Lasers and surgery

Andrew John Kitching EDICM FRCA
Christopher J Edge MA PhD AFOM FRCA CChem

All anaesthetists need to have a basic knowledge of laser physics and how laser radiation can interact with the surgical environment, including the patient, anaesthetic apparatus and surgical team. Lasers are finding increasing application in both medicine and surgery and their use gives rise to several hazards. Most of these hazards arise as a direct result of the nature of laser radiation.

Basic physics

Light

Laser is an acronym for light amplification by the stimulated emission of radiation. The laser produces an intense beam of almost pure monochromatic light, i.e. single colour or frequency (ν). The beam is almost non-divergent and may have a very small cross-sectional area. The energy of the radiation is given by the equation:

$$E = h\nu \qquad \text{Eq. 1}$$

where E = the energy of the photons that comprise the light beam, h = Planck's constant and ν = photon frequency. The energy of the beam depends only upon frequency.

Atoms

Atoms consist of nuclei (protons and neutrons) and electrons. Quantum theory states that electrons are confined to certain energy levels and that they can only move between

Key points

The principle of the laser was first described by Albert Einstein.

As lasers can cause serious injury to patients, anaesthetists and other theatre staff need to be aware of the basic principles of laser safety.

Fires in the airway can be started by lasers, despite the use of appropriate equipment.

Lasers are potentially dangerous and evidence for their benefit needs to be evaluated in randomised prospective clinical trials.

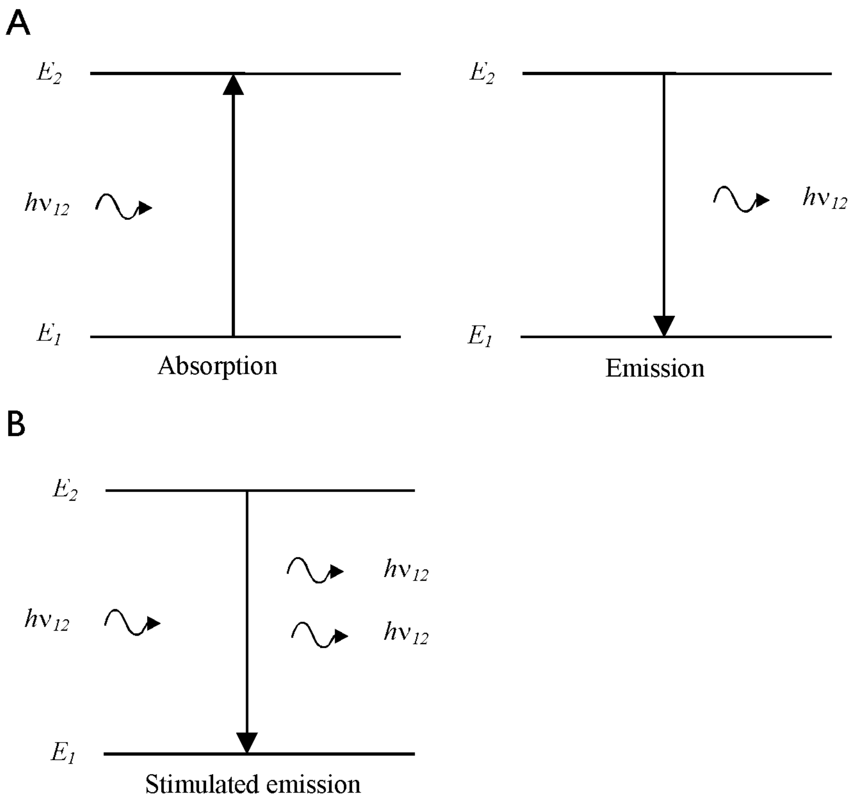

Fig. 1 Diagram illustrating absorption and spontaneous emission of a single quantum of radiation (A) and stimulated emission of radiation (B) between two energy levels E_1 and E_2.

Andrew John Kitching EDICM FRCA
Consultant Anaesthetist, Royal Berkshire and Battle Hospitals NHS Trust, London Road, Reading RG1 5AN
Tel: 0118 987 7065
Fax: 0118 987 7067
E-mail: andrewjkitch@btinternet.com
(for correspondence)

Christopher J Edge
MA PhD AFOM FRCA CChem
Specialist Registrar, Nuffield Department of Anaesthetics, John Radcliffe Hospital, Oxford
Tel: 01865 221590
Fax: 01865 220027

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these levels if they are able to absorb or give up well-defined amounts of energy. Consider a simple atomic system consisting of two different energy levels, i.e. a ground (or low energy) state E_1 and an excited state E_2. Energy can either be absorbed or emitted, depending upon whether the system moves from E_1 to E_2 (absorption) or from E_2 to E_1 (emission; see Fig. 1A). The main characteristic of the emission process is that it occurs as a result of random perturbations in the environment of the atom; consequently, the light waves emitted are out of phase with each other or incoherent. The resultant light intensity is the sum of the intensities of emissions from each atom.

However, suppose that the all the light emitted by each atom was made to be in phase (coherent); this will result in an enormous increase in light intensity. This is seen by supposing that the amplitude (A) of the wave emitted from each atom is the same and equal to A. Then, with n incoherent atoms, the average intensity due to each wave = kA^2 (k is a constant) and total intensity = nkA^2. If the waves are coherent, the amplitude of the resultant wave = nA and intensity = $k(nA)^2$ or kn^2A^2. Since the number of atoms (n) is very large, coherent atoms produce an enormous increase in the light intensity.

In 1917, Einstein pointed out that there was another process by which an atom could emit energy. This process requires stimulation by a photon of energy $h\nu_{12}$ which is equivalent to the energy difference between E_1 and E_2. The emitted photon also has an energy $h\nu_{12}$ and is emitted in phase with the stimulating photon. Amplification is thereby obtained and, in contrast to spontaneous radiation which is random, the stimulated emission produces coherent waves from the atoms concerned (Fig. 1B).

What conditions must prevail for emission to occur rather than absorption in the system when photons of energy $h\nu_{12}$ are incident upon the atoms occupying energy levels E_1 and E_2? If the number n_1 in the lower energy level E_1 is much greater than the number in the higher energy level E_2 (which is usually the case), more photons will be absorbed than are emitted and, on average, atoms will be raised to the level E_2 from E_1. Spontaneous emission will occur from the atoms in level E_2 returning back down to level E_1. Stimulated emission will not occur.

However, if a situation occurs in which an inverted population of atoms can be obtained, such that the number of atoms in energy level E_2 is much greater than that in energy level E_1, then photons of energy $h\nu_{12}$ will, on average, produce more stimulated emission than absorption. If this stimulated emission, in the form of a coherent wave, can be confined to one particular direction, then a very intense, parallel beam of monochromatic light can be generated. This is the basis for the laser.

Types of laser

Solid-state laser

The first laser to operate successfully was designed by Maiman in 1960. It consisted of a ruby crystal in the form of a rod 4 cm long and 0.5 cm diameter. The ends of the crystal were polished and optically flat and parallel. One end of the rod was fully silvered and the other partially. A powerful electronic flash tube was coiled around the ruby.

Ruby consists of aluminium oxide (Al_2O_3) with 0.05% chromium ions in the crystal, giving its characteristic colour. The laser action utilises the energy levels of the chromium ion. The function of the flash tube is to 'pump' the chromium ions from the ground energy state (E_1) to a higher energy state (E_2). The population of atoms in state E_2 becomes much greater than in E_1. A few of these atoms in the high energy state spontaneously emit photons of energy $h\nu_{12}$ which, in turn, cause stimulated emission in other atoms. This effect increases rapidly by repeated photon reflection from the ends of the ruby. The coherent wave builds up and can be detected after passing through the partially silvered end of the ruby.

The Nd-YAG laser is also solid-state. Its crystal is a garnet made from yttrium/aluminium oxide ($Y_3Al_5O_{12}$, YAG) doped with 0.7% by weight neodymium (Nd^{3+}) ions. Laser emission takes place at 1064 nm (infra-red).

Semiconductor laser

The gallium arsenide (GaAs) laser is a semiconductor laser; it consists of two small slabs of GaAs. One of the slabs has been doped with an impurity to form p type material, whilst the other is doped with a different impurity to form n type material. Under the right circumstances, the electrons in the n type material are able to cross the junction between the two materials with a loss of energy in the range of the visible spectrum. This process is very efficient but, as the area of the junction is small, power output tends to be low.

Liquid laser

Organic dye molecules are complex with multiple energy levels. They are contained within liquid lasers and are pumped into higher energy states by other, high-powered lasers. Fine selection or tuning of the required energy levels for laser action can be achieved by using a diffraction grating at one end of the laser tube containing the dye. A more coarse selection can be made by altering the chemical dye in the laser.

Table 1 Classification of laser products

Class 1	Power not to exceed maximum permissible exposure for the eye, or safe because of engineering design.
Class 2	Visible laser beams only (400–700 nm). Powers up to 1 mW. Eye protected by blink-reflex time of 0.25 s.
Class 2m	As Class 2, but not safe when viewed with optical aids such as eye loupes.
Class 3a	Relaxation of Class 2 to 5 mW for radiation in the visible spectrum (400–700 nm) provided the beam is expanded so that the eye is still protected by the blink-reflex. Maximum irradiance must not exceed 25 W m^{-2} for intrabeam viewing. For other wavelengths, hazard is no greater than Class 1.
Class 3b	Powers up to 0.5 W. Direct viewing hazardous. Can be of any wavelength from 180 nm to 1 mm.
Class 4	Powers over 0.5 W. Any wavelength from 180 nm to 1 mm. Capable of igniting inflammable materials. Extremely hazardous

Gas laser

The helium–neon laser is a gas laser. A discharge tube containing a mixture of 90% helium and 10% neon at low pressure is excited by a high voltage. The helium atoms are excited and transfer their energy to the neon atoms. A population of excited neon atoms is created which can emit laser light at three different frequencies. The most commonly used frequency is 633 nm (red part of the spectrum). Other gases can be used; common examples in medical use include carbon dioxide and argon. The carbon dioxide laser emits light in the infrared part of the spectrum, whilst the argon ion laser emits green light.

Laser safety

When lasers are used in surgery, the generated beam often has a high-energy intensity. Additionally, the beam is virtually non-divergent which means that increasing the distance from the laser confers little safety benefit. Laser light, either transmitted directly, or reflected into the eye, may be very dangerous. If the light is in the visible portion of the spectrum, the retina may be burned (permanent blind spot) or the head of the optic nerve may be damaged (partial or total blindness). Infrared laser light can be even more dangerous as it cannot be seen. Infrared light is particularly damaging to the cornea, lens, and aqueous and vitreous humours. Exposure of the skin to laser radiation can give rise to a burning sensation and is therefore self-protective. The skin of sedated or anaesthetised patients must therefore be shielded from the beam.

The international classification of continuously working lasers is shown in Table 1. The National Radiological Protection Board (NRPB) has produced a poster (*Lasers at Work*, NRPB, 2003) which summarises safety precautions, British Standards and the health and safety laws which apply to laser use. There is no specific laser safety legislation but general health and safety laws apply including:

The Health and Safety at Work etc Act 1974
The Management of Health and Safety at Work Regulations, 1999
The Provision and Use of Work Equipment Regulations, 1998

British Standard BS EN 60825 gives guidance on achieving a good standard of laser safety. It is the benchmark against which the safety of laser products is assessed.

Local rules

Hospitals in which lasers are used should have rules governing their safe use in accordance with the Department of Health's *Guidance on the Safe Use of Lasers in Medical and Dental Practice* 1995. These rules describe in detail:

(i) The type of laser in use and its classification according to beam hazard.
(ii) The nature of the hazard.
(iii) The responsibilities and duties of the laser owner and the staff who use the laser. A laser protection supervisor (LPS) should be appointed for every clinical area in which a laser is used. The duty of the LPS is to ensure that the laser is used safely and that theatre staff are educated in its use.
(iv) An appropriate non-water based fire extinguisher should be immediately available in the clinical area in which the laser is used.
(v) All staff should wear appropriate eye protection within the laser-controlled area. This should be suitable for the type of laser and offer adequate protection against accidental exposure to the main beam. Spectacles do not give reliable peripheral visual field protection.
(vi) In order to protect those outside the operating theatre, all doors should be locked and all windows covered.

Clinical use of lasers

Lasers are now used in most branches of surgery. The ability to cut through tissues with precision and achieve almost perfect haemostasis is intuitively advantageous. However, the evidence-base for the advantages of lasers is rather sparse in some surgical specialities.

Laser excision is now regarded as the treatment of choice for destruction of central airway tumours (e.g. bronchial carcinoma). Laser removal of vocal cord tumours is also an established technique, yielding long-term survival results equivalent to radiotherapy. The laser is being used increasingly for the treatment of larger lesions of the head and neck (with encouraging results relating to survival and function), endometriosis, benign prostatic hyperplasia, skin lesions and myopia.

Airway surgery, lasers and anaesthesia

There is always a danger of fire in an oxygen-enriched environment because of the immense thermal energy generated by lasers. The danger of starting a fire can be minimised by:

(i) Air and oxygen mixtures (less flammable than nitrous oxide and oxygen mixtures).
(ii) Inspired oxygen concentration of 25% or less.
(iii) Non-reflective matt-black surgical instruments to minimise reflection from the main laser beam.
(iv) Non-flammable endotracheal tubes (see below).
(v) Protecting other tissues with wet swabs.

Fires are a very real risk during laser airway surgery. All the ingredients required for a fire are present: energy (laser), oxygen and fuel (tube and circuit). Should a fire ignite in the airway, the surgeon and anaesthetist must immediately:

(i) Switch off the laser and flood the operation site with saline.
(ii) Disconnect the anaesthetic circuit temporarily and, if feasible, remove the endotracheal tube – even 'laser' tubes can be ignited.
(iii) Ventilate the patient with air using a bag-valve-mask circuit. After the fire has been extinguished, the surgeon should then inspect the airway via a rigid bronchoscope.

Airway fires can result in significant lung injury with gradually worsening hypoxaemia over the subsequent 48 h. Therefore, it is prudent, at least for a few hours, to keep the patient intubated and, if possible, transfer to the ICU in order to make regular assessments of respiratory function. Following surgery, standard management is dexamethasone (minimises airway oedema), humidified oxygen and re-assessment of the airway bronchoscopically a few days later.

Endotracheal tubes for laser surgery

There are two basic designs of endotracheal tube for use in laser surgery. First, silicone rubber tubes with metal links incorporated into the tube wall with either a sponge cuff (Bivona Fome cuff) or a double cuff (Mallinckrodt 'Laser flex') are available. If the cuff bursts in the former, the sponge will maintain a sealed airway; in the latter, the second cuff can be used. Second, foil wrapped tubes with an outer Teflon coat (Sheridan 'Laser Trach') can be used. The cuff is filled with methylene blue crystals so that, if the laser bursts the cuff, this will be detected quickly by the surgeon. The main problem with laser tubes is that they have a narrow internal diameter because they have thick outer walls. This can make spontaneous ventilation difficult, and airway pressures can be high in the ventilated patient.

A variety of anaesthetic techniques have been advocated for laser airway surgery. Some centres paralyse and ventilate using a laser endotracheal tube, others utilise a jet ventilator device attached to a rigid laryngoscope. However, some centres employ a spontaneous respiration technique using an air/oxygen mixture with a volatile agent administered via a laser tube or a nasopharyngeal airway. Good topical anaesthesia of the airway is also used to minimise the risk of coughing and straining.

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See multiple choice questions 102–106.