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Application principles of excimer lasers in ophthalmology

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Abstract

Excimer lasers (193 nm) can be used for photoablation of the human cornea due to their specific physical characteristics. This laser is applied in corneal refractive surgery for the targeted removal of corneal tissue for the purpose of correcting refractive errors. This article provides a short overview of the scientific development of excimer lasers for use in ophthalmic surgery and of the range of applications of these tools.

Keywords: Excimer laser; Photoablation; PRK; LASIK; LASEK; Refractive surgery

Background

The definition of ametropia as a disease or simply as an incongruence with a presumed optimal anatomy of the human eye has been a matter of discussion, both medically and philosophically, for a long time. As a consequence it is debatable whether surgical correction of ametropia is purely functional or should be considered as cosmetic surgery.

The goal of refractive surgery is to remodel the eye's microanatomy in such a way that the optical properties will be aligned to the ideal focus. A successful procedure will eliminate optical errors and imperfections and enable the patient to enjoy optimal vision without the need for further external support devices.

The principle of any surgical approach to move the focus point of the eye exactly into the fovea is to alter the refractive power of either the cornea or the lens which may be too high (myopia) or too low (hyperopia) or too inconsistent (astigmatism), depending on the nature of the refractive error. Refractive surgery using the excimer laser, also termed as laser vision correction (LVC) is a surgical intervention that takes place on the frontal transparent part of the human eye, the corneal surface and within the corneal stroma.

The concept of remodeling the corneal surface for refractive purposes by lamellar ablation was first applied by Barraquer [1] who performed early experimental procedures by removing or adding thin slices of corneal tissue to ametropic eyes. However, the quality of the results was very limited due to the instruments used. A number of years were to elapse before instruments matching the concept became available and these were excimer lasers.

The excimer laser

In 1970, Nikolai Basov and co-workers developed the first excimer laser at the Lebedev Physical Institute in Moscow. A decade later, observation of the high sensitivity of the corneal epithelium to 193 nm laser pulses emitted by an excimer laser by Taboada and Archibald [2] determined the direction the use would take in tissue ablation of the cornea. Trokel et al. [3] were the first to explore this potential and transfer the method to clinical application.

The excimer laser derives its name from an artificial combination of two descriptive terms that characterize the principal features of the laser, "exited dimer". Dimer refers to the

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medium of the laser source which is in this case a halogen and a noble gas which are mixed in the cavity of the laser source. The wavelength of the emitted light is determined by the specific combination of gases. Ophthalmic excimer lasers use argon and fluoride as laser media, emitting photons in the far UV range at 193 nm. The corneal tissue has an absorption maximum at this wavelength.

The basic layout of excimer lasers used today still follow the original principle as was given in the patent documents from 1981 (patent granted in 1986) co-authored by Blum et al. [4]. The invention however was not primarily described for an ophthalmic application but the authors suggested its use for removal of tissue from bones and for drilling teeth in dentistry. The principal idea of the surgical potential of excimer lasers was laid down in a landmark paper published in 1983 [5] describing the excimer laser etching of bovine corneal tissue. This paper played a pivotal role in inspiring ophthalmologists to develop procedures to be coined later as photorefractive keratectomy (PRK) and laser-assisted *in situ* keratomileusis (LASIK). As early as 1987, the first PRK was performed in a human eye *in vivo* [6–8]. Until now, over 20 million people worldwide have undergone such treatments.

Physical basics

Laser effects on biological tissue can be grouped into three major categories: thermal, ionizing and photochemical. Excimer lasers affect changes in tissue by virtue of their photochemical interaction. When pulsed ultraviolet light, at wavelengths below 350 nm, is applied in the nanosecond (ns) range it causes breaks in the intermolecular bonds of the polymer chains of corneal collagens, disintegrating the target tissue. This process is called photoablation. The resulting small volatile fragments are propelled at high speed above the tissue surface, where they can be evacuated. This process does not involve a significant increase in the tissue temperature as the diffusion time for heat conduction into the surrounding tissue is much longer than the millisecond (ms) range pulse duration. The energy of the laser light is almost entirely absorbed at the surface of the treated tissue without producing relevant collateral effects within the stroma.

The depth of ablation depends both on the excimer laser wavelength and the energy density of the pulse [9]. The absorption maximum of the cornea at 193 nm makes the use of the excimer laser particularly suitable for corneal surgery. Irradiance at 193 nm leaves the immediate vicinity of the ablated stroma unchanged. The wavelength is crucial as the 193 nm pattern ablates creating smooth edges whereas a comparable 249 nm pulse pattern leaves jagged tissue edges [5]. With increasing wavelengths the thermal effects and collateral damage of an excimer laser pulse increase. Ablation starts at irradiance >50 mJ/cm^2, with the ablation threshold being independent of the laser firing rate. For energy levels of 200–2000 mJ/cm^2/pulse, the ablation depth ranges for a 193 nm wavelength from approximately 0.25–1.2 μm/pulse [9]. For comparison, a human hair has an average diameter of 50 μm and an excimer laser pulse would be capable of removing only 0.5% of its thickness. The amount of tissue that is ablated per applied unit of laser pulse energy (ablation efficiency) has a maximum for a laser fluence of 380–600 mJ/cm^2 with an absolute maximum at 440 mJ/cm^2 [10].

Technical aspects

Excimer lasers for refractive surgery can be subdivided into the two major categories, broad beam and scanning lasers [11,12].

- Broad beam lasers operate a beam with a large total diameter of approximately 6–8 mm, which is deformed appropriately during ablation. The "raw laser beam" is guided through an optical system consisting of a series of lenses and mirrors to ensure a square cross section of the homogenized beam at the level of treatment. Earlier machines of this type had an increased risk of leaving central islands of the cornea sub totally treated when the plume from ejected particles would shade the tissue. The large area of simultaneously treated tissue results in short procedure times.
- Scanning lasers apply a beam of smaller diameter to the corneal tissue which consequently has to be scanned across the ablation zone. The size of the laser spot is modulated by rotational mask devices with slit holes of variable size, the laser spot being scanned across the apertures during the procedure. The ablated surface tends to be smoother with this technique than with broad beam lasers.
  Spot scanning lasers operate a pixel-by-pixel computerized control of the scanning process across the cornea which allows for a high degree of precision and versatility for theoretically any possible pattern of the corneal surface. In the earlier days of excimer laser refractive surgery, these devices had a longer treatment time compared to broad beam lasers. However with current high frequency laser pulse application, this is no more relevant.

Nowadays, excimer laser surgery is to a great extent robotic surgery, i.e. the individual photoablation pattern is calculated by software, and the laser beam is being guided by digital control units. Usually, excimer laser devices contain the following components: reservoirs for argon and fluoride gases, the power source and the laser cavity as the "heart" of the machine, optical pathways to form and steer the beam, a shutter and the beam delivery unit, aiming laser systems, a surgical microscope and computer systems for digital control of the machine and the procedures. Typically, the laser itself is combined with a specially designed patient bed that not only supports the patient during the procedure but also allows highly precise three-dimensional micro-movements to ensure optimized positioning of the eye with respect to the laser.