



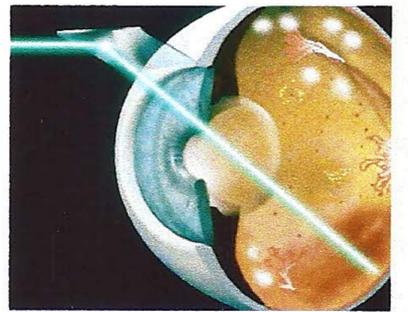
Comenius University in Bratislava

FACULTY OF MEDICINE  
IN BRATISLAVA



Medical Physics & Biophysics

# Lasers in Ophthalmology



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# **Lasers in Ophthalmology**

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## **Abstract**

Laser technology is one of the most rapidly developing areas in modern technology. Laser is a mechanism for emitting electromagnetic radiation, often visible light, via the process of stimulated emission. The emitted laser light is a spatially coherent, narrow low-divergence beam, that can be manipulated with lenses.

The human eye is the organ which gives us the sense of sight, allowing us to observe and learn more about the surrounding world than we do with any of the other four senses. Laser effects in biological tissues can be divided into three general categories, *photochemical*, *thermal*, and *ionizing*. With the improvement of laser technology, the techniques using different types of lasers (ruby, neodymium, neodymium, aluminum, erbium, excimer and argon) allowed to utilize lasers in the treatment and diagnostics of many eye disorders, such as glaucoma, cataract, retinal disorders, tumors and myopia.

It is impossible to imagine ophthalmology today without lasers. The development of lasers for plastic surgery, cataract extraction, ocular imaging and treating myopia is progressing rapidly and is expected to find much greater use and usefulness in the coming years.

**Key Words:** Laser, Laser Physics, Eye Anatomy, Lasers in Ophthalmology, Argon Laser

## **Introduction**

In 1917, *Albert Einstein* established the theoretic foundations for the LASER based upon probability coefficients for the absorption, spontaneous emission, and stimulated emission of electromagnetic radiation. On 16 May 1960, *Theodore Maiman* demonstrated the first functional laser, and in the same year, the Iranian physicist *Ali Javan*, and William R. Bennett, and Donald Herriot, constructed the first gas laser<sup>1</sup>.

Light Amplification by Stimulated Emission of Radiation (LASER) is a mechanism for emitting electromagnetic radiation, often visible light, via the process of stimulated emission. When lasers were invented, they were called "a solution looking for a problem. Since then, they have become ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, entertainment, and the military. The supermarket barcode scanner, introduced in 1974.<sup>5</sup>

Lasers have been used in many fields of medicine, and have the most significant uses nowadays in Ophthalmology. With the improvement of laser technology, the techniques, using different types of lasers (*ruby*, *neodymium*, *neodymium*, *aluminum*,

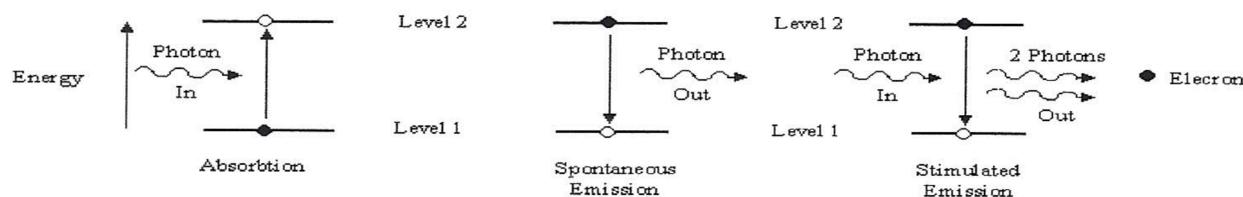
erbium, and argon) allowed to utilize lasers in the treatment and diagnostics of many eye disorders. It is impossible to imagine ophthalmology today without lasers. The development of lasers for plastic surgery, cataract extraction, ocular imaging and treatment of myopia nowadays is progressing rapidly and is expected to find much greater use and usefulness in the coming years.

## Laser Physics Theory

Light is quantised. It may be represented as groups of photons. Each photon carries one quantum of light energy. The amount of energy in a quantum depends upon the wavelength (colour) of the light. So we see that a short wavelength such as blue light at 470 nm has a high energy, and red light at 670 nm has a low energy per photon. The important point is that the wavelength of light is linked to the energy of a photon in a defined way. Thus an electron in the idealised atom which has given out a photon of defined energy emits light of a defined wavelength or 'colour'.

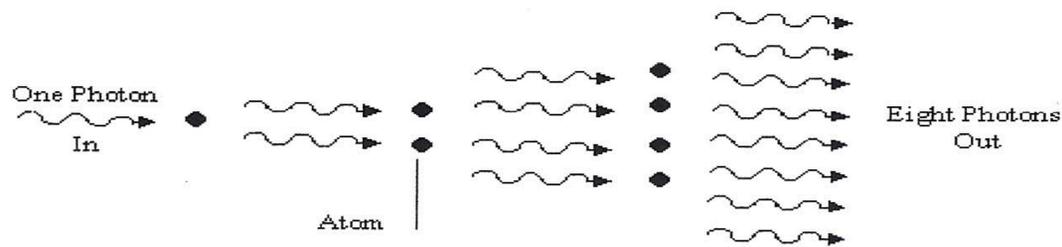
This is seen in street lights which contain Sodium atoms. They take *electrical energy* to move their electrons into higher levels and these electrons then fall back down to the initial, lower, state giving light at **589 nm** the characteristic orange of street lights. This process is known as *spontaneous emission*. The atom emits light spontaneously, without external influences.

If however the atom is not isolated, other effects may occur. Photons of the same energy as the energy of the upper level may use their energy to move an electron from the lower level to the upper one. This is known as *absorption*, as the photon is destroyed in the process. If a photon of the correct energy passes an atom with its electron in the upper level, then it may cause the electron to fall to the lower level. This *stimulated emission* is very different from spontaneous emission. In the spontaneous process the emitted photon may travel in any direction and be emitted at any time. Stimulated emission, however, causes the emitted photon to travel in the identical direction to the passing photon and at the same time.

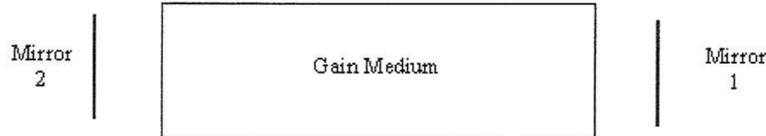


The three processes above all happen if we have a group of  $N$  atoms some of which have their electrons in the upper level and some with their electrons in the lower level. In a laser we want stimulated emission to be the biggest effect (as indicated by the acronym). For stimulated emission to be greater than absorption we require *more atoms to have their electrons in the upper level than have their electrons in the lower level*. This is known as an *inversion* as it is normal for electrons to be in their lowest energy level. This may be readily seen from the fact that in the absence of external influences, ie. no photons  $n=0$ , the only process which can occur is spontaneous emission which will allow any electron which began in the upper level to fall to the lower level, but not vice-versa.

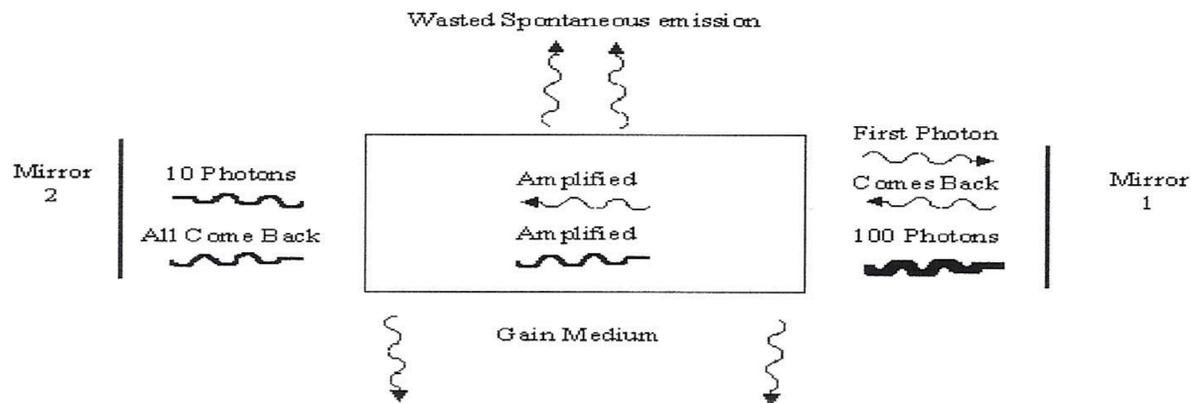
The fundamental difficulty in producing a laser is creating this necessary inversion in the populations of the two levels. Assuming that we have an inversion, then we can get the SE part of laSEr. If a single photon entering a region with the atom having its electron in the upper level, it will cause emission of a second photon travelling in the same direction, by the process of stimulated emission. There are now two photons, each of which can cause stimulated emission in two more atoms to give four photons, and so on.



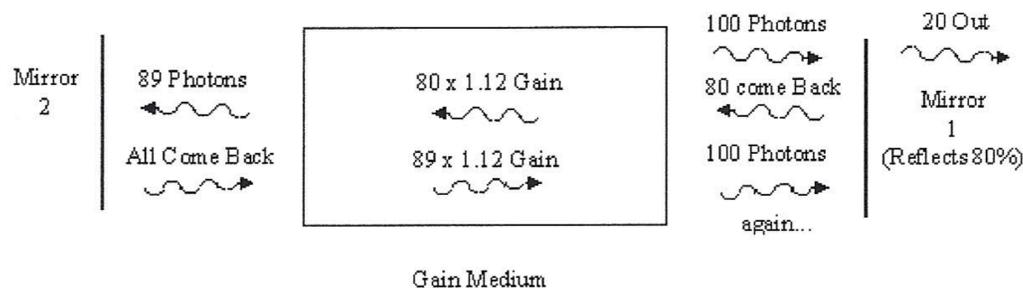
Thus we have **amplification**, which is also known as **gain**. The region containing the atoms is known as the **gain medium**. The final stage in a laser is to get this first photon to amplify. This is done by placing the gain medium between two mirrors. This forms what is known as a **laser cavity**.



Initially there is no light in the cavity. The only possible process for the atoms to undergo is therefore spontaneous emission, and this duly occurs. As stated earlier, this may travel in any direction out of the gain medium, and most is lost from the cavity. However out of the millions of photons emitted by the millions of atoms in any real medium, there is bound to be at **least one** which travels directly to one of the mirrors and is reflected back to the gain medium. **This is now our first photon**. As it passes through the gain medium, it causes stimulated emission, and by the end of the gain medium there are, for example, ten photons. Now the important part is that these are all travelling in the *same direction* as the first photon, so will be reflected back to the gain region by the other mirror. These ten photons now each cause stimulated emission, and when they get out of the medium to the first mirror again there are one hundred which are reflected back to the gain medium again and are amplified to 1000 etc...

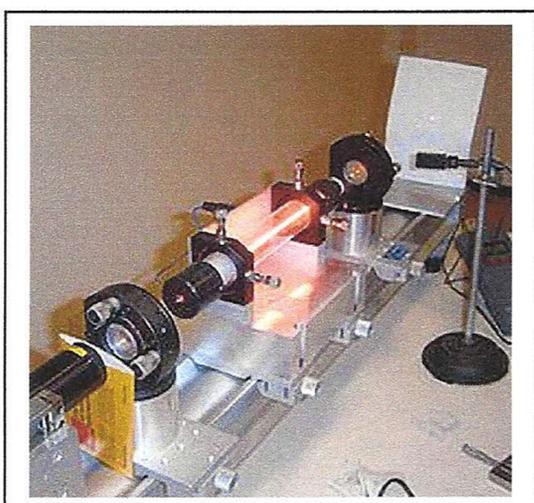


Thus we very rapidly get very many photons travelling back and forward in the cavity. Obviously in this idealised case where no photons are lost from the steadily amplified beam, the photon number just goes on increasing. In any real laser some photons are lost, for many various reasons. One of these is quite deliberate. **One of the mirrors is made to reflect only part of the light, and to allow the rest through**. This is then the output beam of the laser and the 'leaky' mirror is referred to as the **output coupler**. A steady state may then be reached where the gain exactly replaces the photons lost from the cavity by the output coupler. There is then a constant number of photons in the cavity at any time. For example a laser with a gain of 1.2 and an output coupler which reflects just 80% of the light we have:



The output beam thus has photons which are travelling in a fixed direction and also have a fixed wavelength (colour) defined by the energy levels of the electrons in the atoms of the gain medium.<sup>2,6</sup>

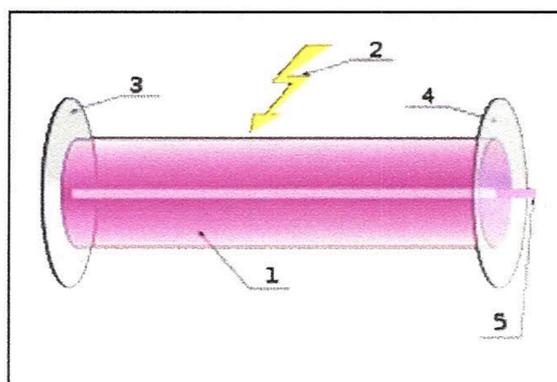
## Laser Terminology



The **gain medium** of a laser is a material of controlled purity, size, concentration, and shape, which amplifies the beam by the process of stimulated emission. It can be of any state: gas, liquid, solid or plasma. The gain medium absorbs pump energy, which raises some electrons into higher-energy ("excited") quantum states. Particles can interact with light by either absorbing or emitting photons. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, **population inversion** is achieved and the amount of stimulated emission due to light that

passes through is larger than the amount of absorption. Hence, the light is amplified. By itself, this makes an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser<sup>1</sup>.

The light generated by stimulated emission is very similar to the input signal in terms of wavelength, phase, and polarization. This gives laser light its characteristic coherence, and allows it to maintain the uniform polarization and often monochromaticity established by the optical cavity design.<sup>4, 5</sup>



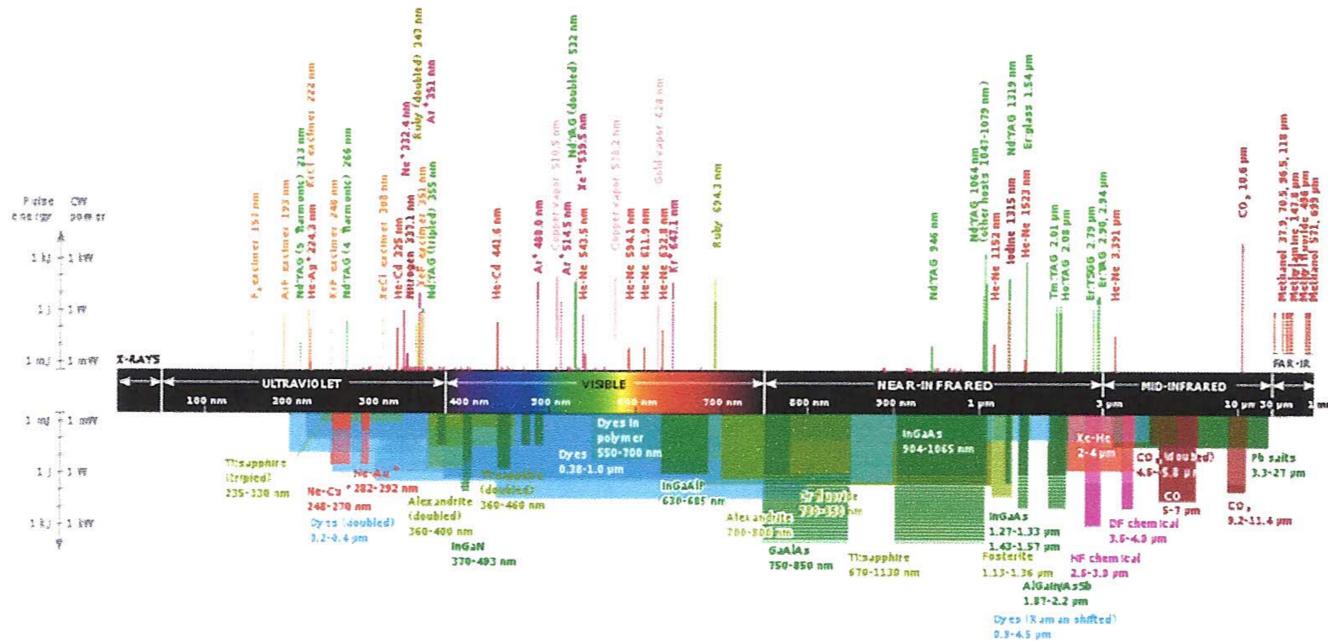
### Principal components:

1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler
5. Laser beam

The optical cavity, a type of cavity resonator, contains a coherent beam of light between reflective surfaces so that the light passes through the gain medium more than once before it is emitted from the output aperture or lost to diffraction or absorption. As light circulates through the cavity, passing through the gain medium, if the gain (amplification) in the medium is larger than the resonator losses, the power of the circulating light can rise exponentially. But each stimulated emission event returns a particle from its excited state to the ground state, reducing the capacity of the gain medium for further amplification. With increasing beam power the gain reduces to zero and the medium is said to be saturated<sup>4</sup>.

The balance of pump power against gain saturation and cavity losses produces an equilibrium value of the laser power inside the cavity; this equilibrium determines the operating point of the laser. If the chosen pump power is too small, the gain is not sufficient to overcome the resonator losses, and the laser will emit only very small light powers. The minimum pump power needed to begin laser action is called the *lasing threshold*. The gain medium will amplify any photons passing through it, regardless of direction; but only the photons aligned with the cavity and capillary axis manage to pass more than once through the medium and so have significant amplification<sup>3</sup>

## Types of Lasers



Wavelengths of commercially available lasers. Laser types with distinct laser lines are shown above the wavelength bar, while below are shown lasers that can emit in a wavelength range. The color codifies the type of laser material (see the figure description for more details)<sup>1</sup>.

### Gas lasers

Following the invention of the **HeNe** gas laser, many other gas discharges have been found to amplify light coherently. The helium-neon laser (**HeNe**), the **Argon-ion** lasers emit light in the range **351-528.7 nm**.

### Chemical lasers

Chemical lasers are powered by a chemical reaction, and can achieve high powers in continuous operation. In the Hydrogen fluoride laser (2700-2900 nm) and the Deuterium fluoride laser (3800 nm) the reaction is the combination of hydrogen or deuterium gas with combustion products of ethylene in nitrogen trifluoride.

### Excimer lasers

Excimer lasers are powered by a chemical reaction involving an *excited dimer*, or *excimer*, which is a short-lived dimeric or heterodimeric molecule formed from two species (atoms), at least one of which is in an excited electronic state. They typically produce ultraviolet light, and are used in LASIK eye surgery.

### Solid-state lasers

Solid-state laser materials are commonly made by "doping" a crystalline solid host with ions that provide the required energy states. For example, the first working laser was a ruby laser, made from ruby (chromium-doped corundum).

### Dye lasers

Dye lasers use an organic dye as the gain medium. These lasers are highly tunable, or produce very short-duration pulses (on the order of a few femtoseconds).

### Free electron lasers

Free electron lasers, or **FELs**, generate coherent, high power radiation, that is widely tunable, currently ranging in wavelength from microwaves, through terahertz radiation and infrared, to the visible spectrum, to soft X-rays. *They have the widest frequency range of any laser type.* Unlike gas, liquid, or solid-state lasers, which rely on bound atomic or molecular states, FELs use a relativistic electron beam as the lasing medium, hence the term *free electron*.

### Uses

**Medicine:** Bloodless surgery, laser healing, surgical treatment, kidney stone treatment, eye treatment, dentistry

**Industry:** Cutting, welding, material heat treatment, marking parts, non-contact measurement of parts

**Military:** Marking targets, guiding munitions, missile defence, electro-optical countermeasures (EOCM), alternative to radar, blinding troops.

**Law enforcement:** used for latent fingerprint detection in the forensic identification field

**Research:** Spectroscopy, laser ablation, laser annealing, laser scattering, laser interferometry, LIDAR, laser capture microdissection, fluorescence microscopy

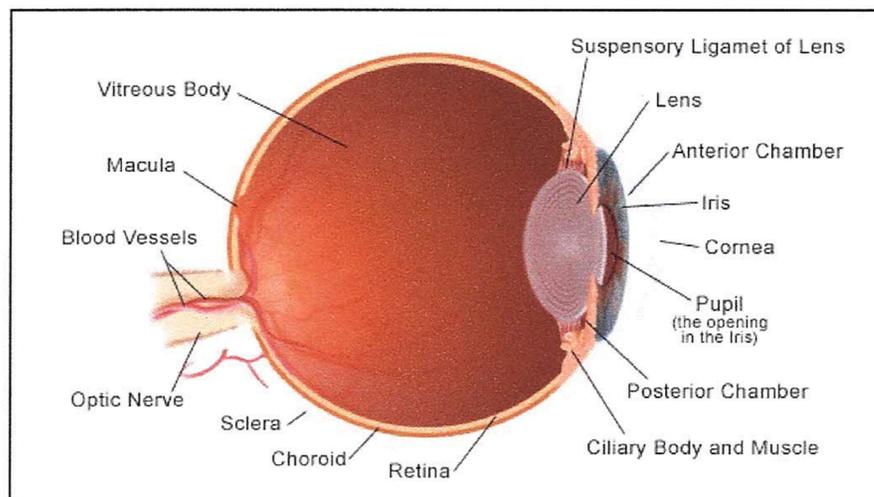
**Product development/commercial:** laser printers, optical discs (e.g. CDs and the like), barcode scanners, thermometers, laser pointers, holograms, bubblegrams.

**Laser lighting displays:** Laser light shows <sup>1</sup>

## Optic anatomy and function - Lasers in Ophthalmology

The human eye is the organ which gives us the sense of sight, allowing us to observe and learn more about the surrounding world than we do with any of the other four senses. We use our eyes in almost every activity we perform, whether reading, working, watching television, writing a letter, driving a car, and in countless other ways.

Most people probably would agree that sight is the sense they value more than all the rest.



The eye allows us to see and interpret the shapes, colors, and dimensions of objects in the world by processing the light they reflect or emit. The eye is able to detect bright light or dim light, but it cannot sense objects when light is absent

### Process of vision – Use of Lasers

Light waves from an object (such as a tree) enter the eye first through the **cornea**, which is the clear dome at the front of the eye. The light then progresses through the **pupil**, the circular opening in the center of the colored **iris**.



Initially, the light waves are bent or converged first by the cornea, and then further by the **crystalline lens** (located immediately behind the iris and the pupil), to a

nodal point (N) located immediately behind the back surface of the **lens**. At that point, the image becomes reversed (turned backwards) and inverted (turned upside-down).

The light continues through the **vitreous humor**, the clear gel that makes up about 80% of the eye's volume, and then, ideally, back to a clear focus on the **retina**, behind the **vitreous**. The small central area of the retina is the **macula**, which provides the best vision of any location in the retina. If the eye is considered to be a type of camera, the retina is equivalent to the film inside of the camera, registering the tiny photons of light interacting with it.

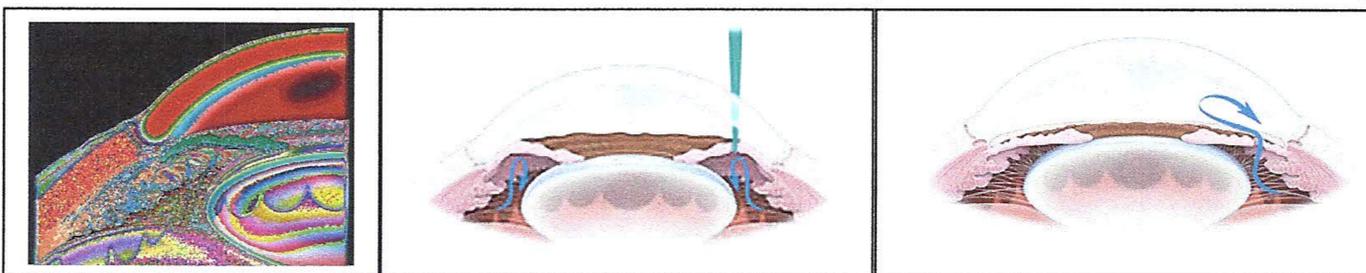
Within the layers of the retina, light impulses are changed into electrical signals. Then they are sent through the **optic nerve**, along the **visual pathway**, to the occipital cortex at the posterior (back) of the brain. Here, the electrical signals are interpreted or “seen” by the brain as a visual image. Actually, then, we do not “see” with our eyes but, rather, with our brains. Our eyes merely are the beginnings of the visual process.<sup>6</sup>

If the incoming light from a far away object focuses before it gets to the back of the eye, that eye's refractive error is called “myopia” (nearsightedness). If incoming light from something far away has not focused by the time it reaches the back of the eye, that eye's refractive error is “hyperopia” (farsightedness).

The cornea is the primary (most powerful) structure focusing light entering the eye (along with the secondary focusing structure, the **crystalline lens**). Behind the cornea, in the anterior chamber, aqueous humor fills the space, giving the eye the correct pressure. That aqueous begins from the ciliary body, a formation behind iris. Whenever the circulation of the humor is disrupted, the intraocular pressure rises high. The same condition appears, whenever there is difficulty for the aqueous humor to pass from the anterior chamber to veins of the eye, in order to preserve constant intraocular pressure. That situation called **glaucoma**<sup>6,7</sup>.

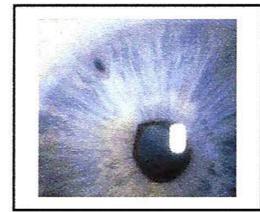
### Glaucoma Laser Treatment

Glaucoma laser treatment is often recommended when medical therapy alone is insufficient in controlling intraocular pressure, for those patients who have contraindications to glaucoma medications or, for any reason, are unable to use eye

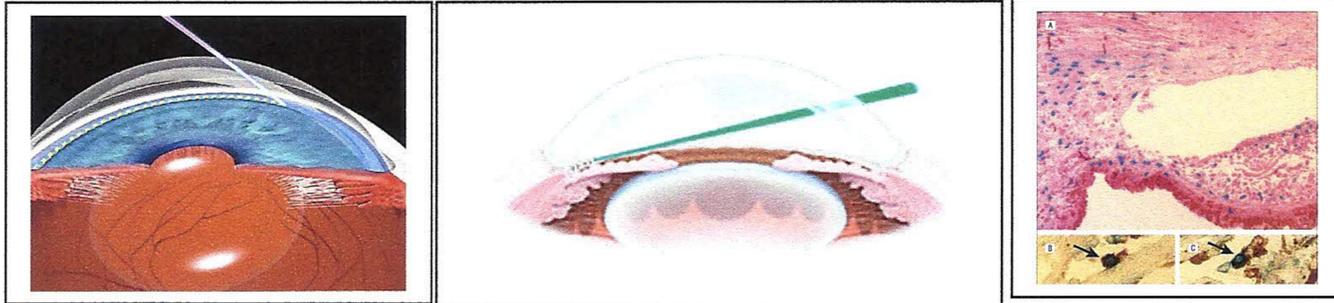


drops. As we mentioned in Part B, in glaucoma there is difficulty for the aqueous humor

to pass from the posterior chamber to the anterior chamber, or from the anterior chamber to the ocular veins outside the globe through the trabecular meshwork. So, the most common glaucoma laser procedure is laser **peripheral iridotomy** (PI) involves creating a tiny opening in the peripheral iris, allowing aqueous fluid to flow from behind the iris directly to the anterior chamber of the eye. This typically results in resolution of the forwardly bowed iris and thereby an opening up of the angle of the eye. There are two types of lasers in use today - *Nd:YAG* Q-switched laser (2 – 8 mJ) or *Argon* laser (800 – 1000 mW). These lasers replaced surgical iridectomy as a safer, non-invasive method of making an iridotomy in the late 1970s.



Argon laser **trabeculoplasty** (ALT) is a procedure which has been proven to be

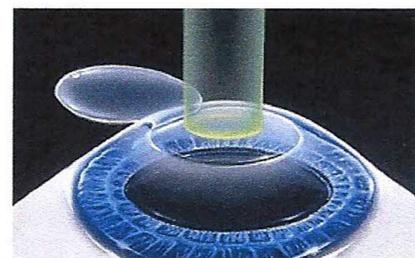
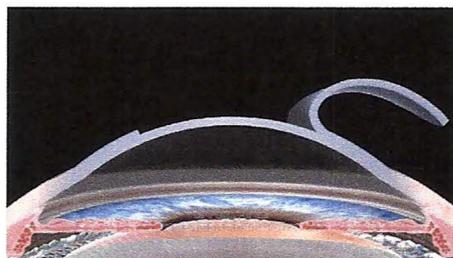


efficacious for different types of glaucoma. Patients with poor medical compliance can benefit from ALT before other surgical intervention is considered. In the ALT procedure, the eye surgeon directs a laser beam into the trabecular meshwork, which is the drainage region of the eye. The effect of the procedure is increased drainage of aqueous fluid out of the eye and intraocular pressure reduction to 20 – 25%. Efficacy of the ALT procedure lasts for about 5 years.<sup>8,10,11</sup>

### Corneal Laser treatment

The **cornea** is composed, for the most part, of connective tissue with a thin layer of **epithelium** on the surface. The transparency of the cornea is due to the fact that it contains hardly any cells and no blood vessels. In the front part of the cornea, when we treat myopia or hyperopia with lasers, the laser “cuts” a very thin flap, 90 – 100  $\mu$ , and then another type of laser (excimer) “builds” the desired shape (curvature) in that part of the eye, in seconds. This technique is called **Lasik**<sup>6,7</sup>.

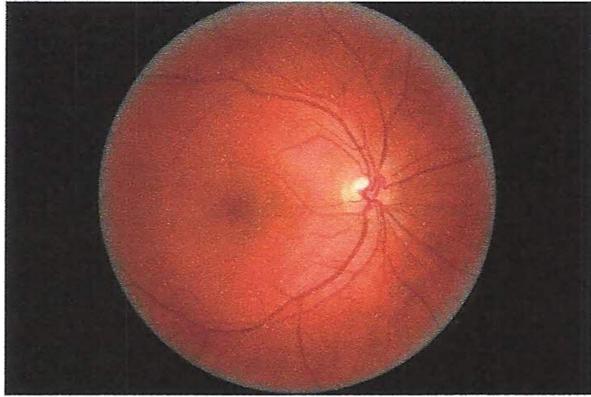
**LASIK.** Corneal laser surgery with the modern **excimer** laser is known to be the most frequently applied laser procedure in medicine. The use of lasers to **reshape** the anterior corneal curvature to correct refractive errors has become an established clinical procedure. Surgical techniques such as **photorefractive keratectomy** (PRK) and **laser in-situ keratomileusis** (LASIK) are used to correct optical aberrations of the eye, such as myopia or hyperopia, as well as astigmatism. Lasik is the most used technique in treating myopia today. A microkeratome makes a lamellar flap (average thickness, 120-160  $\mu$ m) of anterior corneal stroma, followed by refractive ablation of the exposed stromal bed. This flap is then repositioned on the exposed stroma, and good adhesion is usually obtained without the need for sutures.<sup>8,9</sup>



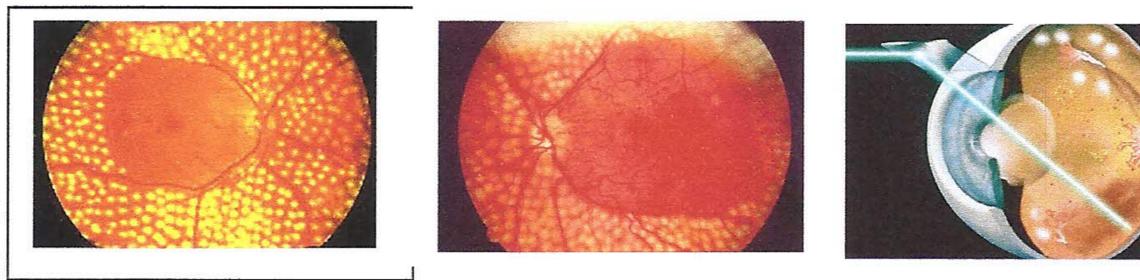
## Retina Laser treatment

The **retina** is the innermost layer of the eye and is comparable to the film inside of a camera. It is composed of nerve tissue which senses the light entering the eye. This complex system of nerves sends impulses through the **optic nerve** back to the brain, which translates these messages into images that we see. That is, we “see” with our brains; our eyes merely collect the information to do so.

The retina is composed of 10 layers, from the outside (nearest the blood vessel enriched **choroid**) to the inside (nearest the gelatinous **vitreous humor**). The diverging light passes through 9 (clear) layers of the retina and, ideally, is brought into focus in an upside-down image on the first (outermost) retinal layer (pigmented epithelium). Then, amazingly, the image is reflected back onto the adjacent second layer, where the rods and cones are located. Normally, with age, the **vitreous** gel collapses and detaches from the retina—an event known as a **posterior vitreous detachment**. Occasionally, however, the vitreous membrane pulls on and creates a **tear** in the retina. Vitreous fluid can seep into or beneath the retina, detaching it from the pigmented epithelium underneath.



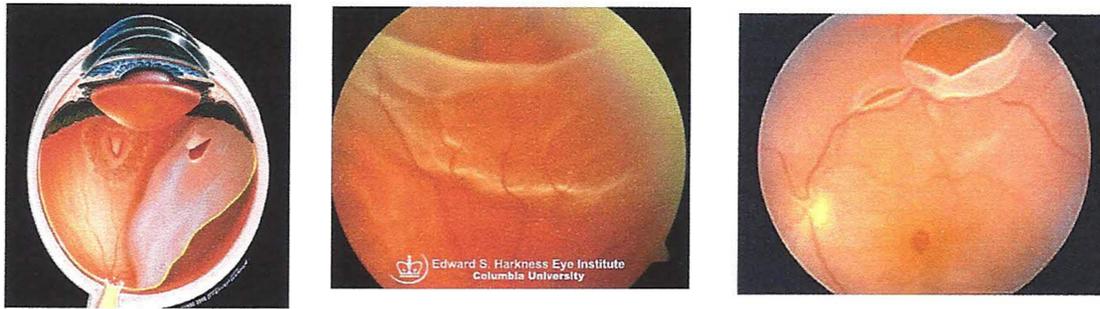
Light coagulation and laser treatment of the **retina** are widely used for the treatment of **diabetic retinopathy** and other **ischemic** retinopathies. Retinal laser photocoagulation improves inner retinal oxygenation, which affects retinopathy through the relief of hypoxia. Our efforts in retina diseases are to maintain appropriate blood circulation and oxygen transport to the macula region. So, with lasers we “burn” and “destroy” areas outside the macula, in order to minimize their oxygen demands and “feed” only the fovea and the macula.



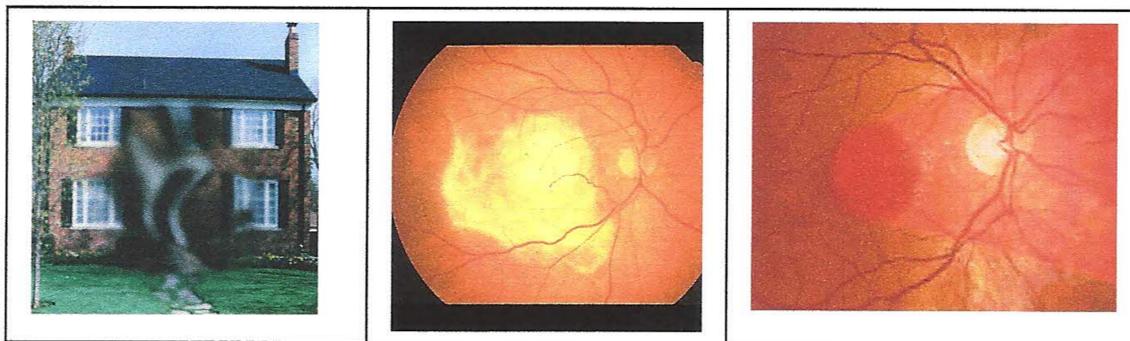
**Retinal vein occlusion (RVO)** is a common retinal vascular disorder that frequently is associated with severe visual loss. Following a vein occlusion, the primary concern is to treat the secondary complications: macular edema, macular ischemia (non-perfusion) and neovascularization (growth of new abnormal blood vessels). Argon or diode laser treatment may be useful in managing these complications. One type of laser treatment, focal laser, can be used to *close off areas of leakage from the blood vessels* that cause macular edema. Another type of laser treatment, *panretinal photocoagulation (burn shots everywhere in the retinal periphery, except macula area)*, can cause neovascularization to regress by making the retina less starved for oxygen.<sup>6,7</sup>

Laser photocoagulation is also mainly used in the retina abnormalities such as: tears, breaks, holes, lattice degeneration or retinoschisis, which predispose to a . With argon laser photocoagulation a **thermal burn** is created to surround the lesion and any

subretinal fluid associated with it. The burn becomes an adhesion between the retina and retinal pigment epithelium, and this limits potential flow of fluid from the vitreous cavity through a break.<sup>8,11,12</sup> On these situations, laser can “burn” these holes in the retina and “glue” the retina to the underneath sclera.



Nowadays, laser treatment is also available in the **age-related macular degeneration (AMD)**, a disease of our civilization. Macular degeneration is a progressive eye condition affecting the central vision and causing irreversible blindness in people over the age of 60. The concept of the new treatment for AMD is the closure of subretinal choroidal neovascularization (CNV) without significant damage to the surrounding tissues, such as photoreceptors (cones and rods). In PDT, a photo sensitizer, **Verteporfin** is administered intravenously and allowed to perfuse the CNV, as well as the remainder of the body. Fifteen minutes after the start of intravenous infusion, the **verteporfin** is activated by a red laser of a specific wavelength (689nm). The non-thermal laser light activates the verteporfin producing the singlet oxygen that



both coagulates and reduces the growth of abnormal blood vessels. This, in turn, inhibits the leakage of fluid from the CNV.

### **Tumour laser Treatment**

**Tumors.** Lasers are an irreplaceable tool in the management of malignant and benign intraocular lesions. Transpupillary **thermotherapy (TTT)** using an **810nm** infrared laser has become one of the most popular treatments for small melanomas. Lasers can be also used as an adjunctive tool in combination with other treatment modalities in therapy regimens for medium or even large melanomas. The main advantages of laser treatment compared to other modalities like irradiation are the broad availability, the relatively easy performance and thus reproducibility, the high precision during the treatment, and the safety for the adjacent tissues.<sup>12</sup>

### **Conclusion**

It is impossible to imagine ophthalmology today without lasers. A rapid explosion of argon laser techniques occurred in the late 1970s and early 1980s. In the 1990s, another explosion occurred in the treatment of posterior segment disorders, including macular degeneration and intraocular tumors. The development of lasers for plastic surgery, cataract extraction, ocular imaging and treating myopia is progressing rapidly and is expected to find much greater use and usefulness in the coming years.

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