increased in depth (Fig 1B). With relief patterns in excess of 30 μm it was more difficult to achieve uniform smoothness because of a meniscus effect where the masking agent met the vertical sides of the pillars of non-ablated tissue. It was found that blotting the edges with cellulose (Weck-cell) sponges reduced this effect.

(2) In this experiment a 1 mm diameter cylinder of corneal stroma was ablated and filled with HPMC. On ablat ing the area around the cylinder there was differential fluorescence – the central spot (HPMC) bright blue, the surrounding stroma dark blue-black. The end-point was reached when the blue spot disappeared and the entire area of ablation became uniformly black – that is, the surrounding stroma had been ablated to exactly the same depth as that of the original cylinder. The number of pulses required for these two processes was similar.

EXCIMER LASER SMOOTHING OF SURGICAL LAMELLAR KERATECTOMY BEDS

Scanning electron microscopy of the base and walls of a surgical lamellar keratectomy showed surfaces with a marked degree of destruction and dissociation of cellular and extracellular components. The walls of such sites showed stratification with alternate layers of compression and shearing. There was an annulus in which epithelial cells were wiped off Bowman's layer because the surface tissue was displaced and compressed against the barrel of the trephine and debrided as the trephine rotated. The floor never displayed a cleavage plane and always consisted of ripped, torn lamellae and displaced ruptured keratocytes (Fig 3A).

Figure 3 Scanning electron micrographs of the corneal surface subsequent to (A) surgical lamellar keratectomy; (B) and (C) excimer laser irradiation. (A) The bed of a lamellar keratectomy showing rough, disorganised and torn tissue. (Bar=50 μm.) (B) A surgical lamellar keratectomy bed smoothed by excimer laser irradiation. The surface has a confluent membrane-like quality seen as wrinkles and folds produced during preparation for scanning electron microscopy. (Bar=50 μm.) (C) A lamellar keratectomy bed smoothed by application of multiple overlapping zones of excimer laser irradiation. The slight discontinuities between different zones are seen as variations in ablation depth and defined by arcuate boundaries (arrowed). (Bar=500 μm.)

The most appropriate method of smoothing lamellar beds was achieved by frequently applying small amounts of masking agent and constantly readjusting local distribution with cellulose (Weck-cell) sponges. This enabled removal of multiple small surface perturbations without unnecessary removal of deeper stroma. The resultant surface was smooth, with some wrinkles and folds suggesting a surface membrane (Fig 3B). Multiple overlapping ablation zones were used to smooth the entire keratec
tomy base (Fig 3C). Zones already smoothed

Table 1 Rough band keratopathy treated by several overlapping ablation zones

<table>
<thead>
<tr>
<th>No.</th>
<th>Sex</th>
<th>Age</th>
<th>Band type</th>
<th>Antiglory</th>
<th>Preop. symptoms</th>
<th>VA</th>
<th>Postop. symptoms</th>
<th>VA</th>
<th>Time (months)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>49</td>
<td>Rough surface very irregular</td>
<td>Increased serum Ca'++</td>
<td>Pain, photophobia decreased VA</td>
<td>6/36</td>
<td>Asymptomatic</td>
<td>6/12</td>
<td>30</td>
<td>Band reccurred after 18 months</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>45</td>
<td>Rough, very irregular</td>
<td>Trauma</td>
<td>Pain</td>
<td>PL</td>
<td>Asymptomatic</td>
<td>PL</td>
<td>30</td>
<td>Stable</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>50</td>
<td>Rough, raised, thick band</td>
<td>Trauma</td>
<td>Pain</td>
<td>NPL</td>
<td>Asymptomatic</td>
<td>NPL</td>
<td>30</td>
<td>Stable</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>34</td>
<td>Rough, irregular disrupted sten. seg</td>
<td>High myope, failed retinal detachment surgery</td>
<td>Irritable, red, pain on blinking</td>
<td>PL</td>
<td>Asymptomatic, pleased with cosmesis</td>
<td>PL</td>
<td>14</td>
<td>Stable</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>66</td>
<td>Central, proud Ca'++ plaque early stage of senile cataract</td>
<td>Keratosis due to herpes simplex virus</td>
<td>Pain, decreased VA</td>
<td>CF</td>
<td>Asymptomatic (occasional ache)</td>
<td>6/36</td>
<td>14</td>
<td>Stable</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>72</td>
<td>Classic band</td>
<td>Herpes zoster</td>
<td>Pain, epiphora decreased VA</td>
<td>6/24</td>
<td>Asymptomatic</td>
<td>6/18</td>
<td>12</td>
<td>Stable</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>33</td>
<td>Islands of Ca'++ (previous edetic acid treatment)</td>
<td>Uveitis (childhood)</td>
<td>Poor cosmesis, minimal discomfort</td>
<td>NPL</td>
<td>Unchanged</td>
<td>NPL</td>
<td>10</td>
<td>Highly mobile eye during treatment (surgery abandoned)</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>78</td>
<td>Central Ca'++ area and diffuse Ca'++</td>
<td>HSP Keratitis</td>
<td>Pain, epiphora, decreased VA</td>
<td>CF</td>
<td>Asymptomatic, slight increase in VA</td>
<td>4/60</td>
<td>10</td>
<td>Stable</td>
</tr>
</tbody>
</table>

VA = visual acuity. (N) PL = (no) perception of light. CF = counting fingers. HSV = herpes simplex virus.
were masked with HPMC to avoid unnecessary ablation. This technique was important in establishing criteria for treating large areas of stroma in the subsequent clinical cases.

TREATMENT OF BAND KERATOPATHY AND OTHER SUPERFICIAL CORNEAL PATHOLOGY

Twenty-five patients have had excimer laser treatment of band keratopathy or superficial corneal pathology since February 1988 (Tables 1–5). The six cases reported here in detail represent the spectrum of disease and illustrate different techniques of band removal with the excimer laser.

GROUP 1. ROUGH SYMPTOMATIC (UNCOMFORTABLE) BAND KERATOPATHY

Case 1

A 49-year-old female with systemic lupus erythematosus requiring renal dialysis since 1981 had a parathyroidectomy in 1984 for primary hyperparathyroidism. Her left eye had been painful since 1974 and was treated with artificial tears. In 1987 she had removal of band keratopathy with edetic acid (EDTA). In spite of this she still had severe pain in the left eye, aggravated by blinking, which disrupted sleep. There was extensive irregular, thickened band keratopathy with a visual acuity of 6/36. Islands of calcium protruded through unstable epithelium (Fig 4A). The right eye was normal.

In February 1988 she became the first sighted patient to undergo excimer laser superficial keratectomy (ELSK). She had multiple overlapping zones located in the central 6 mm of the cornea (Fig 4B). Approximately 300–400 pulses were delivered to each site of ablation. The procedure was pain-free. One hour later, however, she complained of some discomfort, which resolved over 36 hours when the cornea had re-epithelialised. One week later she was asymptomatic. At this stage the area of photoablation was smooth, with minimal central thinning and a faint anterior stromal haze. The acuity was 6/24 improving to 6/12 with pinhole. At five months there was early recurrence of band keratopathy (Fig 4C). By 18 months it began to cause...
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Figure 6 Case 3. Even, diffuse band keratopathy. (A) Appearance one year after excimer laser ablation of a single, 'on-axis' zone. The photograph was taken slightly eccentrically in order to highlight the enhanced transparency of the ablated zone against the iris. (B) Photokeratoscopic image preoperatively. (C) Appearance one month following central ablation.

Figure 6A.

Figure 6B.

Figure 6C.

discomfort. A small central epithelial erosion and faint central stromal haze were noted at this time, with the zone of ablation remaining markedly clearer than the surrounding area (Fig 4D).

Case 2
A 45-year-old male had sustained blunt trauma to his left eye at the age of 24. Band keratopathy, cataract, and glaucoma had resulted, and he underwent a series of procedures between 1984 and 1987 – corneal graft, cataract extraction with lens implant, two trabeculectomies and drainage tube insertion, and revision. He had discomfort and the vision was perception of light with poor projection. There was a dense band keratopathy and a grossly roughened corneal surface with disrupted epithelium (Fig 5A).

In August 1988 he had ELSK. The large central calcium deposit was completely ablated with HPMC to mask the surrounding tissue (Fig 2B). After re-epithelialisation he has remained asymptomatic. Eighteen months later the central corneal zone was still clear and the more peripheral band remnants were unchanged.

GROUP 2. SMOOTH BAND KERATOPATHY

Case 3
A 23-year-old West Indian male had pulmonary
Figure 8  Case 5. Even, diffuse band keratopathy.  
(A) Preoperative appearance showing an even band keratopathy distributed over the inferior cornea. Deep, white stromal deposits and a dense cataract can also be seen. (B) Postoperative appearance at 48 hours. The overlapping zones of ablation are clearly seen. Re-epithelialisation was complete at this stage. (C) Appearance at one year. Although the ablation zones are still clearly seen, there are signs of calcium deposition along the margins of some of the ablation sites and in the centre of two of these zones. The patient was still asymptomatic.

In June 1988 he had left ELSK with a 3 mm diameter beam centred on the visual axis. Approximately 200 pulses were delivered, of which 150 were required to remove the epithelium. Re-epithelialisation was complete within 48 hours.

One year later the visual acuity had improved to 6/12, though no conclusions can be drawn from this improvement, since the panuveitis had responded to treatment (Fig 6A). The surface quality postoperatively was best demonstrated by photokeratoscopy (Figs 6B, C).

Case 4
A 72-year-old male had bilateral idiopathic evenly distributed band keratopathy (Fig 7A). He had no discomfort but complained of glare and impaired vision: 6/24 right and 6/18 left. He had a right 4 mm axial ELSK without HPMC and the appearance at three months is seen in Figs 7B and 7C. Fig 7C, using sclerotic scatter, highlights the clarity of the central cornea compared to the adjacent band keratopathy against the background of the dilated pupil. Visual acuity in the right eye improved to 6/12, but veiling glare was subjectively unchanged.

Case 5
A 32-year-old Jamaican female had been blind in the right eye (no perception of light) from childhood. The cause was unknown. The eye was very uncomfortable. The left eye was normal.

There was a moderately dense band keratopathy across the inferior two thirds of the right cornea and discrete white deep stromal deposits in the same area (Fig 8A). There was sculeus pupillae and a dense cataract. ELSK was carried out with five 3 mm diameter partially overlapping zones (Fig 8B). Within 48 hours she was asymptomatic with an intact epithelium.

One year after treatment she had occasional mild photophobia. There was a faint anterior stromal haze in areas of ablation, with evidence of recurrence of band keratopathy in the centre of these zones, with a further peripheral deposition causing irregular boundaries (Fig 8C).
Case 6
A 67-year-old male developed a dense evenly distributed band keratopathy in his right eye after retinal detachment surgery which had included injection of silicone oil (Fig 9A). He had also undergone extracapsular cataract extraction with insertion of a posterior chamber intraocular lens. Before photoablation there was only a limited view into the anterior chamber in which silicone oil was present. Vision was hand movements in the inferior field only. EL5K was undertaken for cosmetic reasons and to improve the view of the posterior segment.

Overlapping ablation zones were used to clear the cornea of band. 1% HPMC was used to mask previously ablated areas. At three months the cornea was clear, with an optically smooth surface (Fig 9B). A good view of the anterior chamber, intraocular lens and retina was obtained. As expected, there was no significant improvement in vision.

GENERAL COMMENTS
No patients reported discomfort during the procedure. Postoperatively most of them experienced some discomfort for 24–48 hours. The intensity and duration of discomfort was related to the area of ablation. All patients required oral analgesics for 24 hours. In all cases re-epithelialisation was complete by 48 hours.

Sixteen of the 25 patients had an improvement in visual acuity (Tables 1–5). The 13 patients with uneven, symptomatic (painful) corneal surface became symptom free.

Improvement in visual acuity occurred in those patients who had an even band keratopathy which responded well to photoablation with minimal or no masking. In the seven patients troubled by glare (typically eyes with good visual potential and an evenly distributed 'ground glass' band keratopathy) all were markedly improved postoperatively. Three patients in the series were pleased with the improved appearance of their eyes.

In most of the cases treated it was impossible to assess the central endothelium preoperatively owing to the overlying band keratopathy. Examination by slit-lamp specular microscopy was carried out postoperatively at various stages of the follow-up, and none of the patients was found to have any endothelial disturbance.

Discussion
Our studies have not identified any complications or undesirable findings that would preclude further investigation of the clinical use of excimer lasers in ophthalmic practice.

Excimer laser ablation is a surface phenomenon and therefore irregular surfaces cannot be levelled as a single stage procedure by irradiation. If a rough surface of homogeneous tissue is irradiated, a uniform layer of tissue will be removed with each laser pulse (Fig 10), and in order to produce a smooth surface a masking agent with a similar ablation rate to that of the target material must be used (Fig 11). A liquid more easily ablated than the surrounding tissue would have to be constantly reapplied so as not to perpetuate surface perturbations. If the ablation rate were less than the surrounding tissue, less frequent applications would be required, and flow of the liquid between laser pulses would ensure that smoothing still occurred.

The viscosity and the surface tension of the masking agent are also of importance. If liquids have high viscosity or surface tension, they may form droplets and, on irradiation, contribute to further surface disturbances rather than smoothing. Surface tension and surface adhesion may also create problems in relation to filling deep surface excavations or those with low aspect ratios in terms of width to depth. The wetting agents selected are in clinical use and have a relatively prolonged contact with the corneal surface. All agents used were adequate for smoothing, but polyvinyl alcohol and 2% HPMC were too viscous and did not have good surface contour-following properties. 1% HPMC, however, was found to have ideal viscosity and was also convenient to apply and remove.

In the laboratory investigations it was possible to produce only models of uneven surfaces with uniform ablation rate – for example, superficial keratectomy beds. While these models are identical to some surfaces encountered clinically, as during lamellar keratoscopy or following removal of pterygia, a special case is encountered.
Figure 11. Production of a smooth surface by excimer laser radiation. (A) The irregular surface, analogous to a rough corneal surface, is covered with a masking liquid. (B) After initial exposure to excimer laser radiation both the masking liquid and surface projections have been partially ablated, the normal stroma between projections having been shielded from unnecessary ablation. (C) The resultant smooth surface at the end of the procedure (determination of the end point is assisted by observation of a uniform fluorescence).

Figure 12. Ablation of dense calcium deposits embedded within the stroma and projecting from the surface. (A) Initial surface. Calcium deposits are shaded. (B) After excimer laser irradiation without masking. The calcium deposits, having a lower ablation rate than that of intervening tissue troughs (Fig 12). Surface smoothing in this case requires an adjustable ‘shield’ through which the calcium peaks protrude and are ablated while the troughs are protected. The shield may then be lowered to complete the smoothing process. An ablation fluid with a slow ablation rate would be preferable for shielding. In practice, though 1% HPMC may not be optimal, it was certainly adequate as a shielding agent.

The control of the distribution of 1% HPMC during the ablation was an interactive process between manual application and removal. The closed tip size and curvature of Colibri forceps facilitated delivery of small quantities of HPMC without impairing the surgeon’s view. Cellulose (Weck-cell) sponges applied to the edge of the target zone were used to remove excess liquid; however, the fluid movement thus created by capillarity was found to be too fast for accurate adjustment. We are now examining alternative sponges whose capillarity engenders less rapid fluid uptake.

All three masking agents fluoresced when irradiated, and the difference in the intensity and wavelength of fluorescence between the masking agent and the corneal substrate was helpful in monitoring the ablation process. The difference in fluorescence was best appreciated when viewing ablation of masked patterns of regular geometry. Discrimination became more difficult during ablation of masked irregular shallow surface perturbations.

It has been shown that the penetration depth of 193 nm radiation is 3–4 μm. At 248 nm it exceeds 25 μm; and at 308 nm may be as high as 100 μm. These observations support previous studies using broad band sources of radiation which showed that penetration depth increased with wavelengths between 100 nm and 400 nm. Excimer laser radiation at 193 nm does not induce mutagenic response in cells deep to the ablation zone. This has been attributed to two aspects of the ablation process. First, that at the fluences used for clinical procedures the absorption of high energy photons results in bond breaking and ablation, and secondly that virtually no photons penetrate beyond the zone of ablation damaged cells. As a result of target fluorescence longer wavelength photons are generated which have deeper penetration and potential for DNA damage.
associated with such secondary radiation at sites remote from the ablation surface is so low that it has been calculated to be negligible (Sliney D, personal communication). The fluorescence of the masking agent was predominantly in the short wavelength visible portion of the spectrum and was therefore not considered to be a secondary hazard.

The use of masking agents did not affect the nature of the ablated surface, since it was uniform in the pattern experiments (Figs 1B, 2B). Although we did not undertake chemical analysis of the resultant surface after ablation, the homogeneity seen in our morphological studies indicates that no chemical interactions have occurred between the masking liquid and adjacent biological tissues. All surfaces were sealed with a pseudomembrane as shown by wrinkling (Fig 3B), and previous studies have shown that, whatever the nature of the pseudomembrane, its existence is transitory, and it does not interfere with subsequent healing processes.  

Although preoperative visual acuity was poor in a large proportion of patients, all except four could fixate with the eye undergoing treatment. In these four patients adequate alignment was achieved with the normal eye fixating an adjustable target at one side of the laser aperture. In only one patient (case 7) was it impossible to treat the band keratopathy because of eye movement. None of these patients detected the induced fluorescence during ablation in spite of this being clearly visible to all observers. In a further group of patients undergoing photorefractive keractomy some were aware of a faint blue haze with each pulse. In contrast to the lack of visual stimulation auditory and olfactory sensations were notable. The patients were warned about the noise and the smell of burning, and both were demonstrated prior to the procedure by ablating paper. (The smell is a little disconcerting to some patients as it is rather like that of singed hair.) The biophysics of the smell is difficult to explain. Current concepts of ablation consider that tissue removal occurs owing to a photochemical process of bond breaking rather than a thermal event. Some workers originally considered the process to be an ultrafast thermal event with tissue loss due to massive vibrational modes breaking macromolecular bonds. These thermal events could have resulted in 'burn-like' smells. Since the molecular fragmentation depends on wavelength, most workers now consider that ablation is a photochemical process with residual energy used to eject fragments from the surface. Smells must be related to airborne particles, and the similarity of smell of excimer ablated and thermally damaged biological tissue implies that similar types of particles are generated by both these processes.

### Table 2  Rough band keratopathy treated with single 'on axis' ablation

<table>
<thead>
<tr>
<th>No.</th>
<th>Sex</th>
<th>Age</th>
<th>Band type</th>
<th>Aetiology</th>
<th>Preop. symptoms</th>
<th>VA</th>
<th>Postop. symptoms</th>
<th>VA</th>
<th>Time (months)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>F</td>
<td>20</td>
<td>Central Ca&quot; plaque</td>
<td>Uveitis from childhood</td>
<td>Poor cosmesis</td>
<td>NPL</td>
<td>Improved cosmesis</td>
<td>NPL</td>
<td>10</td>
<td>Epithelial ablation only required Stable</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>80</td>
<td>Rough, central Ca&quot; deposit</td>
<td>Interstitial keratitis</td>
<td>Pain, epiphora</td>
<td>2/60</td>
<td>Marked improvement</td>
<td>2/60</td>
<td>12</td>
<td>Stable</td>
</tr>
</tbody>
</table>

### Table 3  Disorders resulting in rough corneal surfaces treated by excimer ablation

<table>
<thead>
<tr>
<th>No.</th>
<th>Sex</th>
<th>Age</th>
<th>Description</th>
<th>Pathology</th>
<th>Preop. symptoms</th>
<th>VA</th>
<th>Postop. symptoms</th>
<th>VA</th>
<th>Time (months)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>M</td>
<td>27</td>
<td>Mucus plaque</td>
<td>Atopic, vernal eye disease</td>
<td>Pain, photophobia decreased VA</td>
<td>6/60</td>
<td>Asymptomatic</td>
<td>6/18</td>
<td>14</td>
<td>Re-epithelialised, no plaque recurrence</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>45</td>
<td>Rough, raised granular dystrophy</td>
<td>Recurrent granular dystrophy in a PK</td>
<td>Soreness, photophobia decreased VA</td>
<td>6/24</td>
<td>Asymptomatic</td>
<td>6/18</td>
<td>30</td>
<td>No recurrence</td>
</tr>
<tr>
<td>13</td>
<td>F</td>
<td>46</td>
<td>Extensive lattice dystrophy</td>
<td>Lattice dystrophy</td>
<td>Glare, photophobia decreased VA</td>
<td>6/60</td>
<td>Asymptomatic Marked increase in VA</td>
<td>6/9</td>
<td>6</td>
<td>No recurrence, no glare, hyperopic shift</td>
</tr>
<tr>
<td>14</td>
<td>F</td>
<td>46</td>
<td>Central raised nodules</td>
<td>Salzmann’s</td>
<td>Discomfort, decreased VA</td>
<td>6/18</td>
<td>Asymptomatic</td>
<td>6/12</td>
<td>10</td>
<td>Stable</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>82</td>
<td>Anterior stromal scarring</td>
<td>Cogan’s epithelial dystrophy</td>
<td>Decreased VA, recurrent erosion</td>
<td>4/60</td>
<td>Asymptomatic, improved VA</td>
<td>6/12</td>
<td>10</td>
<td>Stable, Central area treated</td>
</tr>
</tbody>
</table>

PK=punctate keratitis.

### Table 4  Smooth surface band keratopathy treated with multiple overlapping ablation zones

<table>
<thead>
<tr>
<th>No.</th>
<th>Sex</th>
<th>Age</th>
<th>Band type</th>
<th>Aetiology</th>
<th>Preop. symptoms</th>
<th>VA</th>
<th>Postop. symptoms</th>
<th>VA</th>
<th>Time (months)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>F</td>
<td>32</td>
<td>Even, inferior cornea</td>
<td>Trauma in childhood</td>
<td>Discomfort</td>
<td>NPL</td>
<td>Asymptomatic</td>
<td>NPL</td>
<td>30</td>
<td>Stable, recurrence after 18 months (minimal)</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>67</td>
<td>Even, dense thick band in AC</td>
<td>Failed RD surgery, silicone oil</td>
<td>Glare, decreased VA in HM</td>
<td>6/18</td>
<td>Glare unchanged</td>
<td>CF</td>
<td>12</td>
<td>Recurrence after 6 months</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>81</td>
<td>Even, moderately dense</td>
<td>Idiopathic</td>
<td>Decreased VA, glare</td>
<td>6/18</td>
<td>Good cosmesis Reduced glare</td>
<td>6/18</td>
<td>12</td>
<td>Refraction change</td>
</tr>
<tr>
<td>19</td>
<td>F</td>
<td>45</td>
<td>Even</td>
<td>Uveitis, glaucoma surgery</td>
<td>Glare and decreased VA</td>
<td>6/9</td>
<td>Reduced glare</td>
<td>6/18</td>
<td>12</td>
<td>Refraction change and irregular astigmatism</td>
</tr>
<tr>
<td>20</td>
<td>F</td>
<td>70</td>
<td>Even, fine</td>
<td>Idiopathic</td>
<td>Decreased VA. Ablation to improve view for ECCE and IOL</td>
<td>6/36</td>
<td>Improved VA</td>
<td>6/12</td>
<td>10</td>
<td>ECCE/IOL facilitated</td>
</tr>
</tbody>
</table>

AC=anterior chamber. ECCE=extracapsular cataract extraction. IOL=intracocular lens. HM=hand movements.
Tables 1 to 5 show that postoperative progress was related to the extent of the initial pathology. Systematic analysis of the patient subsets was difficult, because there were significant variations in pathology. However, all patients with rough band keratopathy who had experienced pain preoperatively became asymptomatic (Tables 1 and 2). Most were treated with several overlapping ablation zones in order to smooth the cornea completely (Tables 1 and 2). Table 2 includes those patients who had a relatively small rough central area of band which was successfully treated with a single central ablation. In four patients visual acuity improved. Those with no improvement had extensive pathology of which the band formed only one part.

Four of the five patients with allied disorders which resulted in a rough corneal surface showed an improvement in visual acuity. Those with symptoms of soreness, pain, and photophobia were rendered asymptomatic (Table 3).

Smooth surfaced band deposition was treated with either several overlapping ablation zones (Table 4) or a single 'on-axis' ablation 4 mm in diameter (Table 5). The principal symptoms were reduced visual acuity and glare. Those patients with glare had a marked improvement which was sustained throughout the follow-up period (6 months to 2½ years). In the group treated with overlapping zones one patient showed an increase in visual acuity, one a reduced visual acuity, and the other three no significant difference. Where refraction results could be obtained, a 'plus shift' - that is, towards hypermetropia - was noted (cases 18 and 19, Table 6). In case 19 glare was markedly improved but acuity decreased. This reduction was due to irregular astigmatism because of the faceted surface generated by overlapping ablation zones. In contrast, in the group in which a central 'on-axis' zone was ablated (Table 5) visual acuity was improved in each case and glare reduced. In three of these cases a hyperopic shift was noted. In those patients in whom measurements were possible the mean hyperopic shift was 2·85 dioptres (Table 6).

From this study, which is the first reported series of corneal disease treated with an excimer laser, it is possible to put forward recommendations for selection of patients. First, for patients with rough band keratopathy the excimer laser provides successful treatment. All patients with pain and photophobia became asymptomatic (in general these eyes will have limited visual potential owing to the underlying pathology). Secondly, where the pathology is limited to the anterior stroma pain relief is likely to be accompanied by an improvement in visual acuity. Thirdly, in eyes with good visual potential it is best not to cover all of the band keratopathy by using overlapping ablation zones, since, although glare will be markedly reduced, irregular astigmatism may result, which could lead to reduced visual acuity. Thus a single, axial zone of ablation should be employed. We have also shown that a hyperopic shift occurs when the central cornea is ablated, and patients should be warned about the possibility of anisometropia.

The hyperopic shift (equivalent to a myopic correction) was an unexpected finding as the smoothing procedure is not analogous to photorefractive keratotomy. This flattening of the cornea implies that some form of differential ablation must have occurred. There are several potential mechanisms that could account for this. First, if the band progressively thinned towards the visual axis, constant irradiance from the laser would effect greater ablation centrally and induce a hyperopic shift. This effect would be enhanced if the ablation rate of the band was less than stroma. In essence, if bands do have such a topography, they act rather like the lens masks currently under investigation for correcting refractive errors. Secondly, although excimer laser radiation will remove an even layer of tissue regardless of the curvature of the surface, the subsurface structure of the cornea is laminated. Removal of central portions of corneal lamellae could lead to centrifugal differential contraction and central flattening. Thirdly, the centrifugal spray of particles of debris and ablation products might be expected to shield the stroma and would theoretically provide progressively greater shielding towards the edge of the ablated zone. Fourthly, the increased obliquity of incident radiation falling on more peripheral cornea might result in a relative decrease in energy density as the edge of the ablation zone is approached. It is unlikely, however, that the degree of differential ablation encountered could arise from inhomogeneities in the excimer beam.
In conclusion, given the encouraging results, the ease with which the procedure can be performed, the patient acceptance of the procedure, and the fact that we have treated all cases on an outpatient basis, we consider excimer ablation the treatment of choice for these cases.

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