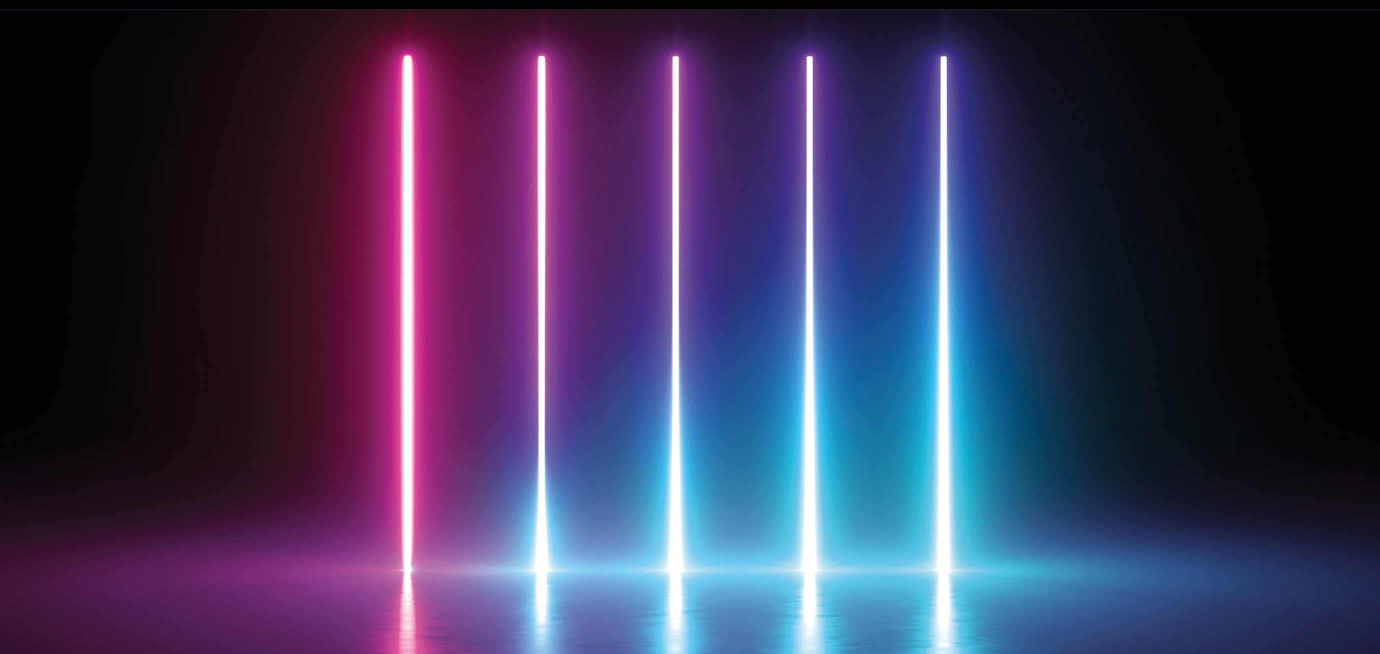
Laser Techniques in Ophthalmology

A Guide to YAG and Photothermal Laser Treatments in Clinic

Anita Prasad



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To my husband, Ajay, and children, Aditya and Tapasya, my pride and joy, for inspiring me to excel in everything I do.

To my parents for encouraging me to believe in myself.

To my family and friends for being there for me.

To my teachers and mentors, who have taught me over the years, and trainees, who have been a source of inspiration, learning, and constant evolution.

Table of Contents

Acknowledgements

Writing this book has been a rewarding and fulfilling experience. **I hope to bring a trainer's perspective, giving essential laser training some structure, based on knowledge and clinical experience.**

The book concentrates on common laser techniques in the eye clinic, bringing clarity on treatment concepts, techniques, and plans, developing good clinical practice and skill sets, with an easy to understand, user-friendly approach, using multiple digitally enhanced illustrations, for ready reference in the laser clinic.

A big thanks to Amy, Tom, and Mike from medical illustration, for their help and advice in collating images for the book.

To the trainees who jogged my memory, and proofread the book in its early stages with encouraging feedback. Thank you, Luke, Francis, Alex, James, Connor, Sejal, Shoaib, and Ellie. I hope you learnt as much from me as I have from teaching you.

Thanks to Gwyn and Patrick for their initial input and encouragement, and to Shivangi, Himani, and everyone on the publishing team. I could not have done this without your help.

Trainee Feedback

I am not aware of any existing book that approaches this subject in this way. I think ophthalmic trainees nationally and internationally would find appeal in a book that provides a structured theoretical grounding in the subject with a practical approach to using ophthalmic lasers. The use of illustrations is vital for teaching this subject and the approach used by annotating these images in this book is ideal for demonstrating techniques.

LP

The pictures are good, in particular I like the treatment plan ones with areas you might deliver lasers. I would have felt a lot more confident having read this before doing my own cases. I think the format with boxes is good with good snippets of information.

JP

About the Author

Anita Prasad is an ophthalmologist with an interest in medical retina, with over 25 years of experience, and a laser lead and trainer at ABUHB Trust for over 20 years. **It has given her a unique insight and approach into an area that is not well taught, using digitally enhanced images to highlight learning points and simplify techniques, making it easy for learners to get started with lasers.** Outside of medical work, Anita is an artist, dabbling in oils and acrylics, and enjoys reading, cooking, and community work.

Glossary

Absorb: To transform radiant energy into a different form, usually with a resultant rise in temperature

Amplification: Growth of the radiation field in the resonator cavity from multiple reflections between the cavity mirrors

Amplitude: The maximum value of electromagnetic wave height

Bandwidth: The width of the optical spectrum of light, expressed in wavelength units (m) or frequency units (Hz)

Brightness: The luminous power of a light beam

Coherence: Waves that are synchronized, with phase difference between their oscillations remaining constant as they propagate. This allows laser light to be concentrated into small spots, or ultra-small pulses

Collimation: Process by which divergent rays (natural light) are converted to parallel rays

CNV: Choridal neovascular membrane

CW mode: Continuous emission of electromagnetic wave of constant frequency or wavelength and amplitude, at constant power

Depth of field: The working range of the beam, based on wavelength and laser focusing mechanisms

Energy: Measurement of laser light to induce change (heating / cutting), measured in watts. Energy is inversely proportional to wavelength.

Excited state: State of higher energy of an atom or molecule

Flashlamp: Source of powerful light used to excite stimulated emission in a solid-state laser

Flux: The radiant or luminous power of a light beam

Fluence: All laser irradiance = laser irradiance + any backscattered irradiance.

Frequency: Number of light waves / complete vibrations in a fixed period of time. Frequency is inversely proportional to the wavelength of light

IOL: Intraocular lens

Irradiance: Laser power per unit area = watts / cm^2. It is a measure of how strongly laser works on a given tissue

Gain: The increase in energy through amplification

Gain medium: The lasing medium that provides the atoms / molecules for stimulated emission and coherent amplification

Ground state: The state of lowest stable energy level in an atom or molecule

Heat sink: Substance or device used to absorb or dissipate unwanted heat

Hertz (Hz): Measurement of frequency of light (cycles / second)

Intensity: Magnitude of radiant energy / light per unit time or area

Joules: Measurement of laser energy in time – watts / second, for pulsed laser

Lifetime: Time taken for an excited atom to spontaneously decay back to ground state or a lower energy state

Luminance: The flux / unit area

Monochromatic: Light consisting of single wavelength of light

Nanometre: Unit of length = 1 billionth of a meter, used to measure wavelength

OHT: ocular hypertension

Optical density: Protection factor of eyewear filter used with lasers. Each unit of OD represents ×10 increase in eye protection

Optical fibre: Light or laser transmitting optical material for great distances

Optical pump: Exciting a lasing material using light as the external source

PCO: Posterior capsular opacification

Photon: Smallest packet of light energy. Energy is directly proportional to the frequency of light

Population inversion: State when the atoms in the excited state exceed atoms in the ground state; forms the basis for stimulated emission

Power: Energy / unit time measured in watts. Power is constant in CW laser or variable in a pulsed laser

Power density: Laser power / surface area (spot size) on which it works. Increasing power or decreasing spot size will increase power density. Excessive power density can rupture Bruch's membrane and cause choroidal neovascularisation.

POAG: Primary Open angle glaucoma

Pulsed mode: Light emitted in short bursts or pulses of highly concentrated energy. Energy of laser in pulsed mode is much greater than CW lasers

Q-switch: Shutter device that allows laser energy to be released in small pulses. Energy is only released when it reaches a higher power

Radiance: A measure of how strong a laser is

Raman effect: When a wavelength of light can be changed by molecular scattering

Refractive Index: Property of a medium that determines how light propagates through it. RI of vacuum is 1 and of water is 1.33 (This means that light travels 1.33 times more slowly in water than vacuum). RI determines how light bends when passing through a medium. RI of lens – 1.386, vitreous – 1.336, RI of silicon oil > RI of vitreous

Resonator: The optical cavity with mirrors on each end that amplifies the stimulated emission, generating a laser beam

Spontaneous emission: Emission of a photon of light by spontaneous decay of an excited atom

Stimulated emission: External source of energy / photon that stimulates atoms to get excited and achieve population inversion; forms the basis of laser light generation

Wavelength: The distance an EM wave travels during 1 cycle of oscillation. Property of light that determines its colour, measured in nanometres. Monochromatic light has a single wavelength, while polychromatic light is multi-coloured. Wavelength determines how effectively light penetrates ocular media and how well it is absorbed by the target tissue

Introduction

LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. To lase is to absorb energy in one form and emit a new more useful form of energy.

Lasers were first conceptualized by Albert Einstein (1917). The first prototype photothermal laser was built by Theodore Maiman (1960), and they have since become essential tools in ophthalmic practice. Recent technological advances and new concepts have renewed interest in the topic.

Lasers can be generated in a spectrum of wavelengths (short UV to long IR) with a multitude of applications including electronics, information technology, science, medicine, entertainment, military, industry, and law enforcement. Modern fibre-optic communication technology such as the Internet uses lasers.

0.1 LASERS IN OPHTHALMOLOGY (DIAGNOSTIC AND THERAPEUTIC)

Lasers can reshape corneas to improve focus, improve IOP in glaucoma and cauterize haemorrhages. Surgical lasers can cut, coagulate, and remove tissues, with minimal, no-touch techniques, improving outcomes. **New concepts and advances have improved laser safety and delivery** including eye-tracking feature, subthreshold, shorter pulse and multispot lasers.

Lasers have branched into diagnostic realms, including the laser-based microscopic technique for early diagnosis of ocular (ARMD, glaucoma) and neurodegenerative conditions like Alzheimer's disease. Laser technology is used in investigative techniques such as laser interferometry, spectroscopy, microperimetry mapping of macula, confocal scanning laser ophthalmoscope (CSLO), optical coherence tomography (OCT and OCT-A), and laser retinal Doppler flowmetry.

Anatomical site	Laser procedure	Type of laser
Ocular adnexa	Removal of lid lesions, blepharoplasty, removal of wrinkles, capillary haemangioma, and port-wine stain, DCR	CO_2 laser
Cornea (keratorefractive surgery)	PRK (photorefractive keratectomy), laser in-situ keratomeleusis (LASIK), laser subepithelial keratectomy (LASEK), phototherapeutic keratectomy (PTK), laser for corneal neovascularization	Excimer laser
Sclera	Laser scleroplasty, laser suture lysis (post trabeculectomy)	Holmium YAG Argon/PASCAL
Iris	Peripheral iridotomy (PI), laser iridoplasty, laser pupilloplasty	Nd-YAG laser, Argon/PASCAL
Angle	Selective laser trabeculoplasty (SLT), PASCAL SLT	Nd-YAG laser
Ciliary Body	Cyclophotocoagulation (CPC) scleral/pupillary/endoscopic	Diode, Nd-YAG
Lens	Cataract surgery (incision, capsulorhexis, nuclear photo-fragmentation) – FLACS – femtolaser assisted cataract surgery, PCO	Femtolaser Nd-YAG laser
Vitreous	Viterolysis	Nd-YAG laser
Posterior Segment	PRP, FLT, Sectoral PRP, retinopexy, laser for ARMD, IO tumours, and other vasculopathies	Argon, PASCAL, Diode

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Other Medical Applications of Lasers	
Speciality lasers	**Uses**
Dermatology CO_2 (10600 nm), Pulsed dye (585–595 nm), Nd-YAG (1064 nm), Ho-YAG (2090 nm), Er-YAG (2940 nm), ruby laser (694 nm), alexandrite (755 nm), HeNe laser, diode laser	Cosmetic surgery – removal of tattoo, birthmarks, sunspots, stretchmarks, scars, wrinkles, hair removal, skin resurfacing and rejuvenation, management of burns, surgical scars, scar contractures, lipolysis, body contouring, removal of freckles, naevi, keratosis, viral warts, vascular/pigmented congenital lesions, acne, cellulite, and striae reduction.
Urology – YAG, thallium fibre laser	Renal stones – lithotripsy, BPH.
Rheumatology, gynaecology, ENT, surgery – CO_2, Er-YAG, HeNe, GaAs laser	Soft tissue surgery, laser scalpel.
Dentistry – HeNe, GaAs, diode, mid-IR lasers	Teeth whitening, endodontic, and periodontic procedures.
Neurosurgery – CO_2, Nd-YAG, argon	Precise removal of brain and spinal cord tumours.
Orthopaedic – diode laser	Cartilage resurfacing and reshaping.
Oncology – dye, metal vapour **laser laser** induced interstitial thermotherapy (LITT)	Superficial skin cancers (BCC, SCC), endothelial – penile, vulval, vaginal, cervical, early non-small cell lung cancer.
Cardiothoracic – argon laser, Nd-YAG laser, CO_2 laser	Coronary artery disease, ventricular and supraventricular arrhythmias, hypertrophic cardiomyopathy, laser thrombolysis, trans-myocardial laser revascularization.

THERAPEUTIC ROLE OF LASERS IN OPHTHALMOLOGY

Section 1 Basic Principles of Laser

This section deals with basic laser principles and their applications in the eye clinic. It gives an overview and understanding of laser physics, delivery, safety, and pathophysiology for safe laser treatment.

1.1 LASER PHYSICS

Laser light differs from ordinary light, with special properties, making it clinically useful.

1.1.1 Properties of Laser Light

1. **Coherent –** all wavelengths are in phase, to accurately focus the beam, allowing precise experiments and measurements.
   - **Coherence allows laser light to be manipulated longitudinally to create short pulses or transversely to get small spots.**
2. **Polarized –** all wavelengths vibrate in one plane.
3. **Monochromatic –** light of single wavelength or frequency or colour. Monochromaticity reduces chromatic aberration and allows selective tissue targeting, based on the tissue absorption spectrum.
   - Ordinary light (natural or artificial) is multicoloured, with a range of visible and invisible (ultraviolet and infrared) wavelengths. A fluorescent lamp has a narrow spectral emission, coloured LED (light emitting diodes) have narrower bandwidth, and He-Ne laser bandwidth is extremely narrow at 632.8 nm (red).
   - **Monochromaticity is not essential; some lasers emit a range of wavelengths.**
4. **Collimated – all waves are unidirectional, parallel over long distances and remain intense and focused** (ordinary light diverges and becomes less bright). **Collimation allows precise focus without losing beam intensity**.

Lasers can be manipulated to make them useful in practice:

- **Ability to be concentrated in short intervals,** generating intense pulses.
- **Ability to produce non-linear effects** – non-linear absorption, refraction, decrease transmission, frequency doubling, Raman effect, frequency amplification, mode locking, and Q-switching.

1.1.2 Understanding Laser Physics

Molecules are made up of atoms, with a central positively charged nucleus (protons and neutrons), orbited by negatively charged electrons.

Ground state (non-excited state) is the lowest possible energy state of an atom. Electrons in ground state absorb energy and rise to an **excited state** (higher orbit).

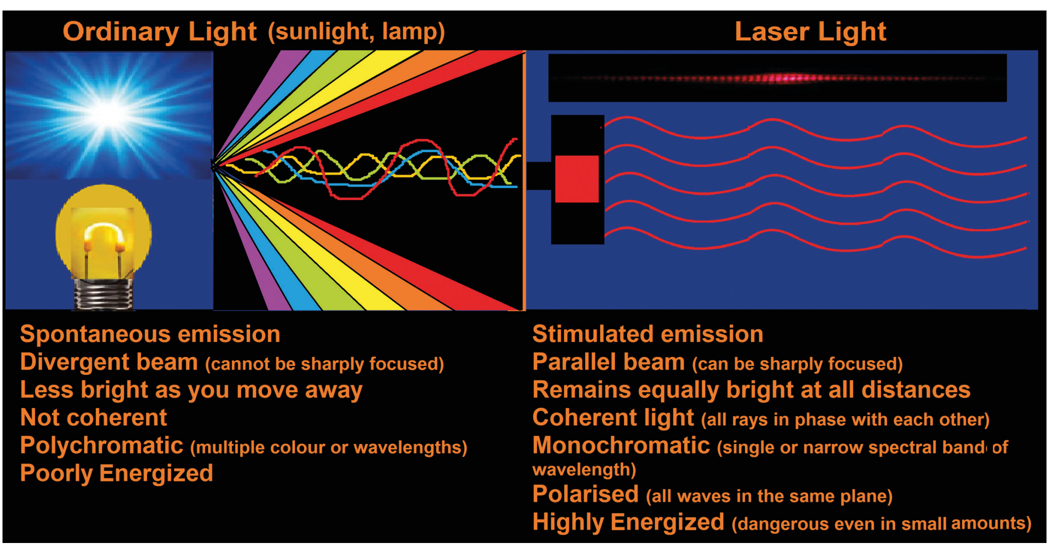

Figure 1.1 Ordinary light vs laser light.

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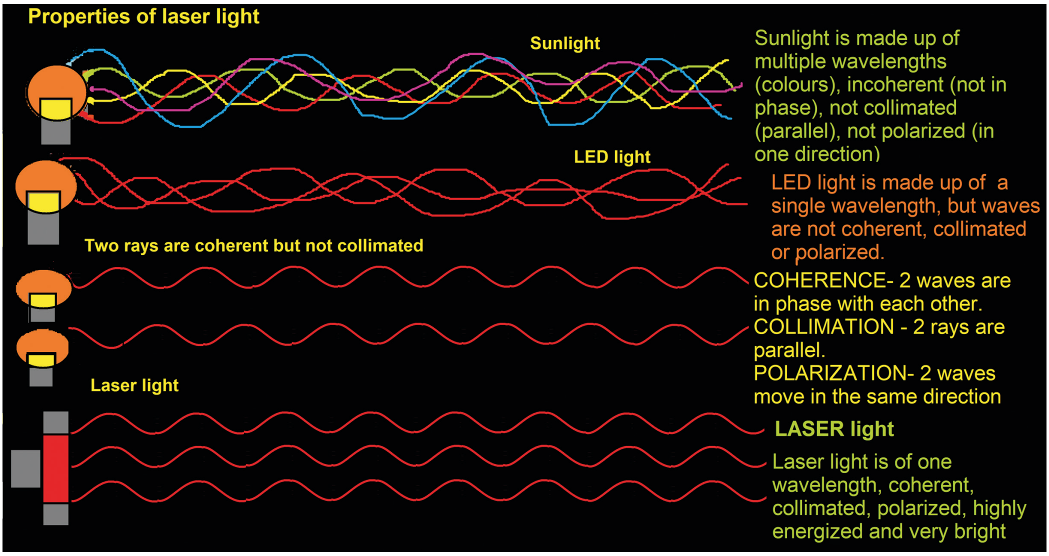


Figure 1.2 Properties of laser light.

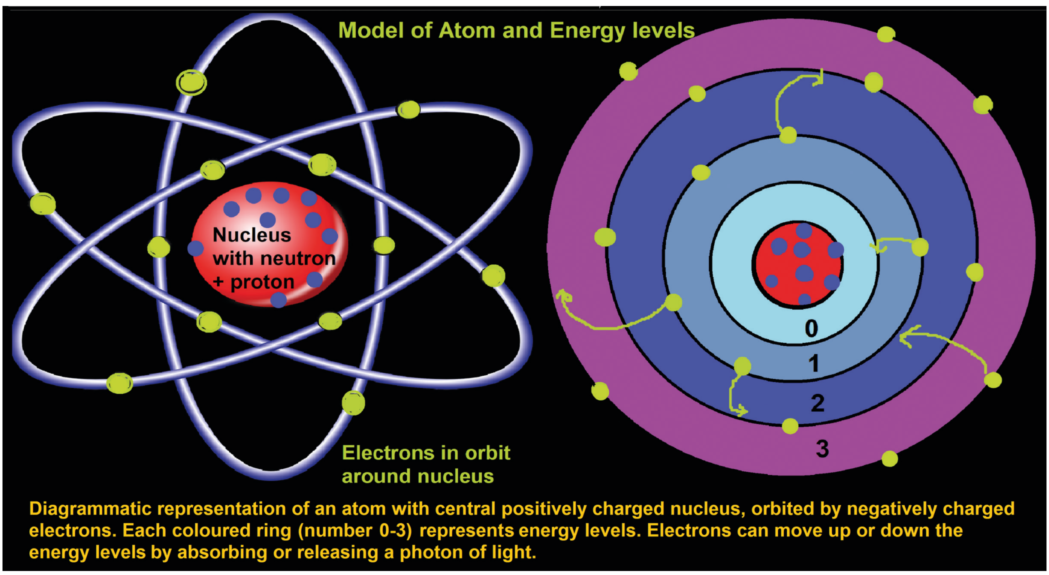


Figure 1.3 Atom and energy levels.

- **Light is an electromagnetic wave, emitting radiant energy** in tiny packets called **photons or quanta.**
- **E = hv** (E is energy in joules, h is frequency of light in hertz, and v is Planck's constant = 6.626×10^{-34} joules times second).
- Each photon has a characteristic frequency or wavelength.
- The **energy of a photon depends on its frequency or wavelength.**
- Wavelength is inversely related to frequency. High frequency = short wavelength, and vice versa. Wavelength (λ) is measured in nanometres.
- One **wavelength** is the distance between 2 successive wave crests or troughs.
- **Frequency** is the number of waves per second, measured in hertz. Higher frequency light has more waves/second (shorter wavelength).

- **Energy is directly proportional to frequency – higher frequency has higher energy and a shorter wavelength.**
- **The blue and UV end of the spectrum has more energy than the red or IR end of the spectrum.**

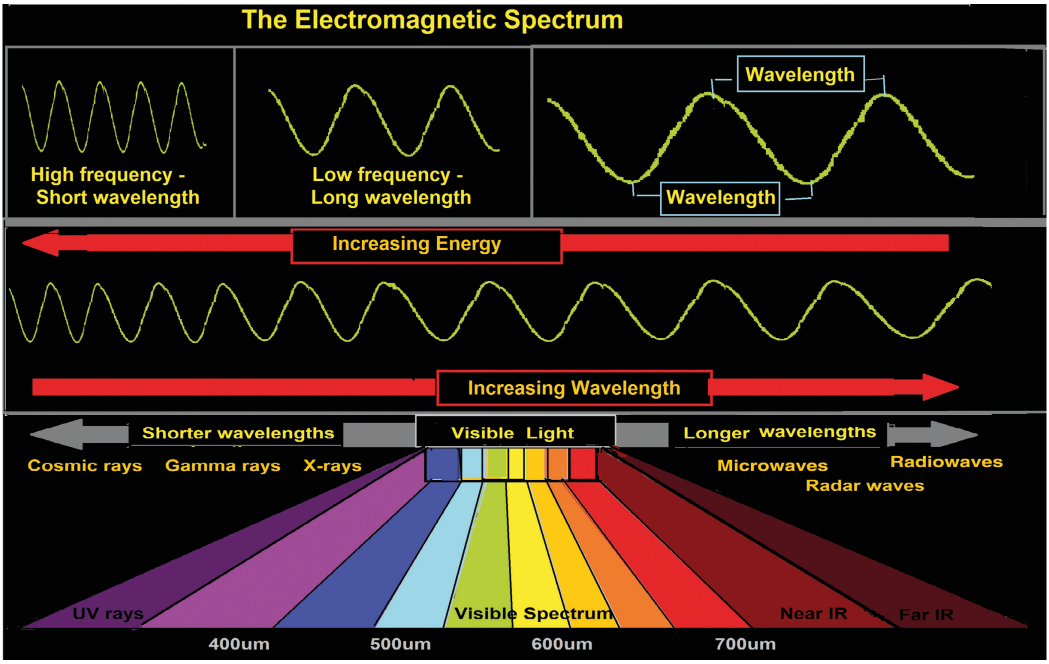


Figure 1.4 The electromagnetic spectrum.

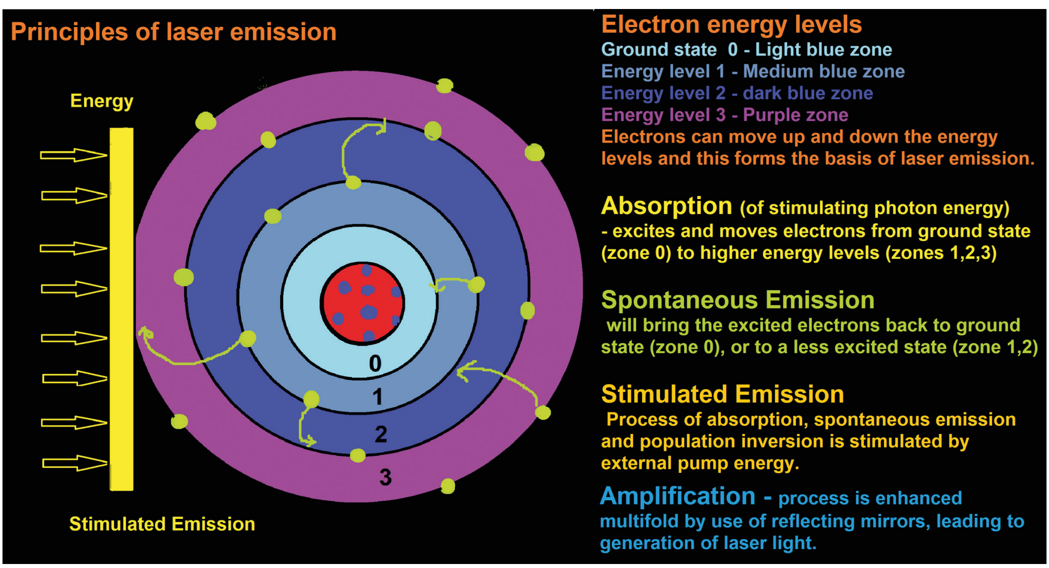


Figure 1.5 Principles of laser emission.

1.1.3 How Does an Atom in the Ground State Move to an Excited State?

- Normally, atoms in a medium are in a stable, low-energy ground state. **When a photon of light stimulates** it, electrons absorb the photon energy and move up to an excited, higher energy state – **absorption**.

- Electrons do not stay excited forever. They decay spontaneously by releasing energy and move down to a lower level of energy or back to the ground state.
- The decay time is called **lifetime.**
- Decay to a lower orbit releases a photon (energy) – **spontaneous emission**.
- The energy of an emitted photon is the difference between the stimulating energy and end energy (same as the stimulating energy if decay is to ground level or lower if decay is to a less excited level).
- **The emitted photon has the same phase, direction, and wavelength as the stimulating photon.**
- **So, transition of electrons up or down the orbit is accompanied by absorption or emission of a replica photon.**

1.1.4 Stimulated Emission

- Absorption excites atoms. If more photons strike the atom, it stimulates more and more electrons at ground state to get excited or already excited atoms to reach higher levels of energy. Eventually, a point is reached where the number of excited electrons is greater than electrons in ground state – **population inversion.**
- Population inversion leads to spontaneous emission of higher energy photons, which stimulates more electrons – **stimulated emission.**
- If this process is repeated multiple times, it generates an extremely high level of energy – **light amplification.**
- The newly emitted photons have the same frequency and direction as the stimulating photons. **Stimulated emission is effectively a process of cloning photons, amplifying light, and forms the core principle of laser action.**

The photons generated are monochromatic, collimated, coherent, highly energized, and very bright. These are all features of laser light.

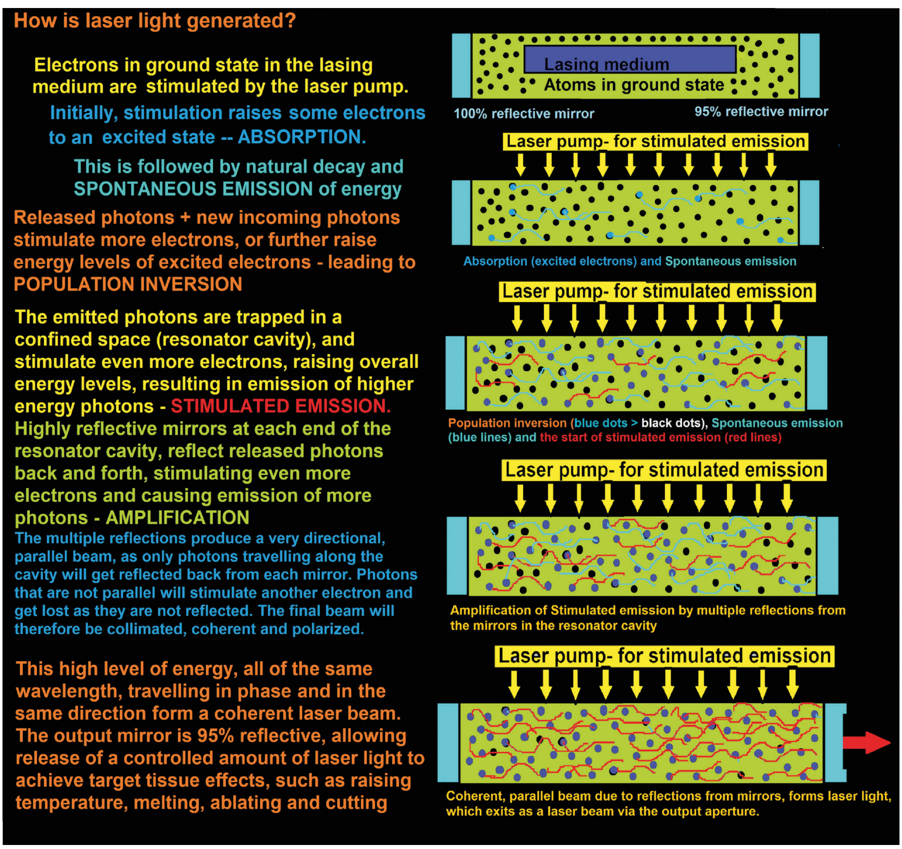


Figure 1.6 How is laser light generated?

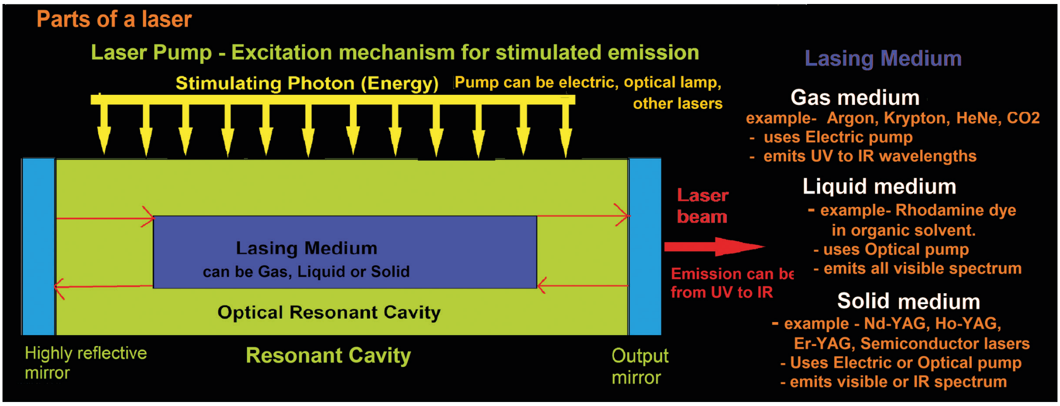


Figure 1.7 Parts of a laser.

1.1.5 Parts of a Laser

A laser comprises a pump, lasing medium, and resonator cavity.

- A **laser pump is the external energy source** that excites the lasing medium and triggers stimulated emission.
- **Gain/lasing medium** (provides atoms for stimulated emission)
- **Optical resonator** – cavity around the lasing medium with mirrors to amplify stimulated emission and an aperture to allow release of a laser beam for clinical effect.

Laser pump – External energy to excite atoms and start process of stimulated emission.	
Pumping can be by	**Variety of laser pumps used**
• Continuous discharge lamp for CW laser	• Optical pump – flashlamp, arc lamps, light from another laser (diode).
• Intermittent flashlamp for intermittent pulses.	• Chemical reactions
	• Explosive devices
	• Electric currents in semiconductors.
	• Pulse duration varies from CW to femtoseconds.
	• A laser can fire a single shot or repetitive bursts of pulses.

Laser or gain medium – Determines laser properties and emitted wavelength. Provides atoms, electrons, or ions to be excited by the pump.			
Gas lasers – Gas enclosed in a tube and pumped by electrical discharge. Three types:			
	Atomic lasers	**Ionic lasers**	**Molecular lasers**
Example	Helium-neon	Argon, krypton	CO_2 laser
Pump	Electric	Electric	Electric, radio waves
Lasing medium	Neon atoms	Argon, krypton ion	CO_2 molecule (10–15% CO_2 gas)
Role of other molecules	Helium carries electric charge to neon atom		Nitrogen is transport gas Helium is heat sink gas
Wavelength emitted	633 nm, used in optical research labs	315–529 nm 458, 488, 514 nm	10600 nm – thermal IR in cutting, welding, used in dermatology
Liquids lasers – Active medium is an organic dye (rhodamine), dissolved in a liquid solvent (ethanol or ethylene glycol), in a glass chamber, pumped by another laser; emits across entire EM spectrum.			
Free Electron Lasers (FEL) – Active medium is an electron beam from a particle accelerator. Generates tuneable wavelengths in widest frequency range of any laser.			
Excimer lasers – excited diatomic molecule (excited dimer) – electrical pumping forms an unstable diatomic molecule (from union of 2 rare gases or a rare gas with a halogen). UV emission occurs when unstable diatom dissociates back to the constituent atoms. Examples: *argon fluoride – 193 nm, krypton chloride – 222 nm, krypton fluoride – 248 nm, xenon chloride*			

Metal-vapor lasers – hybrids lasers (features of atomic and ionic lasers). Examples: helium-cadmium laser, helium-copper, helium-gold lasers.

Chemical lasers – two highly reactive gases form a molecule which becomes the lasing medium. Emit IR spectrum (2700 nm–3800 nm). Example: hydrogen fluoride (HF).

Solids state lasers – use cylindrical crystal (YAG, sapphire) or glass rod that has been doped with the active lasing medium. The crystal is used for its mechanical, thermal, and optical properties.

- **The dopant or lasing medium is a 1% impurity such as chromium, erbium, neodymium, titanium, holmium, and ytterbium ions added to the crystal.**
- **Normally, solid state lasers emit in the infrared spectrum but can be made to emit a wide range of wavelengths by using a variety of crystals and harmonic generation or frequency doubling.**
- *Example: Nd-YAG emits 1064 nm (IR), but can be frequency-doubled 532 nm PASCAL (green, visible), tripled – 355 nm, and quadrupled – 266 nm (UV) rays, by using KTP crystal.*
- **They are pumped by a flashlamp or light from another laser.** *A flashlamp is not the most effective as 70% is wasted as heat in the crystal, requiring cooling.*
- **A laser-generating higher frequency-monochromatic light is a better pump (diode laser).**
- A CW solid laser causes tissue heating (IR emissions), and is **best operated in a pulsed mode, using Q-switch or mode lock to generate ultra-short pulses.**

Dopant	Examples of laser	Wavelength generated
Neodymium	*Nd – yttrium aluminium garnet (YAG)* *Nd – yttrium orthovandate (Nd-YVO4)* *Nd – yttrium lithium fluoride (Nd-YLF)*	*Near IR – 1064 nm, can be made to emit other wavelengths (tuneable)*
Titanium	*Ti – sapphire laser*	*IR, highly tuneable*
Holmium	*Ho – YAG laser*	*Far IR – 2097 nm*
Chromium	*Cr – sapphire laser (ruby laser)*	*Near IR spectrum*

The resonator cavity – optical cavity around the laser medium with highly reflective mirrors at each end, to reflect photons multiple times, cause amplification, and improve laser efficiency.

- **Amplification and directionality of beam –** multiple reflections increase energy exponentially; only parallel beams get reflected.
- **Use of other optical devices –** spinning mirrors, modulators, absorbers, filters, and crystals, placed in the cavity to alter laser wavelength or pulses' duration.
- **Provides means of controlling laser usage –** output mirror is 95% reflective, allowing controlled release of laser for tissue effect.

1.2 PARAMETERS OF LASER LIGHT – DETERMINES ITS TISSUE BIOLOGICAL EFFECTS

Laser is defined by three parameters: wavelength, power, and mode.

1.2.1 Laser Wavelength

Spectrum of wavelengths (measured in nanometres and micrometres) – Determined by the lasing medium and defines tissue penetration, allowing optimal wavelength selection for specific tissue targets.				
Spectrum		**Laser type**	**Wavelength**	
Far IR **Mid IR** **Near IR**		CO_2 laser Er-YAG Ho-YAG Nd-YAG Diode	10,600 nm 2940 nm 2120 nm 1064 nm 810 nm	Infrared wavelengths cause thermal effects on tissues
Visible spectrum 400 nm–750 nm		Diode laser Ruby laser Krypton HeNe laser HeNe laser Dye laser PASCAL laser Argon laser	680 nm 694 nm – red 647 nm – red 632 nm – red–orange 543 nm – green 570–630 nm – yellow 532 nm – green 514 nm – green 488 nm – blue	Visible range wavelengths cause photochemical reactions
Ultraviolet		Excimer laser XeF – xenon fluoride XeCl – xenon chloride Nd-YAG solid laser Nd-YLF solid laser KrF – krypton fluoride ArF – argon fluoride	351 nm 308 nm 266 nm (freq quad) 263 nm (freq quad) 248 nm 193 nm	Shorter wavelengths have higher energy UV lasers energy > IR lasers energy

Common Lasers Used in Ophthalmology			
	IR lasers	**Visible lasers**	**UV lasers**
	High wavelength lower energy	**Red, yellow, and green lasers**	**Shorter wavelength higher energy**
Laser type and wavelength and pulse duration	**CO_2** – 9.2–10.8 µm, **CW or ms pulsed** **Er-YAG** – 2.94 µm, **100–250 ns pulsed** **Ho-YAG** – 2.1 µm, **100–250ns pulsed** **Nd-YAG** – 1064 nm, **100ps – CW** **Nd-YLF** – 1053 nm, **100ps –CW** **Ti-Sapph** – 700–1000 nm, **60fs – 10ps pulsed** **Diode** – 635–1550 nm, **1ns – CW** **Alexandrite** – 720–800 nm, **50 ns–100 µs**	**Ruby laser**- 694 nm, **1–250 µs** **Krypton** – 531, 568, 647 nm, **CW or ms pulsed** **HeNe** – 633 nm, **CW** **PASCAL** – 532 nm (freq doubled Nd-YAG), **ms pulsed** Nd-YLF (freq-doubled) – 532 nm **Argon** – 488 and 514 nm, **CW or ms pulsed. Argon blue (488 nm) no longer used due to risk of macular burn**	ArF **Excimer laser** – 193 nm, **3–20 ns pulsed** KrCl (222 nm), KrF (248 nm), XeBr (282 nm), XeCl (308 nm), XeF (351 nm) **Gas lasers** – second harmonic bands of ionic and metal vapour lasers such as argon – 363–275 nm krypton – 356, 350, 337 nm He-Cd laser – 325 nm gold (Au) laser – 312 nm. *These are examples of visible lasers emitting in UV range by using frequency doubling.*
Laser effect	Absorbed by tissues with high water content, useful for surgical and thermal effects. IR lasers generate heat used in cutting and welding. **Thermal, mechanical, photochemical**	Red, green, and yellow lasers are well absorbed by the RPE, making them ideal for **thermal photocoagulation. Thermal Imaging** (HeNe) laser	High energy breaks molecular bonds and ionizes tissues, without thermal effects. Allows precise tissue sculpting and useful in corneal remodelling and cataract surgery – **photoablation**

1.2.2 Tuneable Lasers

Wavelength output of lasers depends on the lasing material, its refractive index (RI), length, and optical features of the resonator cavity (that alter laser oscillations), wavelength of laser pump, and substances or crystals added, to alter properties of the lasing material.

- **Frequency doubling** – alters long IR wavelengths into short visible and UV ranges;
- **Raman scattering** converts shorter wavelengths into longer wavelengths (far IR).

Lasers can be made to emit variable wavelengths by altering the optical cavity, lasing material, pumping mechanism, or the addition of frequency-changing crystals.

Common non-linear crystals used are KTP (Potassium titanyl phosphate), KDP (potassium dihydrogen phosphate), $KNbO_3$ (potassium niobate), BBO (beta-barium borate), LBO (lithium triborate), GaSe (gallium selenide), $ZnGeP_2$, and $LiIO_3$ (lithium iodate).

Example: Nd-YAG laser normally emits a 1064 nm wavelength in harmonic generation, and can emit at

- 532 nm at second harmonic (green) – frequency doubling;
- 355 nm at third harmonics (UV) – frequency tripling; and
- 266 nm at fourth harmonics (ultraviolet) – frequency quadrupling.

1.2.3 Power

Laser generates high energy light. When focused, energy per unit area reaches extremely high levels, capable of damaging tissues, making them medically useful but potentially dangerous to work with.

Terminology	Description	Measurement unit	Symbol
Radiance	Laser energy measurement	**Joules**	**J**
Fluence	Laser energy per square meter	**Joules/square metre**	**J/m²**
Power	All laser energy (transmitted, emitted, reflected) per unit time	**Watt = joules/second**	**W**
Irradiance or intensity	Laser power per square surface area	**Watts/square metre**	**W/m²**
Power is measured in watts = Joules/sec (energy/time)			
Threshold power is the least power needed to obtain a just visible tissue effect. **Subthreshold energy** uses lower power, to achieve effects without visible burns.			
Power is modulated by altering energy or time **(P= E/t)**, so increasing laser energy or reducing pulse duration will increase laser power.			
Irradiance/power density = power/area = watts/cm². Increasing power or reducing spot size will increase power density, for a more intense effect.			

1.2.4 Mode

CW mode – Lasers emit continuous radiation and are more damaging than pulsed lasers due to longer tissue exposure. Emission >0.25 second is regarded as CW.

Pulsed mode – emissions occur in short bursts of highly concentrated energy.

- Pulses can be **long (millisecond), short (microsecond)**, Q-switched (**nanosecond** – extremely short pulse), or mode locked, emitting **picosecond pulses.**
- Number of pulses delivered per second is the **repetition rate**, which can vary from low (<1 pulse/second) to exceedingly high rates (>100/second)
- Solid-state lasers usually operate in the pulsed mode, to achieve higher power for photo-disruption with reduced risk of heat generation and collateral damage.

A CW laser can be made to operate in the pulsed mode, by

- modulating the pump to stimulate intermittently or
- modulating the output, to release intermittently, using locks and switches.

Modes of Laser Emission		
Laser mode	**Laser type**	**Wavelength**
CW – emits constant laser output from a constant pump source. Generates lower power than pulsed mode.	CO_2 laser **Argon**	10,600 nm 488 nm, 514 nm
Quasi CW – mechanical shutter produces bursts of CW output, or shorter pulses of milliseconds, with slightly higher energy.	KTP laser, **PASCAL** Copper bromide vapour laser Argon pumped tuneable dye laser Krypton laser	532 nm 510 nm, 514 nm 577 nm, 585 nm 568 nm
Pulsed mode – generate higher energy than CW output. **High energy – v. short pulse** The repetition rate can vary from short to long intervals.	Pulsed dye laser (PDL) Q-switched ruby laser Q-switched alexandrite laser **Q-switched Nd-YAG laser** PASCAL Er-YAG CO_2 pulsed laser	585–595 nm 694 nm 755 nm 1064 nm 532 nm 2940 nm 10,600 nm
Very short pulse laser (picosecond)	Nd-YAG Alexandrite laser	1064, 532 nm 755 nm

Generation of Pulsed Laser

- **Pulsed pumping** – Intermittent stimulation, using external switch/modulator (shutter).
- **Pulsed release** – internal modulation or switches that release laser intermittently.

Various techniques are used to alter pulse durations, allowing stored energy to be released as a giant pulse of extremely high energy, in a short pulse duration. Energy generated in a pulsed mode is much higher than a CW mode.

Device/technique to alter pulse duration	Laser pulse duration
Electronic shutters	1 ms
Pulsed flash lamps	1 us
Q-switching	1 ns
Mode locking	1 fs

Generation of pulsed laser – Turning the laser on and off by internal modulation is more efficient in generating higher energy, which is stored and released as a giant pulse when needed.

Gain switch	Q- Switch	Cavity dumping	Mode locking
Pulsed pumping (with flash lamp or another laser), using shutters or switches. Inefficient method. Generates lower power and longer pulses.	Q-switch blocks one mirror, preventing laser amplification, but pump continues to stimulate (energy stored as population inversion). When activated it generates high energy in a short pulse.	Both mirrors 100% reflective, allowing build-up and storage of high energy. Use crystals to diffract laser release via a different outlet (acoustic-optic deflectors, electro-optic modulators).	Uses constructive interference to mode lock or couple ultra-short pulses by altering resonant cavity length. It generates ultrashort pulses (picosecond and femtosecond) with a high repetition rate.
Generates less power – examples are Nd-YAG laser, Ti-Sapphire laser (can use cavity dumping, or q-switch or mode locking to generate pulse			
Excimer laser **Metal vapour laser**	**Nd-YAG laser**	Generate less power than Q-switch.	**Ti-Sapphire laser**

Three Ways to Achieve Q-Switching

- Use mirror or prism rotating opposite to, but not aligned to the output mirror in the resonant cavity, preventing amplification. Periodically, alignment is achieved, producing a Q-switched pulse.
- Insertion of electro-optic or acoustic-optical device in the in the resonator cavity, which modulates the laser pathway and its release in short bursts.
- Insertion of a non-linear absorbent element in the cavity, which blocks one of the mirrors and only becomes transparent when a certain amount of energy is attained in the resonant cavity, generating a Q-switched pulse.

1.3 LASER DELIVERY SYSTEMS

Laser treatment can be delivered by various routes.

1. A **slit lamp Slit lamp – Contact lens contact lens is the commonest, safest, and most controlled method of laser delivery**, with a standardized spot size, due to a stable working distance.
2. **Indirect ophthalmoscopy with a +20D condensing lens.** Spot size varies, based on working distance and power of condensing lens.

3. **Trans scleral –** cyclodiode.
4. **Endo-laser –** during vitrectomy.
5. **Fundal camera-based delivery** (Navilas).

1.3.1 Slit Lamp Laser Delivery

The slit lamp is a high-powered, compound microscope with a long focal length, flexible slit-shaped illumination, and variable magnification, to provide a binocular, stereoscopic, and dynamic view of the eye. Accessory lenses (contact or non-contact) are used for fundal view. Contact lenses offer better control, focus spots, and improved laser safety.

Basics of slit lamp – a slit lamp has three main parts: mechanical system, illumination tower, and biomicroscope.

The mechanical system – provides coupling (common axis of rotation) of the microscope and illumination systems, which coincides with their focal plane (parfocality), to ensure that light will always fall where the microscope is focused.

The illumination system/tower – Consists of a light source, condensing lens, filters, horizontal and vertical slit diaphragms, projection lens, and reflecting mirror or prisms. Illumination comes from above (Haag Streit), or below (Zeiss), to provide a bright light, which is projected onto the eye under examination.

The illumination tower can be swivelled 180° on the horizontal axis and 20° on the vertical axis (slit lamp tilt). It houses filters, including:

- Neutral density and heat absorption filter (reduces brightness and discomfort for photosensitive patients).
- Cobalt blue filter (for tonometry, and corneal examination).
- Red-free (green) filters enhance blood vessels and haemorrhages.

Biomicroscope observation system – Provides an enlarged, stereoscopic image of the eye. The LED filament is imaged on to the objective lens, but the mechanical slit is imaged on to the patient's eye – Kohler's Principle (ensures a bright beam with no glare).

The observation system comprises:

- **Objective lens** – Two plano-convex lenses (power +22D and **telescope system** (between eye piece and objective lens) to alter magnification (Grenough flip lever ×10, ×16, or Galilean magnification wheel ×6, ×10, ×16, ×25, and ×40).

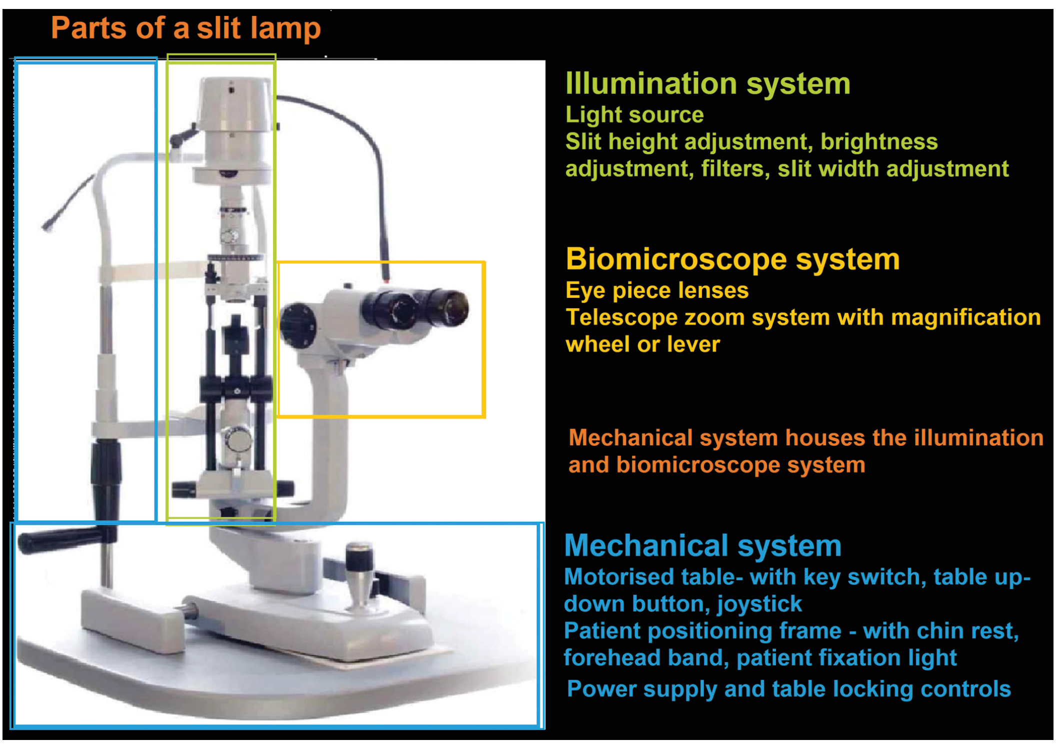


Figure 1.8 Parts of a slit lamp.

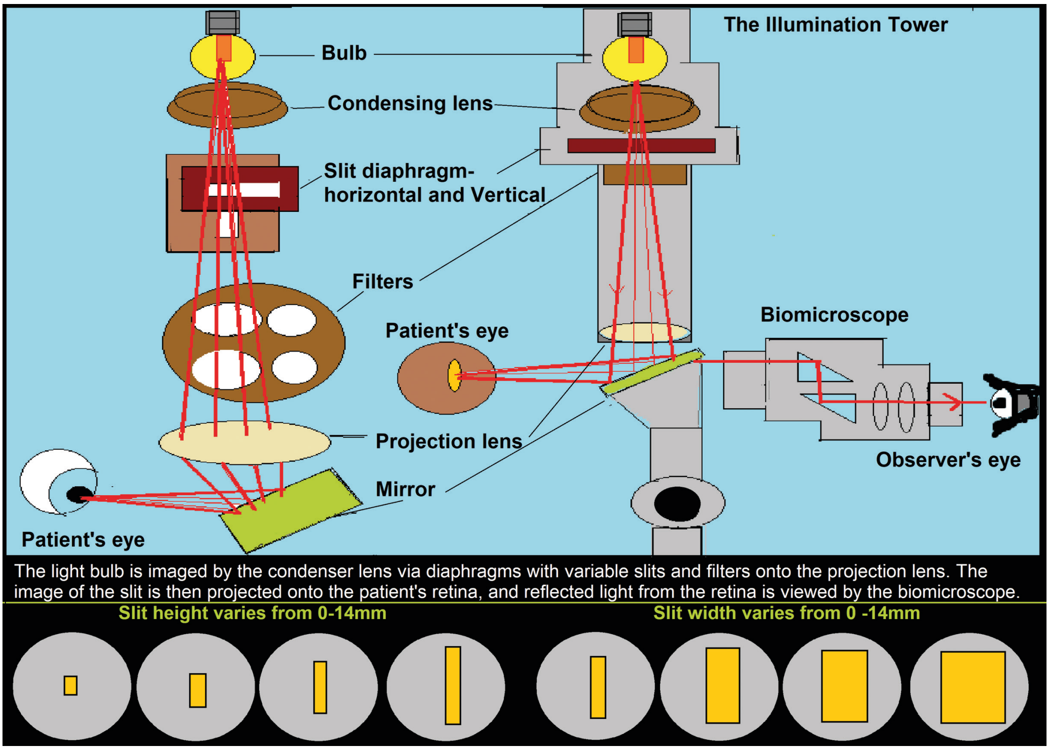


Figure 1.9 The illumination tower.

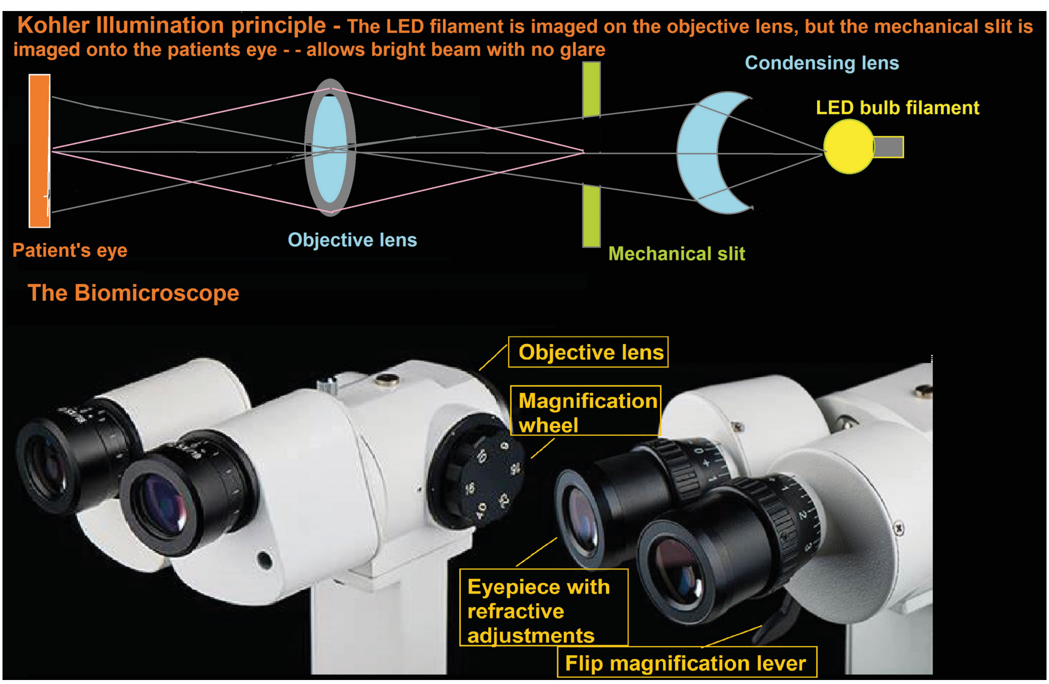


Figure 1.10 The biomicroscope.

- **Eyepiece lens** – Magnifying lenses (+10/+12D), with refractive adjustments from +7 to –7 dioptres, housed in converging tubes (10–16°), to provide good stereopsis. Eyepiece IPD can be adjusted, from 52mm to 78mm.

The slit lamp has three types of laser delivery systems:

- **Parfocal system (Zeiss, PASCAL)** – Slit lamp and laser have the same focal plane, with low beam divergence (parallel beam), leading to a sharp spot, uniform energy delivery and well-defined retinal burn. The size of the beam is the same at the cornea, lens, and retina, leading to potential risk of corneal or lenticular damage, with media opacities or poor focus.
- **Defocused beam delivery (Ellex) –** beam has high divergence, which reduces laser energy at the cornea and minimizes risk of inadvertent corneal burns. As the 2 focal planes are not the same, the spot is less well defined.
- **Surespot system (Lumenis)** – defocused system with a more controlled spot, to improve precision, reduce power density at the cornea, and increase laser efficacy and safety.

<table>
<tr><td colspan="2">Slit lamp examination and laser treatment is preferably done in a semi-dark room</td></tr>
<tr><td colspan="2">Adjust eyepieces, for IPD, refractive errors, and focus.</td></tr>
<tr><td>• Set IPD slightly less than normal to account for proximal convergence of slit lamp.
• Set a fraction more minus than user refractive error to overcome proximal accommodation and convergence of the eyepieces.
• Set focus of eyepiece when first using slit lamp or laser.</td><td>Setting slit lamp eyepiece focus.
• Use focusing rod (in slit lamp drawer). Mount it in front of microscope, by removing the flat groove alloy plate. Set slit beam 1–2mm wide and direct it at the centre of the rod.
• Set one eyepiece at a time, by moving from the + side of scale, until the image first appears sharply focused (to avoid stimulating accommodation)
• Make a note of the readings on the eyepiece and use this in the future. You do not need to use the focusing rod after this first occasion.</td></tr>
<tr><td colspan="2">• Adjust table height and chin rest for comfort.
• Ensure slit beam is evenly illuminated with sharply demarcated edges.
• Pull joystick back and move slit lamp in to focus on area of interest. The final focus is sharpened by small movements of the joystick.</td></tr>
<tr><td colspan="2">Set Slit Parameters
• Slit brightness – Just visible level. Excessive brightness causes glare, adversely affecting procedure and safety.
• Slit height – Tallest position (remains unchanged during treatment).
• Slit width – moderate wide (5–6mm), keeping disc and fovea in view.
• Narrow slit – reduces FOV (smaller area of illumination) but increases depth of focus, useful to identify subtle details, treat mA, and sharpen focus.
• Wide slit – allows larger FOV, good for faster treatment in PRP.
• Do not make the slit so narrow that you lose your bearings on the retina.</td></tr>
<tr><td colspan="2">Set slit lamp magnification
Low ×6 for initial examination and PRP
High magnification ×10 or ×16 for details and FLT</td></tr>
</table>

1.3.2 Binocular Indirect Ophthalmoscopy (BIO); Laser Indirect Ophthalmoscopy (LIO)

BIO offers good illumination, stereopsis, and FOV but lower magnification and can be difficult to learn. Movements affect size and clarity of the fundal image.

- **Fundal image is inverted and laterally transversed.**
- **Power of condensing lens determines retinal magnification and field of view**.
- **The 20D lens with working distance of 47mm provides a reasonable FOV, stereopsis, and magnification, and is the most common lens used.**
- **Fundal view and spot size are influenced by lens used, working distance, and patient's refractive error.**

Indirect ophthalmoscope-delivered laser (LIO) – For retinal vasculopathies and peripheral retinal diseases, in patients where slit lamp delivery is difficult (anxious, physically or mentally handicapped patients, paediatric patients, presence of media opacities, perioperative laser treatment after surgery). Patients lie supine – a lid speculum is used to keep the eye open and saline drops to keep the cornea moist.

LIO is a less controlled method of laser delivery, with no standardization of spot size and inability to treat the posterior pole safely.

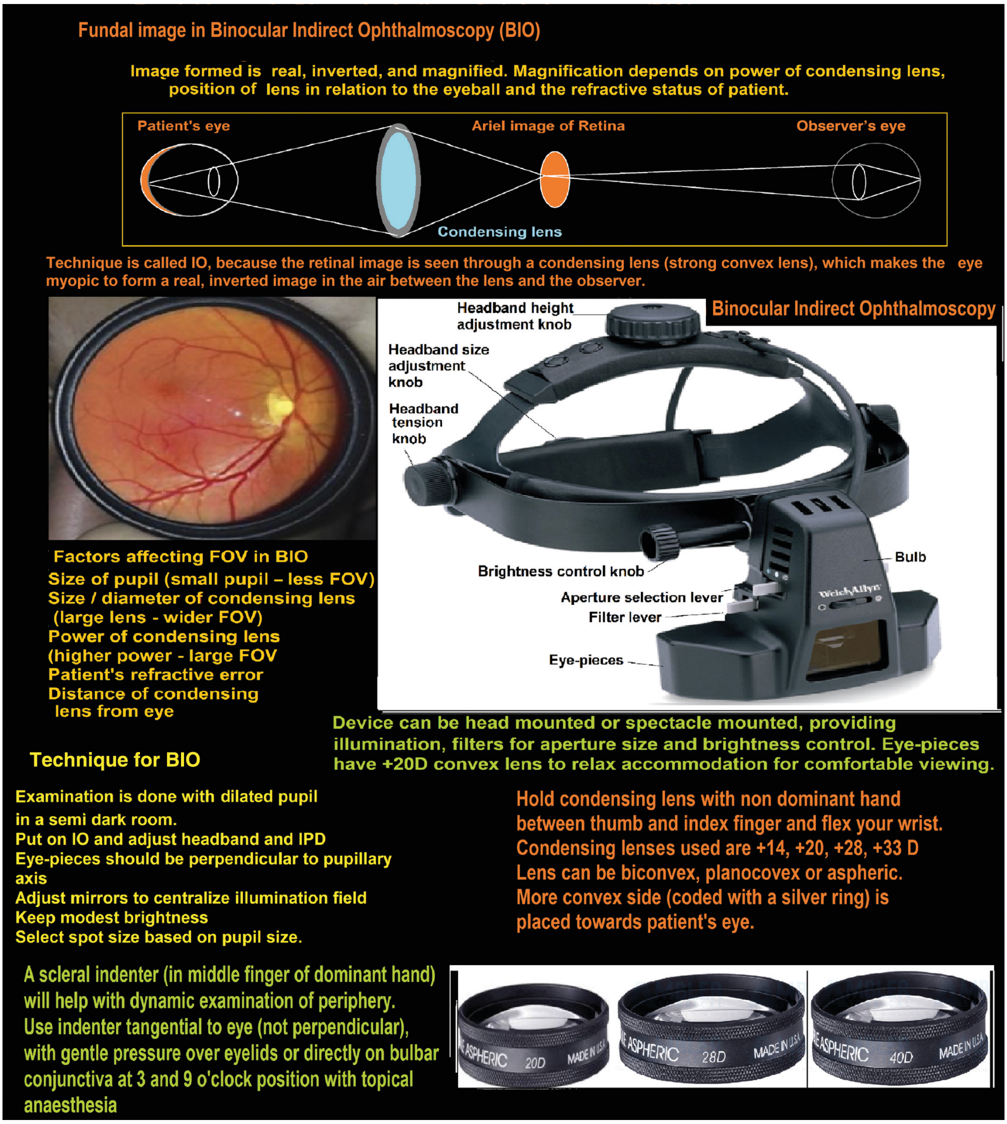


Figure 1.11 BIO.

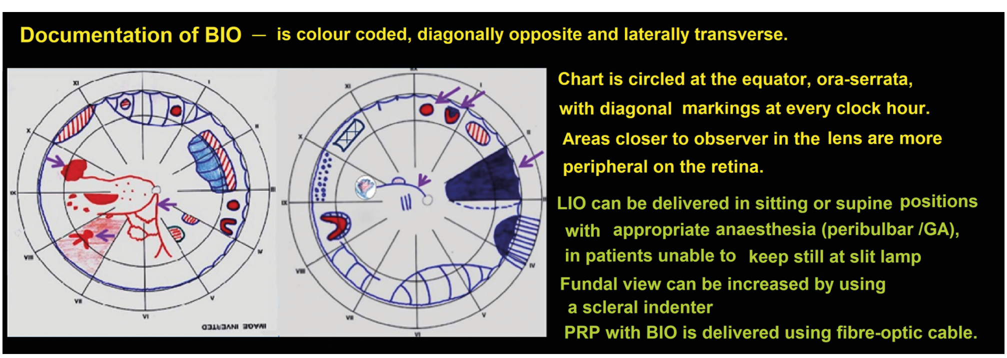


Figure 1.12 Documentation of BIO.

1.4 LASER TISSUE INTERACTION

Chromophores are pigments that absorb laser light to achieve tissue effect. The main ocular chromophores are melanin and haemoglobin. Understanding laser absorption spectrum of ocular tissues helps appropriate laser selection. (*Example: Blue lasers are not used for macular treatment. Red lasers can be used with macular haemorrhages.*)

Light falling on the retina is absorbed by melanin (RPE and choroid) and blood haemoglobin. The neurosensory retina is transparent and does not absorb laser wavelengths significantly. Laser effects (heating and coagulation) occur primarily in the pigmented outer retina.

The depth of penetration increases with longer wavelengths (red and IR) and absorption occurs more at the level of the choroid. Red krypton (647 nm) and the IR diode laser (810 nm) are absorbed mostly by choroidal melanocytes (only 8% RPE uptake).

Yellow krypton (568 nm) or diode (577 nm) are absorbed by oxyhaemoglobin, but not by xanthophyll pigment, making them useful in the treatment of juxta foveal microaneurysms and telangiectasias.

<table>
<tr><th>Chromophore (endogenous pigment)</th><th>Wavelengths absorbed optimally</th><th>Lasers used in practice</th></tr>
<tr><td>Melanin in RPE and Choroid</td><td>IR and visible spectrum (300–1300 nm)</td><td>Argon, PASCAL, Krypton laser</td></tr>
<tr><td>Haemoglobin (oxy and deoxyhaemoglobin)</td><td>Blue, green, and yellow (420–520 nm)
(red light is not absorbed)</td><td>Argon, PASCAL, Krypton laser</td></tr>
<tr><td colspan="3">Melanin absorbs green, yellow, and red wavelengths efficiently. Peak absorption is at 577 nm – yellow wavelength.
Oxy-haemoglobin in vascular tissues strongly absorbs 418, 542, and 577 nm (blue, green, yellow) wavelengths. Peak at 577 nm.</td></tr>
<tr><td colspan="3">Xanthophyll – ocular pigment concentrated at the macula has maximum absorption of blue light and minimal absorption of red light. A blue laser (Argon – 488 nm) should not be used in FLT, due to a high risk of macular burns (patients and doctor). Green, yellow, and red lasers are safer for treatment close to the macula.</td></tr>
<tr><td colspan="3">Water – IR lasers vaporize cellular and extracellular water to achieve effect (Nd-YAG, Diode, CO_2 lasers).</td></tr>
<tr><td colspan="3">Exogenous pigments injected intravenously to accumulate in ocular tissues can also contribute in laser action, for example PDT.</td></tr>
<tr><td colspan="3">Penetration of lasers – depends on wavelength and scattering. As wavelength increases, depth of penetration increases and scattering decreases. Visible ranges and near IR wavelengths penetrate tissues more than UV wavelengths.</td></tr>
<tr><td colspan="3">Media opacity will increase scattering and reduce the laser effect.</td></tr>
<tr><td>Factors that affect laser – tissue interaction

Laser variables:
Laser wavelength (affects energy)
Spot size (affects irradiance= power/area)
Laser power (watts=energy/time)
Pulse duration – affects power

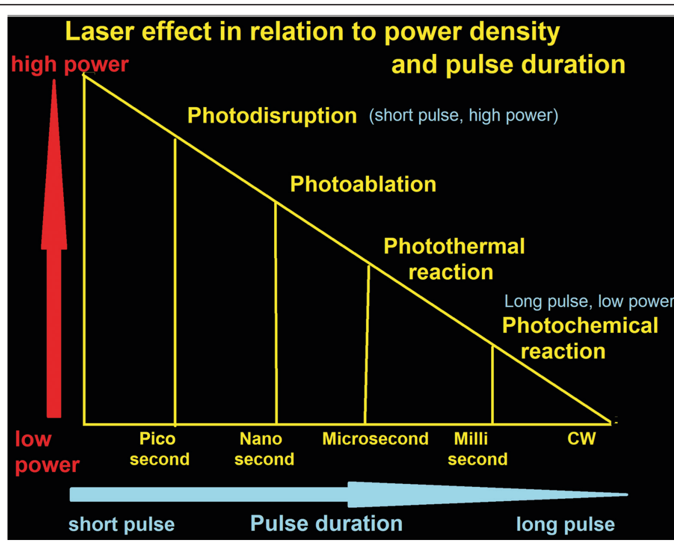
Tissue variables:
Tissue transparency
Tissue pigmentation
Tissue water content</td><td colspan="2">

Figure 1.13 Laser effects in relation to power and pulse.</td></tr>
</table>

1.4.1 Principles of Laser Tissue Interactions

As irradiance (power) increases and pulse decreases, the effect varies from photochemical (at low power and long pulse) to photodisruption (high power and extremely short pulses).

Tissue effect	Irradiance=watts/cm²	Pulse duration=sec
Photochemical effect	Low power	T >1 sec (CW)
Photothermal	Slightly higher power	T <1 sec–1 μs
Photoablation	Higher power	T <1 μs–1 ns
Plasma induced ablation and photodisruption	Very high powers in a very small area	T <1 ns

Photodisruption or Photoionization

Mechanical effect, with high-energy, short-pulse lasers. Causes optical breakdown of tissue molecules, generating a plume of plasma, which generates an acoustic shockwave that moves forwards to disrupt the target tissue nearby without any heat generation.
(Plasma is a pool of highly energized electrons that cause a precise optical breakdown.
Useful in breaking down tissues (YAG PI or capsulotomy), gallstones, or renal stones.)

Photoablation
- UV wavelengths (high-power lasers) break chemical or ionic bonds that hold tissues together, without heating, to cause clean-cut incisions. Excimer lasers in photorefractive keratectomy and Lasik.

Photovaporization
- When temperature rises to 60–100°C, cellular and extracellular water vaporize causing damage and disintegration, incision, and heat-related cauterization. Forms the basis of treatment in CO_2 and Femtolasers.

Photothermal
- Laser energy generates heat in target tissue, causing denaturation and coagulation of tissue proteins. The effect varies from **photocoagulation and photoevaporation to photocarbonization (charring)**, based on energy levels used
- Photothermal effect is utilized to cauterize blood vessels and weld tissues without sutures.
- Temperature rises of 10–20°C cause coagulation, protein denaturation, thrombus formation, and collagen contraction, and form the principle of PRP and FLT. Examples: argon, krypton, diode (810), and PASCAL lasers.

Photochemical
- Laser light triggers photochemical reaction (biostimulation) in target tissues to achieve therapeutic effects. Example: PDT, in treatment of ocular tumours and CNV.
- An exogenous photosensitizer (hematoporphyrin, benzoporphyrin) injected intravenously is selectively absorbed by blood vessels in metabolically active tissues such as CNV or tumours. When activated by a diode laser, the temperature rises and cytotoxic free oxygen radicals are released, to cause CNV destruction.

Photoradiation
- Laser light-generated cytotoxic effects to damage or kill cells. Dye lasers and wavelengths are absorbed by the injected dye to generate cytotoxic radicals.

1.4.2 Laser Mechanisms in the Retina

Ischaemia-driven vascular diseases, characterized by capillary non-perfusion and reduced oxygen availability, predominantly involve the inner retina. How does destroying the outer retina influence the inner retina?

The retina has a dual blood supply (retinal capillaries and choriocapillaris). Oxygen from choriocapillaris diffuses into the outer retina and is consumed by photoreceptors but does not reach the inner retina under normal circumstances.

Retinal vascular homeostasis is a balance between factors that promote neovascularization and leakage, and those that inhibit it. Hypoxia stimulates production of pro-inflammatory factors, cytokines, and angiogenic factors, such as VEGF, angiotensin II, leucocyte adhesion factor, inducing vasodilatation, and neovascularization. Retinal photocoagulation improves tissue oxygenation and reverses the consequences of hypoxia.

Retinal changes following laser photocoagulation
Laser energy absorbed by RPE heats retinal tissue causing scarring and pigment migration. Damage in the centre of the spot is greater than surrounding tissues (gaussian beam).

Temperature up to 42°C induces reversible changes – vasodilatation, release of chemical mediators, damage to intracellular organelle, endothelium, and reduced enzyme activity. New non-damaging, subthreshold lasers work in this region.

Temperature >50°C causes irreversible damage – cellular death reduces hypoxia and VEGF production, and increases production of PEDF. Current lasers work in this zone.

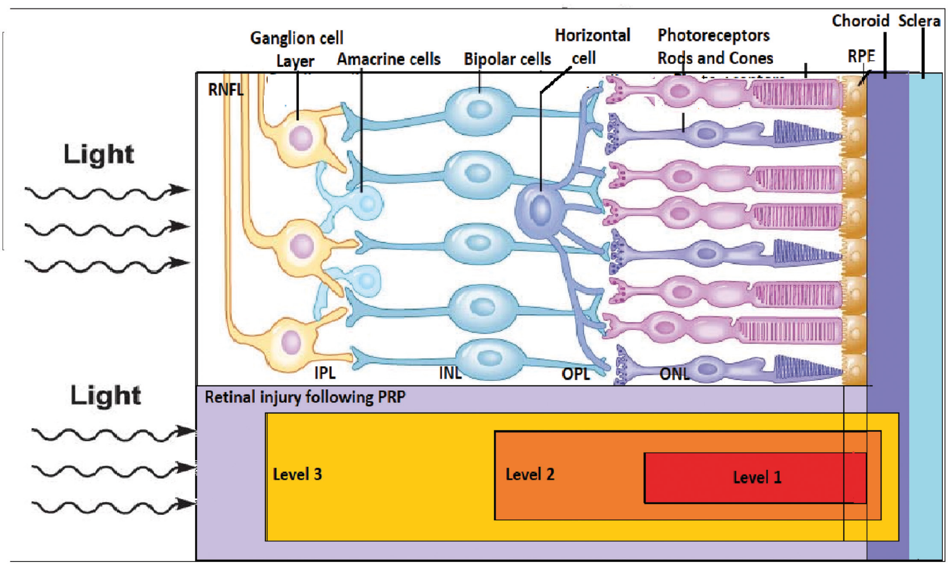


Figure 1.14 Retinal injury following PRP.

High energy, long exposure time and a large spot cause larger areas of retinal injury.
Level 1 – damage confined to choriocapillaris, RPE, and outer photoreceptors.
Level 2 – damage from choriocapillaris to outer nuclear and plexiform layers.
Level 3 – extends from deep choroid to ONL, IPL, and ganglion cell layer.

1.4.3 Starling's Law and Macular Oedema

Starling's law explains water exchange between vascular and extracellular tissue compartments in formation of vasogenic oedema, stating that

- If hydrostatic pressure = oncotic pressure – there is no movement between 2 compartments.
- If oncotic pressure > hydrostatic pressure, fluid will leak out, causing oedema.
- If hydrostatic pressure > oncotic pressure, it will drive fluid out, causing oedema.

Retinal arterioles are resistance vessels that control hydrostatic pressure downstream. **Diameter of retinal arterioles is controlled by oxygen levels**. In hypoxia, arterioles dilate, reducing resistance and increasing blood flow downstream, increasing the hydrostatic pressure, causing capillary dilatation and leakage. As fluid and proteins leak out, tissue oncotic pressure increases, attracting more fluid out and increasing the oedema. The process is controlled by VEGF, which in turn is influenced by oxygen levels.

1.4.4 How Does Focal Laser Treatment Reduce Macular Oedema?

The exact mechanism is unclear and likely to be multifactorial. It is established that **retinal blood flow and vessel diameters are inversely related to oxygen tension**. FLT increases retinal oxygenation, causing vasoconstriction, reducing blood flow, hydrostatic pressure, and oedema.

- **Direct coagulation of leaky capillaries** reduces vascular permeability and oncotic pressure.
- **Reduced hydrostatic pressure (improved oxygenation causing vasoconstriction)**.

- **Improved RPE pump mechanism** to drain fluid. Regeneration and migration of surrounding healthy RPE cells, explains how gentle, subthreshold laser is effective.
- **Laser scars decrease local production of VEGF and inflammatory factors.**

Photothermal effects are dependent on:
Duration of laser action (pulse duration) • **Longer exposure causes deeper tissue penetration and heat dissipation, leading to larger burns**. A CW laser causes more scarring than pulsed laser. Reducing pulse duration shortens treatment time, reduces pain, and minimizes scarring. • **Thermal relaxation time (TRT)** is time taken for tissue to dissipate 60% of absorbed energy. Pulse duration <TRT vaporizes intracellular water (no time for heat diffusion), causing an explosive effect, with rupture of Bruch's membrane, and occurs with use of very high energy with an extremely short pulse.
Power density or irradiance (mW/cm^2) Increasing laser power or reducing spot size results in increased power density, with increased thermal effects.
Photoreceptors are mitochondria-rich, high oxygen-consuming cells. Destroying them is an effective way of reducing oxygen consumption in the outer retina, allowing choroidal oxygen flux to reach the inner retina, improving hypoxia, and reducing neovascularization. **A typical PRP session reduces photoreceptors and oxygen consumption of outer retina by approximately 20%.**
Improved oxygenation • **Reduced demand –** photoreceptors have high metabolic activity and oxygen demand. PRP destroys them, reducing oxygen requirement. • **Improved availability –** loss of some photoreceptors, improves oxygen supply to remaining photoreceptors, reducing hypoxic drive for angiogenesis. • **Oxygen bridges –** loss of photoreceptors at site of laser allows oxygen flux from the choroid to travel through glial scars to the inner retina. • **Vasoconstriction, reduced leakage –** improved oxygenation and direct coagulation of mA.
Reversal of angiogenic drive • PRP reduces angiogenic burden by removing ischaemic retina from the equation. This reduces release of angiogenic factors (VEGF reduced by 70% after PRP). • Remaining healthy retina produces anti-angiogenic factors.

Angiogenic factors that promote NV	**Anti-angiogenic factors that inhibit NV**
VEGF – vascular endothelial growth factor SDF-1 – stromal cell derived factor. PDGF – platelet derived growth factor Ang-2 – angiopoietin 2 EPO – erythropoietin Cytokines and multiple growth factors (TNF, Integrin)	PEDF – pigment epithelium derived factor TIMP3 – tissue inhibitor metalloproteinase 3 Endostatins Angiotensin TSP – Thrombospondin

Long-term effects of laser treatment
Gene regulations provide sustained effects. (Increased expression of genes related to healing and repair of organelles, inhibition of angiogenesis and axonal growth promotion, and reduced gene expression of angiogenic and inflammatory factors).

Gene upregulation	**Gene downregulation**	**Repair / regeneration**	**RPE stimulation**
Improve photoreceptor metabolism, cell renewal/remodelling. Increase axonal growth and synaptic function. Increased heat shock protein (HSP), increase matrix metalloproteinases (MMP) for structural repair. Increase TSP-1, Agtr2 anti-angiogenic factors.	Decrease endothelial proliferation/ dysfunction. Decrease angiogenic and vascular permeability factors (Fibroblast Growth factor-FG14, FG16), IL-1, plasminogen activator inhibitor-2, inhibitors of MMPs, calcitonin like receptor (CLR).	Activation, migration polarization, and phagocytic activity of microglia. Injured photoreceptor releases endothelin and activates Muller cells, leukocyte infiltration. RPE healing, and migration over treated area.	Gentle laser with short pulses and sub-threshold treatment causes thermal stress (photo-stimulation). Promotes cell repair and remodelling. Anti-angiogenic, anti-inflammatory, Neuroprotective effects.

1.5 LASER HAZARD AND LASER SAFETY PROTOCOLS

Lasers are associated with potential hazards for patients and clinicians, and laser safety is paramount to avoid laser related accidents.

The hazards relate to phototoxicity from high radiance (brightness) and high irradiance (ability to be focused into a small spot of concentrated energy), making lasers extremely dangerous to work with.

Visible and near IR light (400–1400 nm wavelength) can penetrate ocular media, causing retinal damage. UV and IR wavelengths (<400 nm and >1400 nm) are absorbed by the cornea and lens, causing corneal burns and cataracts. IR wavelengths are particularly dangerous, as they do not stimulate the protective blink reflex. Skin injury is more likely with prolonged exposure. UV rays cause sunburn type injury, while visible and IR rays cause thermal damage.

The extent of injury depends on laser wavelength, energy, exposure time, spot size, and target tissue factors (reflectivity, absorption, dispersion, and thermal properties). Short wavelengths and short pulses equate to higher energy with higher risk of injuries.

1.5.1 Laser Classification and Safety (ANSI Standards)

Lasers' safety is classified by their wavelengths and their maximum output power.

Classification of lasers – based on accessible emission limits (AEL) – *maximum power (watts) or energy (joules) that can be emitted in a specified wavelength range and exposure time.*	
Class 1 lasers	Safe under all conditions, due to low output or enclosed laser – no risk of exposure. Example: CD player, laser printer
Class 2 lasers	Associated with exposure to very bright light. Output power is up to 1 mw. Relatively safe because blink reflex reduces exposure to <0.25 sec. If blink reflex was supressed or patient stared into laser light, eye injury can occur. Example: supermarket scanner, laser light toys.
Class 3 lasers	**3A lasers –** output power is up to 2.5 mw, dangerous if used with optical instruments that focus light and increase power density. Examples: Laser pointers, laser sight on firearms. **3B lasers –** output is 5–500 mw. Dangerous if enters the eye, protective eyewear recommended, risk of skin burns, fire hazard. Diffuse reflection is safe, but specular reflection is dangerous.
Class 4 lasers	Power output >500 mw, high risk of ocular and skin injury, dangerous with both specular and diffuse reflections. Includes all industrial, scientific, military, and medical lasers. Protective eyewear recommended.
MPE – maximum permissible exposure – highest irradiance (power density w/cm^2), or fluence (energy density – J/cm^2) of light that is considered safe, measured at the cornea at a given wavelength and exposure time. It is usually 10% of the dose causing damage 50% of the time. MPE for UV and IR rays > visible rays, with a higher risk of injury.	

Laser hazards are classified as non-beam and beam related hazards.

Ocular injury can be reversible or permanent. Inadvertent exposure causes headache, lacrimation, gritty sensation, floaters, sudden visual loss with macular burn, or gradual loss from cataract, reduced retinal sensitivity, and colour vision.

Skin injuries – photochemical effects of mid/far UV rays cause sunburns, reddening, blisters, premature ageing, and skin cancers (UV – 290–320 nm). Thermal burns are rare – they occur with high energy and prolonged exposure (CO_2 and some IR lasers). **There is a higher risk of burns in photosensitive patients (idiopathic or drug related).**

Non beam related hazards – safety related to:	
Laser path	Avoid reflectors – jewellery, metal fittings, mirrors. Avoid absorbers – trapped eyelash, mascara. Avoid flammables – oxygen cylinder, cleaning solution, chemicals.
Unregulated equipment	Unregulated laser pointers, toys available on the internet, may cause ocular injury with flash blindness. Regulations may vary in countries.
Electrical hazards	Lasers are high voltage devices with electrical and fire hazards. Risk is higher during maintenance and servicing. Ensure cables are not frayed and floor is not wet.
Chemical hazards	Chemicals in lasing media can be toxic/hazardous substances, dyes, flammable solvents, heavy metal vapours. Toxic plume (dust, metallic, chemical, biologic fumes) can contaminate the air with industrial lasers. Room must be well ventilated, and protective masks may be used.
Mechanical hazards	Explosions, laser leakage from damaged cables, unstable table. Periodic checks and laser maintenance are essential.

Beam-related hazards	
Wavelength ranges	**Pathological effects**
180–315 nm (UV-B, UV-C)	Photokeratitis, corneal inflammation, erythema, increased skin pigmentation, accelerated skin aging, skin cancer
315–400 nm (UV-A)	Photochemical cataract, skin pigmentation, skin burns
400–780 nm (visible light)	Photothermal retinal injury, skin pigmentation, light photosensitivity, cataract, skin burn
780–1400 nm (near IR)	Cataract, retinal burn, skin burn
1400–3000 nm (IR) **>3000 nm (far IR)**	Aqueous flare, cataract, corneal burn, skin burn
Type of beam exposure **Direct exposure or indirect exposure** (reflections from grade 4 lasers). **Specular reflection –** from flat reflectors (mirror) – risk of harm is high. **Diffuse reflection –** from irregular reflectors (jewellery, metal tools) – lower risk of harm. A surface may be a diffuse reflector for one, but specular for another wavelength.	
Factors that affect laser hazards	
Laser parameters	
Wavelength (determines energy and absorption)	UV rays (180–390 nm), mid-far IR (1400 nm–1 mm) – corneal and lens injury. Visible and near IR (400–1400 nm) penetrates ocular media, absorbed by the retina and macula. **Maximum retinal absorption is at 400–570 nm, making Argon and PASCAL lasers hazardous for eye injuries.**
Energy	Higher energy – higher risk of injury. Shorter wavelength (UV) has higher energy than longer (IR) wavelengths.
Spot size	Smaller spot (focused laser) has higher energy density with higher risk of injury, especially if used with high energy. (Reduce power with small spots.)
Pulse duration	A short pulse is associated with a risk of photomechanical injury, while a long pulse is associated with photothermal injury (longer exposure).
Pulse Repetition	Faster rate – associated with less heat dissipation and phototoxicity.
Eye factors – the biconvex lens acts as a magnifier and focuses laser light on the retina. Even a low-powered laser or diffuse laser reflection can cause retinal injury.	
Self-defence mechanisms – blink reflex, light aversion, and head turn protect against visible light. UV and IR lasers do not stimulate the blink reflex and can be harmful. Sustained exposure with laser pointer directed at an eye can cause injury. **Size of pupil** – small pupil is associated with lesser exposure. **Degree of pigmentation** in target tissue – dark fundi have a higher risk of injury. **Aphakia and Pseudophakia** – aphakes have a clear media and pseudophakic IOL focuses laser light, increasing the risk of injury.	

1.5.2 Laser Safety Protocols

Know Your Laser Safety Officer in the Hospital.
Ensure treatment is performed in a controlled environment, to mitigate laser hazards.

Laser Room

Figure 1.15 Laser hazard image.