In 1917, Albert Einstein recognized the existence of stimulated emissions [21]. The first description of stimulated optical emission of monochromatic light using ruby as the active material—the ruby laser—was provided by Theodore Maiman in 1960 [45]. The more powerful neodymium-in-glass laser was discovered a year later. It was hoped that lasers would be useful in medicine for the excision of tumours, but initial expectations were not realized. Their poor absorption by non-pigmented tissues necessitated the use of large amounts of energy, with the result that the thermal effect could not be localized to diseased tissue [80].

In 1966, at the American Optical Corporation Laboratories, Yahr and Strully discovered that the carbon dioxide (CO\textsubscript{2}) laser can cut tissue [103]. Strong and Jako first appreciated the potential of the CO\textsubscript{2} laser for use in otolaryngology in 1971 [87]. The development of the micro-manipulator by Polanyi in 1974, enabling the CO\textsubscript{2} laser to be used with an operating microscope, greatly facilitated its use for microlaryngeal surgery [63]. The argon laser has been used extensively in ophthalmic surgery and dermatology since about 1970 [16], and the neodymium-yttrium-aluminium-garnet (Nd-YAG) laser was first introduced in 1975 for the endoscopic treatment of gastrointestinal haemorrhage [37].

A knowledge of the physical properties of lasers enables a better understanding of their application in surgery and is essential for the implementation of effective safety measures. The fundamental physics of medically used lasers, and the hazards of their use, will be presented. The anaesthetic implications and management of laser surgery of the upper airway is emphasized. The complications of laser usage and the precautionary measures to minimize them are discussed and likely future developments in laser surgery are outlined. The following discussion of the physics of lasers and their applications is a simplification; the interested reader is directed to two reference works on the subjects [4, 47].

**Laser physics**

Lasers are intense sources of electromagnetic radiation. The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The terms “light” and electromagnetic radiation are used interchangeably in this discussion, although not all lasers operate in the visible range of the spectrum. The electromagnetic description of “light” enables one to understand the characteristics of laser “light”, including its monochromatic nature, temporal and spatial coherence, and collimation. This “light” is of one wavelength and the waves travel in phase and parallel across a wavefront. In contrast, conventional light sources emit light of varying wavelengths in all directions. According to Bohr’s theorem, the electrons of an atom can be imagined to circle the nucleus in discrete orbits; the orbits populated by the electrons determine the energy level of the atom. Radiation is absorbed or emitted when electrons are transferred from one orbit to another. The frequency of the radiation emitted or absorbed is related to the energy difference of the two states according to the Bohr formula, $E = h\nu$, where $E$ is the energy difference between two energy levels, $h$ is Planck’s constant and $\nu$ is frequency. The basis of the quantum theory is that energy exists in discrete packages, quanta or photons. Atoms, molecules and ions
undergo transition from a higher to a lower energy state with the emission of a photon as the electron drops from a higher orbit to a lower one in the case of an atom, or as a molecule changes from one vibrational state to another as, for example, in the carbon dioxide molecule. An atom or any other quantum system tends to move from a higher to a lower energy state by spontaneous emission of discrete amounts of radiation; spontaneous emission is propagated in any direction. Conversely, when an atom, molecule or ion at a lower energy level is exposed to specific amounts of radiation, it may absorb that energy and be "excited" with an electron raised to a higher orbit or a molecule changed to a different rotational or vibrational state.

When, during stimulated emission, an atom in an excited state is exposed to the radiation (photonic energy) of a frequency matching the energy difference between two orbits (excitation energy), the atom can then emit the newly "absorbed", in addition to the existing, amount of "excited" energy by return of its electron to the lower level. Two photons are then emitted—the injected photon plus the photon emitted by the electron returning to the lower orbit; the atom reverts, thereby, to its lower energy level (fig. 1). The two emitted photons have the same energy level \((h\nu)\), frequency, phase and direction or, in other words, the stimulated radiation has the same frequency, phase and direction as the stimulating radiation. The stimulating radiation has thus been amplified. For a predominance of stimulated emission to occur, a large majority of atoms need to be in a higher energy, or excited state rather than a lower state, in order to compensate for the loss of photons that escape without participating in the process. The resulting condition is called a population-inversion, because normally the higher energy levels of atoms, ions or molecules are less populated than the lower ones. In fact, spontaneous emission is minimized by maintaining the population-inversion. The method by which the higher energy levels are achieved is
ised pumping; it is the process of supplying high intensity energy to the atoms or molecules and is accomplished by an electrical discharge or a radiant source such as another laser or an intense light source. The energy conversion process is usually rather inefficient, resulting in the generation of heat. A laser device provides the conditions which optimize the process of population-inversion and stimulated radiation as well as the supply of energy. Because of the generation of heat, most laser devices require a cooling system.

Laser devices have three components, a laser medium, an optical cavity and a pumping source (fig. 2). The name of the laser refers to the type of material used within the optical cavity as the laser medium, which may be a solid, liquid or gas. The laser medium determines the wavelength of the emitted radiation. The most important lasers in medicine today are the CO2, the Nd-YAG, the Nd-YAG-KTP, argon, krypton and the helium-neon laser. The Nd-YAG-KTP laser is formed by the addition of a potassium titanate phosphate

---

**Table 1. Characteristics of lasers used in medicine. CW = Continuous wave**

<table>
<thead>
<tr>
<th>Laser</th>
<th>Wavelength (nm)</th>
<th>Spectrum</th>
<th>Medium</th>
<th>Pumping</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>460–520</td>
<td>Visible Blue green</td>
<td>Argon ion gas</td>
<td>Elec. discharge</td>
<td>0.0001–5</td>
</tr>
<tr>
<td></td>
<td>(488, 514)</td>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>CO2</td>
<td>10600</td>
<td>Invisible Infra-red</td>
<td>CO2 in helium + nitrogen gas</td>
<td>Elec. discharge</td>
<td>0.1–100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>Helium–neon</td>
<td>632</td>
<td>Visible Red</td>
<td>Helium–neon gas</td>
<td>Elec. discharge</td>
<td>0.001–0.100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>Krypton</td>
<td>400–700</td>
<td>Visible Blue–red</td>
<td>Krypton gas</td>
<td>Elec. discharge</td>
<td>≲ 10</td>
</tr>
<tr>
<td></td>
<td>(476, 521, 568, 647)</td>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>Nd–YAG</td>
<td>1064</td>
<td>Invisible Infra-red</td>
<td>Nd–YAG crystal</td>
<td>Krypton or xenon flashtube</td>
<td>CW: 0.5–100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulsed: $10^{16}$ W cm$^{-2}$</td>
</tr>
<tr>
<td>Nd–YAG-KTP</td>
<td>532</td>
<td>Visible Emerald green</td>
<td>Nd–YAG-KTP crystals</td>
<td>Krypton or xenon flashtube</td>
<td>0.5–12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>Ruby</td>
<td>694</td>
<td>Visible Red</td>
<td>Ruby rod</td>
<td>Flashtube</td>
<td>≲ 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulsed: ≲ 10</td>
</tr>
</tbody>
</table>
(KTP) crystal to the Nd–YAG crystal. The KTP crystal doubles the frequency and, thereby, halves the wavelength of the Nd–YAG laser beam. The ruby laser is, medically, of historical value only. The tunable dye laser has more recently been added.

Characteristics of the medically used lasers are given in table I. The optical or resonator cavity provides the controlled environment to which the laser medium is confined. As energy is being supplied to the laser medium by the pumping process, its atoms are raised to their excited states followed by spontaneous emission. Emission occurs in all directions including the long axis of the cavity—the axis of propagation. Usually, two mirrors are positioned, one at each end of the axis of propagation. “Light” emitted along the axis of propagation is reflected back into the optical cavity at an angle depending on the curvature of the reflective surfaces. The reflected radiation may traverse along the long axis to reflect once again off the opposite mirror. Alternatively, the radiation may be absorbed by another atom in the cavity, raising the latter to a higher energy state or, if the atom was already excited, it may result in stimulated emission of the atom. If the latter process is set up along the axis of propagation, multiple reflections between the mirrors (oscillations) will enhance the absorptive and emissive process, building an avalanche effect which increases the intensity of the stimulated emission (along the axis of propagation). The stimulating radiation has thus been amplified. In most lasers, one mirror is fully reflective, while the other is partially transmissive. Various strategies are used to increase the intensity of the stimulated emission, including the intermittent interruption of the reflections. The pattern and distribution of the oscillations in the resonator cavity are influenced by the curvature and position of the mirrors. Ultimately, an equilibrium is reached between radiation leaving the cavity and the rate at which the pumping mechanism can replenish the excited population.

Lasers of the same medium can differ according to their intensity distribution and power output. The latter depends on the particulate size of the active medium and on whether the laser beam is generated by a pulsed or a continuous wave technique. Pulsed lasers can generate a peak energy that is orders of magnitude greater than continuous wave (or CW) lasers. Pulsing can be achieved by Q-switching. The Nd–YAG laser, for example, can be Q-switched by placing a time variable-absorbing cell in the laser cavity. The cell intermittently blocks light reflection at one mirror, but pumping continues so that very high levels of population-inversion are achieved. The cell is suddenly made transparent, allowing stimulated emission to recur with the result that very high power pulses of short duration are generated. Pulses in the gigawatt range and of nano- to picosecond duration are produced. The mode-locked pulsed laser uses a similar absorbing cell strategy. Pulsed laser techniques can also be applied to the CO₂, argon, ruby and dye lasers.

The pulsed laser should not be confused with the terminology for the intermittent use of a laser beam, also referred to as a “pulsed” mode. In the latter case, the duration of a beam output can be set from milliseconds to seconds before firing the beam; the laser will cease output when the time limit is reached if it is not already deactivated by the operator's foot switch. When no time limit is set, the laser is said to operate in the “continuous” mode; the foot switch determines the duration of firing. Typical power outputs for lasers used in medicine are depicted in table I. The aiming beams from the visible helium–neon, argon, krypton, tunable dye and KTP lasers have very low power outputs, the highest being 1–2 mW in the case of the helium–neon laser. Their low outputs are achieved by “splitting” and attenuation of the original beam. The helium–neon laser is used widely in applications requiring precise alignment in medicine and industry; it serves as the aiming guide for the CO₂ and Nd–YAG laser beam.

In addition to the geometrical arrangement of the mirrors around the medium, the intensity distribution within the laser beam depends on focusing lenses through which the beam passes. The shape of the beam determines, in part, the contour of the tissue removed. The intensity distribution in common medical use is the “Gaussian” or transverse electromagnetic mode beam (TEM₀₀ mode). The mode of a laser refers to the distribution of energy across the beam—the energy profile. Smaller focal spot sizes and higher power intensities are possible with the TEM₀₀ mode beam than with beams of other shapes such as the doughnut of TEM₀₁ mode (“Donut”) used only experimentally in medicine (fig. 3). The spot size of a laser beam depends also on its wavelength, so that smaller spot sizes are possible with the shorter wavelength of the argon laser as compared
with the CO\textsubscript{2} laser. It is the laser beam's coherence that enables it to be focused to an extraordinarily small point, thereby giving a very high power density. It is impossible to attain such focusing with non-coherent radiation.

Power density, the power contained in a unit area of beam, is a function of power output and intensity distribution (fig. 3). It is a measure of the concentration of energy of the beam and, in part, determines the area and depth of penetration. Duration of exposure of tissue to the laser is the other important factor in determining depth of penetration. Focusing of the laser beam by suitably placed lenses leads to high power densities. If, for example, a CO\textsubscript{2} laser is unfocused, its beam diameter can approach 1 cm, so that a 10-W laser gives a power density of 10 W cm\textsuperscript{-2}. If the same power is focused on a 1-mm spot size, the power density is approximately 1000 W cm\textsuperscript{-2}. A laser beam which is transmitted through a quartz fibre loses its collimation upon exit from the fibre when it diverges up to 12\degree.

**Interactions of lasers with biological tissues**

Electromagnetic radiation falling on tissue is reflected, absorbed or transmitted, or both. The absorbed radiation interacts with the absorbing matter, the nature of the interaction depending on the frequency of the radiation in addition to the composition of the absorbant. Gamma radiation and x-rays travel a greater distance in tissues than lasers and cause molecular excitation and ionization. Most medical lasers utilize light of wavelengths in the visible and the infra-red (invisible) portion of the spectrum; their absorption leads predominantly to heating, not to ionization. Depending on the rate of energy delivery or flux, heating, caused by a laser beam with a low flux, initially causes coagulation of proteins but, if further energy is absorbed, the intracellular water expands, vaporizes and the cell ruptures. The flux of a well-focused CO\textsubscript{2} laser beam is so high that almost immediate vaporization of cells takes place and the dehydrated residues break down in the laser beam. Carbonization of proteins and other cellular components occurs at the edge of this process. The flux of the Nd–YAG laser beam causes predominantly coagulation of proteinaceous elements of the tissues and carbonization occurs in an area larger than that affected by the CO\textsubscript{2} laser beam. Because of differences in power density, energy flux and depth of penetration of the various laser beams, their effects on tissues differ greatly.
The depth of penetration, and the width of the area affected by a laser beam, depends on many factors. Consider a beam of intensity \( I_0 \) impinging on a thin slab of thickness \( X \) (fig. 4). \( I_0 \) represents the reflected portion and \( I_t \) the transmitted portion of the beam. The absorbed component, \( I_a = I_0 - I_t \), where \( I_0 = I_t + I_r \), and the transmitted beam \( I_t = I_0 \times 10^{-\frac{d \cdot X}{a}} \), where \( a \) is the absorption coefficient and \( X \) the thickness of material. 

Beer’s law, \( I_t = I_0 \times 10^{-\frac{X}{a}} \), indicates that the intensity of the transmitted beam is related to the net beam intensity transmitted past the incident interface. The intensity of the transmitted beam, \( I_t \), is related to the net beam intensity, \( I_0 \), by Beer’s law, \( I_t = I_0 \times 10^{-\frac{X}{a}} \), where \( X \) is the thickness of the material and \( a \) is the absorption coefficient. The latter depends on the wavelength and on the physical and chemical composition of the absorbing material. The greater the value of \( a \), the lesser the value of \( I_t \). When \( X \) equals \( I_t / a \), then \( I_t = I_0 \times 10^{-1} \), or 0.1 \( I_0 \); that is, 10% of the incident beam \( I_0 \) is transmitted in thickness \( X \) of the material. In other words, 90% of the incident beam is absorbed in this distance \( X \), which is termed the extinction length (EL). In three EL, absorption is virtually complete, the bulk of the radiation being present to a depth of one extinction length. Part of the laser beam transmitted past the incident interface is scattered by the tissues. Scattering is strong if absorption is low and if the material is very inhomogeneous. The overall effect is to reduce EL. The effective cross-sectional area of the incident beam is increased by scattering and the critical volume (CV), the volume in which 90% of the interactions with the material take place, is enlarged.

The application of lasers is influenced strongly by the aforementioned physical properties and they are applied to a wide range of pathology (table II). Correct selection of the type of laser most efficiently absorbed by the target tissue reduces the chance of damage to adjacent tissues. Brief intermittent exposures allow controlled destruction and dissipation of heat in addition to assessment of the treatment. The CO\(_2\) laser beam is absorbed strongly by water, blood and biological tissues. The EL is approximately 0.03 mm in most tissues and water, and it has thereby the shallowest penetration of the medical lasers. Reflection and scattering are negligible. Most of the energy is used for vaporization and little is dissipated as heat at the margins of the CV where only small amounts of coagulated and carbonized material collect. Oedema formation is minimal. The limited penetrance with minimal surrounding damage makes the CO\(_2\) laser especially suited as a “cutting” tool. At lower power settings, coagulation and fair to good haemostasis are possible of vessels up to 0.5 mm in diameter. The overall effects can be summed up as “what you see is what you get”, unlike the effects resulting from the Nd—YAG laser beam. The CO\(_2\) laser beam is not transmissible through standard quartz fibres, but is transmissible through others such as the near-infra-red silica-based fibres and metal halides (e.g. thallium bromoiodide, Matsushita Co.) [27, 66].

The Nd—YAG laser beam, on the other hand, is absorbed weakly by pure water, in which it has an EL of 60 mm. Its absorption is greatly increased by pigmentation and scattering in tissue is strong, with back scattering of 20–40%. The EL for Nd—YAG in soft tissue is 2 ± 1 mm, which is 30–100 times longer than the EL for a CO\(_2\) laser; it provides the deepest penetration among the medical lasers. An Nd—YAG laser beam diameter expands approximately three times when traversing a 2-mm thickness of bladder mucosa, increasing the cross-sectional area nine-fold. Thus, the CV of the Nd—YAG laser beam is 300–900 times larger than the CV of the CO\(_2\) laser. Because greater volumes of tissue are involved, the devitalization process is much slower with the Nd—YAG laser and the dissipation of heat leads to a more diffuse thermal effect which also results in more oedema formation; it can be called a coagulator of tissues.

The area affected by the Nd—YAG laser beam can be likened to the shape of an iceberg; only the tip of the affected area is visible on the surface of the target tissue. Because of the deeply seated
TABLE II. Surgical applications of lasers commonly used in medicine

<table>
<thead>
<tr>
<th>Laser</th>
<th>Medical field</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Dermatology and plastics</td>
<td>Excision of burns, haemangiomas, keratosis, telangetactia, spider nevi, melanomas, basal and squamous cell carcinomas, subcutaneous mastectomies, mammoplasties</td>
</tr>
<tr>
<td></td>
<td>General surgery</td>
<td>Liver and spleen resections, breast lumpectomy, mastectomy, gastroctomy, colostomy, polypectomy</td>
</tr>
<tr>
<td></td>
<td>Gynaecology</td>
<td>Cervical, vaginal and vulval neoplasms, tuboplasties, condylomata excision, endometriosis</td>
</tr>
<tr>
<td></td>
<td>Neurosurgery (Vascular) tumours</td>
<td>All tumorous and obstructive processes of the naso–orotlaryngo–tracheal area (polyps, cysts, haemangiomas, lymphoma, papillomas, carcinomas, choanal atresia, etc.)</td>
</tr>
<tr>
<td></td>
<td>Otolaryngology</td>
<td>All tumorous and obstructive processes of the naso–orotlaryngo–tracheal area (polyps, cysts, haemangiomas, lymphoma, papillomas, carcinomas, choanal atresia, etc.)</td>
</tr>
<tr>
<td>Nd–YAG</td>
<td>General surgery</td>
<td>Liver and spleen resections, polypectomy, mastectomy</td>
</tr>
<tr>
<td></td>
<td>Gynaecology (See CO₂ applications and menorrhagia)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neurosurgery (Vascular) tumours</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gastroenterology</td>
<td>Bleeding gastric erosions, carcinomas, polyps, vascular lesions (e.g. Osler–Weber–Rendu, etc.)</td>
</tr>
<tr>
<td></td>
<td>Urology</td>
<td>Bladder tumours</td>
</tr>
<tr>
<td></td>
<td>Otolaryngology</td>
<td>Tracheobronchial tumours</td>
</tr>
<tr>
<td></td>
<td>Pulmonology</td>
<td>Tracheobronchial tumours</td>
</tr>
<tr>
<td></td>
<td>Ophthalmology</td>
<td>Vitreous and posterior capsular surgery (Pulsed mode)</td>
</tr>
<tr>
<td>Nd–YAG–KTP</td>
<td>Neurosurgery (Vascular) tumours</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Otolaryngology</td>
<td>Tympanoplasty, myringotomy, stapedectomy</td>
</tr>
<tr>
<td>Argon</td>
<td>Ophthalmology</td>
<td>Glaucoma, retinal surgery (detachments, many retinopathies such as in diabetes)</td>
</tr>
<tr>
<td></td>
<td>Dermatology and plastics</td>
<td>Port wine stains, haemangiomas, tattoo removal</td>
</tr>
<tr>
<td></td>
<td>Neurosurgery (Vascular) tumours</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Otolaryngology (See Nd–YAG applications)</td>
<td></td>
</tr>
<tr>
<td>Krypton</td>
<td>Ophthalmology</td>
<td>(See argon applications)</td>
</tr>
<tr>
<td>Tunable dye</td>
<td>Ophthalmology</td>
<td>(See argon applications)</td>
</tr>
<tr>
<td>Oncology</td>
<td>(See Nd–YAG applications)</td>
<td></td>
</tr>
</tbody>
</table>

Coagulation and oedema formation, other effects, including complications such as haemorrhage or obstruction, may be delayed by 1 or 2 days. When a high flux is used the centre of the “iceberg” may undergo vaporization, with rapid expansion of the tissues, resulting in a limited explosion of the overlying tissue—the “popcorn” effect. Its absorption by pigments makes it suitable for the control of bleeding gastric erosions, vascular lesions and polyps. Haemostasis of vessels up to 5 mm can be achieved. The short wavelength of this laser allows the beam to be transmitted by fibreoptic bundles to otherwise inaccessible parts of the body. Various shapes of sapphire tips can be mounted on the end of the fibre, resulting in the concentration of the Nd–YAG laser beam at the tip with considerable divergence just beyond the tip. This technique allows the sapphire tip to be brought into contact with the target tissue where coagulation or slow cutting can be achieved; the sapphire-tipped fibre can be advanced in endoscopes as well as in hand-held tools. The Q-switched (in addition to the mode-locked) Nd–YAG laser, one of the few medical applications of a pulsed laser, is used for posterior capsulotomy after cataract removal and other ophthalmic procedures such as iridotomy and vitreolysis [3, 65]. Very short (nanosecond), very high power density bursts can be delivered to the opacified posterior capsule, creating a “window” without injury to the retina. The very short, high power density pulses shatter the tissue by optical breakdown, tearing the molecules and cells apart with a shock wave effect; the thermal effects are of relatively little importance in this application (2, 46, 93).

The argon laser exhibits considerable variability in its absorptive, scattering and reflective properties. It is absorbed strongly by haemoglobin and pigmented tissue, transmitted by
homogeneous, watery tissue and scattered by non-pigmented, inhomogeneous tissues. The EL in water is 300 mm. The argon laser is ideally suited for retinal photocoagulation and other ophthalmological procedures. Absorption by blood enables excellent haemostasis. It can be transmitted by way of optical fibres so that it can be used for the endoscopic treatment of gastrointestinal bleeding. The haemostatic properties are inferior to those of the Nd–YAG laser because the greater CV of the latter allows control of bleeding from vessels several millimetres in diameter. The argon laser’s short wavelength makes very small spot sizes possible, typically 20 times smaller than the spot size of the CO\textsubscript{2} laser beam and, its beam being in the visible part of the spectrum, misalignment between the laser beam and a separate aiming beam is obviated.

The Nd–YAG–KTP laser beam possesses many of the characteristics of the argon laser with respect to its variability in its absorptive, scattering and reflective properties. It, too, is transmissible by way of quartz fibreoptic bundles. Its absorption by blood is high, by water low and its tissue absorption is less than the CO\textsubscript{2} laser beam but stronger than the Nd–YAG. The 647-nm krypton laser is in the red part of the spectrum; it passes easily through watery, homogeneous tissues as well as blood and is strongly absorbed by certain pigments in the retina. The tunable dye lasers generate frequencies in the range of the argon and krypton laser and are just reaching ophthalmological practice.

The ruby laser has been largely superseded by the argon and krypton lasers, but was used previously in ophthalmic surgery. The EL in water is 300 m, its scatter is high and it is transmissible by quartz fibre. It is absorbed strongly by melanin, but not by haemoglobin, and has a limited coagulation capability. It was used to repair retinal tears, the purpose being to produce an adhesive chorioretinitis. However, its limited haemostatic properties allowed small haemorrhages to occur.

Safety considerations for laser surgery

The lasers used in medical practice today do not cause ionization, are not carcinogenic and do not form a special hazard to pregnant women. It is imperative, however, that the laser beam be in an inactive or standby mode at all times except when the beam is aimed at an appropriate target. The laser beam is reflected by shiny, flat or concave surfaces deflecting it in unintended directions. The beam’s reflections and backscatter (Nd–YAG) can also cause injury. Reflection can be reduced by providing matt finished, convex surfaces for operating room equipment. A matt finish can be obtained by sandblasting or shot-peening, creating microscopic pits from which the beam is deflected in all directions. The microscopic pits and the convex surfaces diverge and defocus the laser beam, thereby reducing its power density over a short distance.

Trauma to the patient’s normal tissues can occur as extensions of the laser treatment with immediate or delayed sequelae including perforations, haemorrhage, pneumomediastinum and pneumothorax. These conditions may require emergency treatment for which the anaesthetic and surgical team need to be prepared. In addition to healthy tissues adjacent to the site of treatment in the patient, the eyes and epidermis of the patient and operating room personnel form accidental targets for a reflected beam.

The eye is the tissue most susceptible to laser injury. The CO\textsubscript{2} laser beam, with its short EL, can lead to corneal damage [43]. Light from the argon, krypton, Nd–YAG–KTP, and ruby lasers passes through the cornea and lens but is absorbed strongly by pigmentation. It may cause retinal damage. The Nd–YAG laser light is also well absorbed by the retina. In order to prevent eye damage, operating room personnel should wear protective eyeglasses which absorb the radiation of the wavelength of the laser in use. Their main purpose is to protect the eyes from accidental reflections and scatter of the beam; appropriate glasses do not protect the eyes against a direct hit from a focused beam at close range. Glass, transparent plastic or quartz glasses with side protectors are worn when the CO\textsubscript{2} laser is in use; contact lenses do not afford sufficient protection. The Nd–YAG laser light is absorbed by glasses which block the 1064-nm light. It should be noted that these glasses do not protect the eyes from the Nd–YAG–KTP laser light, which requires orange–red lenses to be worn. During use of the argon laser, orange–yellow lenses protect the eyes against the short wavelength of the green–blue spectrum; glasses which filter out the appropriate wavelength should be worn for the krypton beam. The “tunnel vision” and the reduced luminous transmission inevitably produced by such eyeware limit observation of the patient and the monitoring equipment, but are minimized by the use of
specially designed glasses with transparent side protectors and nearly "clear" lenses.

The detection of cyanosis is more difficult when coloured lenses are used, and we recommend continuous haemoglobin saturation monitoring (e.g. pulse oximetry). The attenuated aiming beams of the helium-neon, argon, krypton, tunable dye, and Nd–YAG–KTP lasers have very low power outputs and can be viewed indirectly or from the side with the unprotected eye; however, one should not look into these aiming beams directly or "on-end", unless they are specifically attenuated to be used intra-ocularly as in ophthalmic applications (the helium-neon, argon, krypton and tunable dye aiming beams).

In order to prevent injury to the patient's eyes, these are covered with moist pads held on with canvas tape. Plastic or paper tapes may flare up and should be avoided. Wet cloth towels cover the surrounding surgical field. In neonates and infants, in particular during long procedures, care is taken to minimize direct skin contact as it leads to patient hypothermia. Paper or plastic-coated paper towels are similarly avoided, because they wet poorly and may ignite. Heating of metal instruments may lead to burns, especially in the anaesthetized patient. During the use of lasers for colonic surgery and laparoscopy, a non-combustible gas, for example CO₂, is used for insufflation. Gases from the lower gastrointestinal tract should be evacuated, because they may contain methane. Accidental burns from laser-ignited combustion of flammable materials may occur from elastomeric tracheal tubes, flexible endoscopes and other combustible material around the surgical field. Tracheal tube ignition and explosions, and unintended facial burns, are the most common complications of the use of the CO₂ laser [26]. Claims about toxic, carcinogenic and infective properties of smoke, generated by the CO₂ laser beam's interactions with the tissues, have not been substantiated by either in vitro or in vivo studies [90]. Smoke can be suctioned away to improve visibility.

Complications may arise owing to the special equipment and instrumentation required. The CO₂ laser comprises the laser head, attached by an articulated arm to the operating microscope, and a control console connected by a single multipurpose tether. In addition to the invisible CO₂ laser beam, the head carries the helium–neon laser beam which serves as the aiming beam. The microscope is brought into alignment with the larynx and the micromanipulator moves a mirror in the laser head, aiming the helium–neon laser beam at the target. Misalignment of the helium–neon aiming beam with the CO₂ and the Nd–YAG laser beam or poor focusing of a laser beam can lead to trauma to normal tissue. The Nd–YAG laser beam and its helium–neon aiming beam are carried coaxially by a flexible quartz fibre from the laser console to the endoscope; the fibre has a Teflon sheet through which a cooling gas (e.g. nitrogen, helium, helox, air) is pumped, flushing the tip. The total fibre is advanced in a channel of either a rigid or a flexible fibreoptic bronchoscope. The tip of the fibre should protrude beyond the bronchoscope port at all times during its operation, under "direct" vision (via appropriate optics) of the operator. The fibre and the flexible bronchoscope are advanced well beyond the flammable tracheal tube. Firing of the Nd–YAG laser inside a flexible fibreoptic bronchoscope or an elastomeric tracheal tube can cause ignition. The metal bronchoscope excludes this possibility. To avoid combustion during the use of the Nd–YAG laser, it is important to keep the fibre tip clean and flushed with cooling gas. If the fibre tip is allowed to collect debris, it will melt and flare up. Most medically used lasers are high voltage, high current electrical devices with protective circuitry which shuts the laser down when malfunction occurs. The electrical hazards should be kept in mind; a laser should not be operated when the operating room floor is wet [25]. Operators of the laser and their assistants are preferably trained and certified within a given hospital [1]. Warning notices that a laser is in use are posted outside the operating room. The flow of traffic in and out of the operating room is minimized; the windows are blocked. Anaesthesia should not begin until the equipment is set up and checked, otherwise it may be prolonged unnecessarily.

Clinical considerations of airway surgery

The CO₂ laser is used predominantly in the upper airway to excise a variety of benign and malignant lesions (table II). It provides good haemostasis of small blood vessels, minimal postoperative oedema and good healing with little scar formation, making it invaluable in the small paediatric airway [97]. Rigid bronchoscopy permits treatment of tracheobronchial lesions with the CO₂ laser, while both the rigid and flexible bronchoscope permit their treatment with the
Nd–YAG laser [18, 91]. The Nd–YAG laser can be applied more efficiently in the distal tracheobronchial tree through a flexible fibre system with better optical control and secure haemostasis, especially when haemorrhage occurs from larger vessels (0.5–5 mm). It is particularly suited for palliative treatment of obstructive tracheobronchial malignancies [19, 76, 79]. The need to share access to the airway requires close cooperation and understanding of surgeons and anaesthetists [55].

Problems of airway management during laser surgery may arise from the underlying pathology and instrumentation. Specific anaesthetic techniques, suitable for each patient with airway pathology in need of surgery, do not need to be outlined here. However, a few points are worth emphasizing. The pathology for which the patient seeks treatment has often resulted in a marginal airway. Ventilatory obstruction with copious secretion and hypoxaemia may have led to respiratory and cardiovascular compromise or may have exacerbated co-existing disease. Careful preoperative assessment, including roentgenographic evaluation (chest x-ray, computed tomography), is essential. A detailed explanation of the proposed anaesthetic technique and surgical plan may help to produce a calm, relaxed patient. It is prudent not to give sedative or opioid agents to patients with a compromised airway, except after careful deliberation.

Anticholinergic drugs such as atropine, hyoscine and glycopyrrolate, may be useful to dry secretions and may reduce the vagal effects of laryngoscopy. Intra-operative monitoring includes electrocardiogram arterial pressure and breath sounds using a precordial stethoscope. Percutaneous pulse oximetry offers reliable, fast and continuous evaluation of haemoglobin saturation [5, 104]. Direct arterial pressure monitoring and blood-gas analysis may be helpful in some patients.

Securing a patent airway may be the first step towards the patient’s treatment. Satisfactory ventilation may not be established, however, until obstructions or sites of haemorrhage have been treated with the laser. Loss of muscle tone during induction of general anaesthesia may render a partial airway obstruction complete; an inhalation induction or intubation under local anaesthesia may be required. Full muscle relaxation offers optimal conditions for re-intubation should accidental extubation or tracheal tube ignition occur, provided that reintubation is easily accomplished. A deep level of anaesthesia can minimize the cardiovascular responses to instrumentation of the airway.

The larynx is exposed with a Jako or Dedo laryngoscope which is placed on a suspension apparatus. Patients in whom the laryngoscopy is difficult may be prone to injury from this procedure. Tooth damage or temporomandibular joint dislocation can occur during the exposure. A preoperative history of syncope or dizzy spells during neck movement may indicate the presence of vascular insufficiency. Similar concerns regarding positioning apply to the use of the Nd–YAG laser via the rigid bronchoscope.

**Lasers, ventilation and tracheal tubes**

*Polyvinyl chloride and rubber tubes.* When a CO₂ laser beam strikes a tracheal tube, ignition may occur [82]. The likelihood of such an event is determined by the type of tube (combustible material), the wattage of the laser beam, the duration of exposure of the tube to the beam, and a gas mixture supportive of combustion. PVC tubes are more ignitable than red rubber tubes when exposed to CO₂ laser beams of 15 and 30 W intensity for periods of 0.015–0.5 s in an atmosphere of 25 or 60 % oxygen in nitrous oxide [61]. No penetration of either tube occurred in an atmosphere of 25 % oxygen in nitrous oxide and a beam intensity of 15 W. Even at exposures of 0.5 s only superficial burns of the red rubber tubes resulted. However, all the PVC tubes either ignited or were penetrated during exposures of 0.5 s by a beam of 30 W intensity, whereas only one out of 10 red rubber tubes sustained damage. Oxygen concentration had a marked effect, with PVC tubes burning vigorously in 60 % oxygen in nitrous oxide and the burned area being more localized when 25 % oxygen in nitrous oxide was used. Red rubber tubes produced less smoke, and aluminium tape wrapping significantly retarded the ignition of both types of tube.

In another study, PVC and red rubber tubes were irradiated with beam intensities of 5–20 W for durations of up to 1 s in 50 % or 100 % oxygen; the diluent gases were not specified. The greater ignitability of PVC tubes was again confirmed [48]. However, the advantage of red rubber tubes was not demonstrated in a third study in which evidence of combustion was detected in an atmosphere of 30 % oxygen in air at intensities of 15 W or greater, for exposures of
more than 0.05 s [92]. Although the evidence is conflicting, red rubber tubes are generally regarded as safer than PVC tubes. The authors' recommendations for "safe" gas mixtures include 20–25 % oxygen without specification of diluent gases [61], 20–30% oxygen in nitrogen [92] or no critical oxygen limit provided that red rubber tracheal tubes wrapped in aluminium foil are used and direct hits are avoided [48]. However, all elastomeric tracheal tubes are combustible to a variable degree.

Tracheal tube protection. Tracheal tubes can be protected by wrapping with reflective aluminium or other metallic tape. In view of the greater combustibility of PVC tubes, it is preferable to use the less flammable ones such as the red rubber tubes. Wrapping starts at the superior border of the cuff, each turn smoothly overlapping the previous one by at least one \( \frac{1}{3} \) width. This allows the tube to be flexed without exposing the underlying tube and without breaking or kinking the tape. The cuff should be protected with damp cottonoids and can be filled with saline or lignocaine [41]. Disadvantages of this wrapping method are that it reduces tube flexibility, increases the external diameter, can produce rough serrated surfaces which may be traumatic and may be more difficult for intubation; the foil wrapping may become detached. These factors limit their usefulness in the small paediatric airway. Depending on the wattage and exposure time of the laser beam, in addition to the thickness and coating (Milar, glue) of the aluminium, foil, reflection, pitting and penetration of the aluminium foil are still possible. However, the processes are much retarded. Copper foil is also used for wrapping; it is less reflective than aluminium foil, has a greater heat capacitance and conductivity and may lead earlier to burn injury of adjacent tissues. Muslin wrapped tubes may ignite if the muslin is allowed to dry out. It adds bulk and the technique offers little advantage over wrapping with aluminium foil [85]. Metallic foil wrapping of elastomeric tracheal tubes does not offer protection from damage caused by an impinging Nd–YAG laser [28].

Silicone tracheal tubes. The safety of metal-loaded (aluminium oxide) silicone tracheal tubes, such as the Xomed Laser-shield, has not been fully evaluated. A preliminary communication reported that penetration of the silicone tube was not possible with pulses of 5–25 W for a duration of 0.1–1.0 s in an atmosphere of 30–100 % oxygen in nitrogen or nitrous oxide [31]. These preliminary data suggest significantly different characteristics compared with other silicone and PVC based tubes. Silicone tubes were associated with the least amount of gross anatomical and histological damage compared with PVC or red rubber tracheal tubes [59]. A 30-W CO\(_2\) laser beam impacted on the tubes until an intraluminal, blowtorch-like airway fire existed. Thirty percent oxygen in 70 % nitrous oxide and halothane formed the anaesthetic gas mixture in this canine model.

In a recent study, the relative flammability, rather than the ignitability, of PVC, silicone and red rubber tubes were compared in oxygen–nitrous oxide–nitrogen atmospheres using a standard ignition source [100]. Ignition refers to the amount of energy needed to ignite a fuel in a given atmosphere, whereas flammability of a fuel is its ability to sustain a flame in a given atmosphere. In a given gas mixture, red rubber tubes were the most flammable, followed by silicone tubes in turn followed by PVC tracheal tubes, which were the least flammable. PVC tracheal tubes sustained a flame when a minimum of 26 % oxygen in nitrogen was present.

The Milhaud and Rusch Injecto-Flex silicone rubber tubes are other examples of attempts to reduce fire-hazards. The Milhaud tracheal tube utilizes nitrogen as a "flushing" gas above the cords to cool the tube and to reduce the risk of explosion [49]. A silicone rubber shield loaded with aluminium powder is positioned just proximal to the cuff, preventing radiation reaching the balloon and distal structures. The Carden tube is a short (5-cm), cuffed, silicone rubber tube which utilizes nitrogen as a "flushing" gas above the cords to cool the tube and to reduce the risk of explosion [49]. A silicone rubber shield loaded with aluminium powder is positioned just proximal to the cuff, preventing radiation reaching the balloon and distal structures. The Carden tube is a short (5-cm), cuffed, silicone rubber tube which is placed in the trachea [11, 12]. Two small rubber catheters pass through the vocal cords, one for "jetting" gas and one for inflation of the latex cuff. This tube is used also for microlaryngeal laser surgery, in which case the pilot lines are covered with wet cottonoids. All elastomeric tracheal tubes are damaged by the Nd–YAG laser [28].

Trans-tracheal catheters and needles. In an attempt to increase visibility and to reduce exposure of combustible material to the laser beam, plastic or silicone rubber catheters and small diameter metal tubes (long needles or small tubes) have been inserted into the trachea [34, 36, 58, 64, 67, 69, 83]. Ventilation is accomplished by "jetting" a gas mixture, controlled manually or mechanically, down the trachea. These forms of ventilation do not predominantly, if at all, depend
on the Venturi principle. The catheters provide combustible material and, when severed, parts may be lost in the tracheobronchial tree. Mucosal tears may be generated at the tip of the metal ones. Pressures, generated during the “jetting”, are directly transmitted to the lung and are more likely to result in barotrauma than other techniques. The amount of gas delivered to the lungs is not limited by inspiratory obstructions, since the catheters usually bypass these points. Exhalation becomes a limiting factor. In order to avoid barotrauma care must be taken to ensure a patent exhalation route. Patients with pulmonary disease, especially those with air trapping, are susceptible to barotrauma with these techniques. This difference between inhalation and exhalation does not exist in Venturi jet ventilation through an operating laryngoscope.

**Metal tubes.** The only non-combustible tubes are made of metal. The Norton tube is a matt-surfaced, convex, reflective, segmented metal tracheal tube; its coils are not airtight, so that gas flow through the coils aids cooling of the metal [57]. A standard anaesthetic breathing system with a reservoir bag is connected to the tube; the fresh gas flow is increased to compensate for the gas escaping through the coil and around the tube. If sufficient ventilation cannot be maintained a latex cuff, which may be inflated with a liquid (water) and needs to be covered with wet cottonoids, can be added to the tube. However, these manoeuvres provide combustible material. Alternatively, a Woo–Pilling Venturi jet tracheal tube coupler with a 12-gauge needle is clamped onto the proximal end of the metal tracheal tube and gaseous exchange is established by Venturi jet ventilation [102]. The Norton tube needs an introducer during intubation because of its flexibility. The smallest, 4.4-mm i.d. Norton tube has an external diameter of 6.5–8.0 mm. The Porch tube is an airtight flexible metal tube (3 mm i.d., 7 mm o.d.) connected directly to a high pressure gas source via a Luer-Lok fitting [34]. Its behaviour, in terms of gas dynamics, is that of a large metal needle below the vocal cords rather than that of a tracheal tube. It is not commercially available. Both metal tubes are relatively large and do not give an unobstructed view of the larynx; their use in patients with a narrow airway, as in small children, is precluded.

**Gases and vapours.** Some authors recommend the substitution of nitrous oxide, which supports combustion, by inert gases such as nitrogen or helium, thereby delaying ignition of combustible material. Evaluating PVC tracheal tubes, Pash-ay and Gravenstein demonstrated that oxygen in helium retards ignition, but only if the oxygen concentration is less than 40%; the laser beam intensity is less than 10 W and continuous exposure is less than 10 s [60]. All PVC tubes could be penetrated easily at the lowest power settings, but they did not ignite under these conditions. The mean time to ignition of PVC tubes is shorter when 2% halothane is added and when the laser beam is directed at the barium sulphate indicator strip. It is suggested that nitrous oxide and halothane be avoided because of the formation of toxic products at high temperatures [61]; however, these concerns are of little clinical relevance during laser surgery [6, 42]. The anaesthetic gases and vapours (halothane, enflurane and isoflurane) are not themselves combustible under medical conditions.

**Venturi ventilation.** Venturi jet ventilation through an operating laryngoscope provides an unobstructed view, avoidance of combustible material, clearing of smoke and is usable for small openings in the smallest neonate without the need to restrict oxygen content. The intermittent use of Venturi jet ventilation permits the taking of biopsies, the removal of tumours or debris and the lasing of vocal cords in the absence of vibrations.

The application of the Bernoulli theorem and the Venturi principle to gases is outlined diagrammatically in figure 4 [52]. Gas under high pressure (the jet) exits from a needle or nozzle placed within the lumen of a specially shaped open-ended tube. In addition to the propulsive effect of the jet on the resting gas column, the pressure around the needle and behind the jet exit point becomes lower with respect to the pressure in the mainstream gas flow, with the result that ambient gas is entrained through the open proximal end of the tube (the entrainment orifice). The shape of laryngoscopes and bronchoscopes is not optimized for an optimal Venturi effect to take place. Other important factors are the site and size of the entrainment orifice, the force of the jet, the placement of the jet within the outer tube and the dimensions of the outer tube. The force of the jet leaving the needle depends on the driving pressure, the needle diameter, length, angulations and restrictions. The density and viscosity of the gas mixtures determine in part the type and volume of gas flow. The volume of gas leaving the outer tube may be 20 times that of the jet, and it is at a lower
pressure. The best position of the needle tip for maximum safety and efficient gas exchange is at the middle one-third of the laryngoscope [101]. A stainless steel needle is inserted coaxially into the lumen of the operating laryngoscope, which is in alignment with the trachea. A screw clamp holds the stainless steel needle in place. The needle is angled just proximal to the clamp, and is connected by “pop-off”, non-locking fittings to light weight, pliable, low pressure tubing, a manually operated, all-or-none trigger valve and a pressure gauge with a reducing valve connected to a high pressure (400-kPa) gas source (fig. 5). The trigger valve releases a stream of gas to flow down the laryngoscope into the trachea. Although the trigger can be operated automatically, manual operation is preferable because it enables greater control of the airway pressure and ventilation can be co-ordinated with the needs of the surgeon. The “needle-on-clamp” construction (fig. 6) is applicable to all operating laryngoscopes without modification, while all light and suction ports remain available. The light channel of an operating laryngoscope can also be used satisfactorily for delivery of the jet [73].

Peak inflation pressures and tidal volume depend on the driving pressure, needle diameter and length, internal diameter of the operating laryngoscope and compliance of the ventilatory system. Regulator pressures of 150–300 kPa in adults and 30–150 kPa in children are recommended, with the use of a 12–14 gauge needle for patients heavier than 100 kg, a 14–16 gauge needle for patients of 50–100 kg and a 16–18 gauge needle for those weighing less than 50 kg [101]. Before its use, the gas jet issuing from the needle is tested, at a distance of 1 cm, on the skin of the forearm, where it should generate a slight depression. Jet ventilation should start at low driving pressure settings and the driving pressure is increased gradually according to chest expansion, “breath” and transmitted sounds and other clinical criteria. The lowest regulator pressure which gives chest expansion is utilized. Sufficient time for exhalation is provided. The pressures generated by the gas stream leaving the operating laryngoscope are not the same and much lower than the driving pressures supplied to the needle [39,71,73]. Ventilation takes place with either oxygen or an oxygen and nitrous oxide mixture, although it is realized that the gas mixture delivered to the patient is altered by the entrainment of ambient gas [73]. Arterial blood-gas measurements have demonstrated the adequacy of gaseous exchange [54,56,73]. There is usually a tendency to hyperventilate, and inadequate oxygenation is rarely a problem. Full muscle relaxation provides a maximally compliant chest with minimal cord movement, while the incidence of laryngospasm and coughing are reduced.

Suction devices for evacuation of smoke can interfere with Venturi jet ventilation [50]. Complications of Venturi ventilation include barotrauma of the respiratory tract, but this is a rare complication. Venturi ventilation through a laryngoscope is also an option in the patient with a tracheostomy. The stoma can be covered with a sterile wet dressing to which gentle pressure is applied to prevent a gas leak. Mucosal drying may accompany the use of Venturi ventilation; it is a possible advantage when excessive secretions reduce the effectiveness of the CO₂ laser.

During Venturi jet ventilation, general anaesthesia is usually maintained by intermittent or
continuous i.v. infusions with anaesthetic agents including barbiturates (methohexitone, thiopentone), short acting opioids (alfentanil, sufentanil, fentanyl), benzodiazepines (midazolam, diazepam), ketamine or droperidol. Inhalation agents can be used if a separate entrainment system provides the desired gas mixtures [39].

**Bronchoscopy.** Laser therapy of the tracheobronchial tree has been undertaken with the CO_2 and Nd–YAG laser beams. The CO_2 laser beam is applied via the rigid ventilating bronchoscope during general anaesthesia [78, 79, 89]. During CO_2 lasing, the working channel of the ventilating bronchoscope is not obstructed by instruments, but ventilation can be impeded by the position of the bronchoscope in the tracheobronchial tree and by obstructive pathology. When telescopes, forceps or other instruments are used, partial obstruction of the working channel of the ventilating bronchoscope occurs; when its proximal end is open, anaesthetic gas can escape to the atmosphere via the proximal end. Inhalation anaesthesia with halothane or enflurane in 100% oxygen or in an oxygen–nitrous oxide mixture delivered by a conventional anaesthetic circuit with an anaesthetic reservoir bag via the side arm (bag ventilation) results in adequate ventilation. The use of 100% oxygen leads occasionally to incandescence of dried carbonized particles, but without sequelae [78, 89].

The Nd–YAG laser has taken over in importance from the CO_2 laser, because of better haemostatic properties, transmission through flexible quartz monofilaments, easier application and the ability to use better optics [8, 18, 79, 91]. It is applied via the flexible or rigid bronchoscope during local or general anaesthesia. Although the use of the flexible bronchoscope for YAG laser application has its proponents, the emphasis of tracheobronchial YAG therapy has shifted to its application via the rigid bronchoscope during general anaesthesia [8, 19]. The rigid bronchoscope allows better access to tracheobronchial pathology with forceps, balloons, dilators, suction catheters, etc. It facilitates treatment of bleeding, allows suction of large volumes of blood, pus, secretions or irrigation fluid, and the easier retrieval of tumour and debris. The rigid broncho-
scope also permits palpation and delineation of the tumour and the tracheobronchial wall; when obstructive pathology threatens airway patency, it can provide and maintain a patent airway by advancing the bronchoscope beyond the tumour mass. Rigid bronchoscopy is particularly well suited for large, obstructive lesions in the trachea and mainstem bronchi, whereas the flexible endoscope is useful for smaller and more distal pathology which may not be reached with the rigid bronchoscope [76, 79].

The flexible fiberoptic bronchoscope for YAG laser application (o.d. ≥ 6 mm) can be passed nasotracheally in the awake patient, via a tracheal tube (i.d. ≥ 8 mm) with swivel or membrane connector during general anaesthesia or via the rigid bronchoscope during either local or general anaesthesia [9, 17, 44, 68]. Flexible fiberoptic bronchoscopy is well suited for the preoperative assessment of the pulmonary pathology; local anaesthesia for the nasotracheal passage of the fibroscope is accomplished easily by the use of lignocaine applied through a nasal spray and an ultrasonic nebulizer. Flexible bronchoscopy for the YAG application under local anaesthesia may appear attractive since it avoids general anaesthesia. It may be reserved for selected patients. However, coughing and restlessness during local anaesthesia, especially in the hypoxaemic patient, provides less suitable operative conditions and general anaesthesia provides better airway control [19]. Hypoxaemia, haemorrhage and perforation are the main complications of Nd-YAG laser therapy of the tracheobronchial tree [75]. Maintenance of a patent airway with adequate ventilation and oxygenation, in addition to control of haemorrhage, are the key to successful therapy. Short (≤ 1-s), low power (≤ 50-W) bursts are associated with fewer complications [8, 19, 23].

The literature on bronchoscopic laser surgery is conflicting with respect to the optimum mode of ventilation and anaesthesia. Differing recommendations are made regarding local v. general anaesthesia, spontaneous v. controlled and (Venturi) jet v. bag ventilation. Differences regarding the efficiency of ventilation may stem from variations in patient selection, pulmonary pathology (type, location, pulmonary function), partial obstruction of the lumen of the ventilating channel by flexible bronchoscopes or instruments, and use of different types of jet and bag ventilation techniques. The description of the instrumentation and the technique of ventilation and its efficacy are often minimal; consequently, the characteristics of ventilation are difficult to evaluate from the literature, for example the report of Perera and Mallon [62]. Several large series of YAG applications via the rigid bronchoscope allude to achieving satisfactory ventilation as assessed only by adequate oxygenation [19].

Methods of ventilation during rigid bronchoscopy have been examined by many authors; this has led to the development of various approaches, including side-arm bag, jet and “high frequency” ventilation [10, 29, 70, 71, 94, 95]. Tracheal catheters are also used for rigid bronchoscopy; they have been discussed above. Mild hypercapnia has been associated with ventilation through a tracheal tube during flexible bronchoscopy in addition to side-arm bag ventilation via the rigid bronchoscope [9, 17, 98]. The anaesthetist’s ability to assess the delivery of an adequate tidal volume by side-arm bag ventilation has been questioned [29, 51]. Hypercapnia during bag ventilation has led other practitioners to favour jet ventilation during bronchoscopic laser surgery [62]. In the case of the bronchoscope, efficacy of ventilation depends on the site of jet entry, the amount of entrainment possible, the type of rigid bronchoscope used, its diameter, length and shape, and the space left in the working channel after instruments, telescopes or flexible bronchoscopes have been inserted [50]. The latter applies also to ventilation through the tracheal tubes and bag-via-side-arm ventilation with the rigid bronchoscope. Different siting of the jet, for example at the proximal end of an open-ended rigid bronchoscope [71] or at the distal end [94, 96], results in rather different gas dynamics, as illustrated by Conacher, Paes and Morritt [14]. If the jet exits in close proximity to tumour or the bronchial wall (increased resistance, reduced compliance), it may lead to back pressure in the Venturi system, diminishing ventilation [35]. If the method of jet ventilation relies not at all or only minimally upon entrainment of ambient gas, driving pressures need to be high enough to deliver an adequate volume of ventilation unless “high frequency” ventilation is used [39, 84]. Jet flow depends on the diameter and length of the injection assembly and on the type, density and viscosity of the gas mixtures. Satyanarayana and colleagues required a driving pressure of 345 kPa (≈ 50 lb in⁻²) to establish adequate ventilation through the working channel of a flexible bronchoscope (68 cm long, 2 mm i.d., inspired gas
100% oxygen) [72]. In this example of jet ventilation, no entrainment takes place and, by definition, it is not Venturi ventilation.

It is apparent that a variety of techniques provide satisfactory ventilation and surgical conditions, provided that the limitations of the techniques are realized. Vigilance is required, especially in view of the potential for hypoxaemia and hypercapnia. Bronchoscopic jet equipment should undergo systematic analysis of its flow, pressure and volume characteristics [53], but only a few systematic studies of ventilation through a bronchoscope under standardized conditions have been reported [35].

Rigid ventilating bronchoscopes have been adapted specifically for use during CO₂ and Nd–YAG laser bronchoscopy [14, 19, 78, 94]. These efforts have led to the commercial introduction of new rigid bronchoscopes designed specifically for the application of the CO₂ and Nd–YAG laser beam. The Wolfe–Dumon bronchoscope features two proximal ports, which immediately enter the main shaft, one for introduction of the laser fibre and one for a semi-rigid polymeric suction tube. A T-adaptor provides a swiveling side arm placed at a 90° angle to the shaft for bag or jet ventilation from each side of the operator of the bronchoscope; telescopes and forceps with cold light illumination are inserted in the usual manner [19]. Similarly, side-arm bag ventilation via a swivel adaptor placed at a 90° angle to the shaft can be managed from each side of the bronchoscopist in the Storz–Shapshay version. A separate jet arm at a 30° angle to the shaft is incorporated in the adaptor. Through the use of a proximal adaptor, which provides two metal channels, one for the laser fibre and one for the semi-rigid polymeric suction catheter, better control of the distal aspect of the fibre and the suction catheter is achieved [77]. Alternatively, an adaptor providing three ports without metal guiding channels can be used. Distal illumination is provided via a prism in the swivel adaptor as well as via the telescopes and forceps.

The Pilling Company produces a rigid bronchoscope for Nd–YAG laser application. It provides one channel (2.5 mm i.d.) for suction catheters and one 4-mm i.d. channel through which the largest YAG fibre equipped with a sapphire tip can be guided. The channels enter the main shaft 2 cm above the distal end of the bronchoscope, as does the separate cold light channel. The latter can also be used as a second suction or instrument channel. Illumination of the field is also provided by a cold light guide in the telescopes. A non-swivel side arm fixed at a 45° angle to the shaft allows both bag and jet ventilation. The fibre is directed by manipulation of the bronchoscope.

The Nd–YAG bronchoscopes have distal side vents to allow passage of gases if the bronchoscopic tip is obstructed. All three companies also market bronchoscopes for CO₂ laser beam application. No systematic evaluation of gas dynamics during jet or bag ventilation has been undertaken with these new bronchoscopes. A bronchoscope in which the jet enters the shaft distally, as proposed by Vourc'h, is not commercially available [94, 96].

Several authors have emphasized the need to maintain an inspired oxygen concentration of, at maximum, 40 or 50% during firing of the YAG laser [96, 98]. Absence of combustion and airway fires is in part attributed to this measure. It should be pointed out that this concentration of oxygen does support ignition and flammability of combustible material such as a polymeric tracheal tube, the flexible bronchoscope and a suction catheter [100]. When direct hits of the combustibles are avoided and the YAG fibre tip is kept clean, flushed and correctly applied, it is unlikely that a fire would occur under clinical conditions. When a rigid metal bronchoscope is used, the only combustible material available is the laser fibre itself and a suction catheter. Tissues and medical gases and anaesthetics do not form combustible material under non-hyperbaric medical conditions.

The inspired fraction of oxygen may be determined by the requirements of the patient. Dried carbonized particles may occasionally glow briefly, but without sequelae. The only reported YAG airway fire occurred in a patient with a tracheal tube, through which a flexible bronchoscope containing the laser fibre was advanced [13]. The inspired fraction of oxygen was intended to have been 0.4, but may have been 0.8; however, both concentrations are capable of supporting ignition and flammability of the polymers used [100]. Others, using the same equipment, have not experienced airway fires in the presence of an inspired oxygen fraction of 0.5 [8]. The “all metal” approach has not produced a fire [19]. In this case, prevention of a fire depends on maintaining the Nd–YAG fibre tip clean and flushed continuously with cooling gas (helium, helox, nitrogen, air), firing under “direct” vision and
avoidance of impinging the beam on the suction catheter. The jet of gas also cools carbonized debris, reducing its potential for incandescence. If diluent gases are used to reduce the inspired fraction of oxygen, nitrogen or helium can be used. Helium enhances oxygen transport beyond narrow passages if turbulent flow occurs; it also has a greater heat capacity and conductance than nitrogen, and is therefore a better coolant.

General anaesthesia may be provided using i.v. or volatile anaesthetic agents with controlled or spontaneous ventilation through a rigid bronchoscope or tracheal tube [19, 96, 98]. I.v. techniques have been associated with prolonged recovery times, sedation and postoperative ventilatory depression, conditions which are of particular concern in patients with potential respiratory obstruction from oedema, bleeding, secretions, debris and residual pathology [18, 19, 75]. General anaesthesia is more readily controlled with inhalation anaesthetics and the trachea may be extubated with minimal residual depressant effects. Thus general anaesthesia with inhalation agents has distinct advantages [98]. However, with the development of shorter acting agents (alfentanil, sufentanil, midazolam) and an increase in experience, anaesthetic and surgical requirements can probably be well provided with an i.v. technique, with a reduction in complications [8]. I.v. anaesthesia is used mainly during bronchoscopic jet ventilation, although the entainment of volatile agents has been suggested as an alternative [15, 40]. If entainment of inhalation agents is required, the vaporizer output should be sufficiently high (up to 10%) to deliver adequate concentrations of halothane from the bronchoscope [15]. With the exception of the copper kettle, most vaporizers currently manufactured are incapable of such high outputs.

**Clinical practice**

The following account reflects our own clinical practice. Oxygenation is of prime concern in patients who frequently have a compromised airway with minimal ventilatory reserve. An inspired oxygen concentration of 30% is the lowest concentration that we use. In the absence of combustible material, the use of oxygen (or nitrous oxide) is not restricted, nor are the halogenated agents (halothane, enflurane and isoflurane). In our opinion, the need for an immobile surgical field and control of the airway and ventilation necessitates, with few exceptions, general anaesthesia with neuromuscular blockade.

Anaesthesia is induced by the i.v. (barbiturates, benzodiazepines, opioids, etc.) or inhalation (halothane, enflurane) route. In this manner, a deep level of anaesthesia is obtained to minimize the cardiovascular responses during instrumentation of the airway. Arrhythmia or myocardial infarction may occur in response to suspension laryngoscopy and rigid bronchoscopy [88]. I.v. propranolol may be given before induction to attenuate the cardiovascular response to laryngoscopy [24]. Topical lignocaine, such as a 4% lignocaine spray applied to the laryngotracheobronchial tree at intubation, an i.v. bolus of lignocaine, or a 0.4% lignocaine infusion have also been used in an attempt to attenuate these responses [38, 86].

After induction of general anaesthesia or, very rarely, by awake intubation, we intubate the trachea with a regular, unwrapped polyvinyl chloride (PVC) tube. After evaluation of the pathology, the ventilation technique best suited for the airway pathology and the surgical mode of treatment is selected; we prefer the use of metal instruments, including the metal tracheal tube, the operating laryngoscope with Venturi jet ventilation and the ventilating bronchoscope with side-arm bag or Venturi jet ventilation. The aluminium foil wrapped, red rubber or Xomed silicone tracheal tube is preferred for CO₂ laser surgery.

When Venturi jet ventilation through the laryngoscope is planned, the PVC tracheal tube is left in place until the patient is positioned with the suspension laryngoscope, the microscope and the Venturi jet needle in place. After a few jet trials, the PVC tube is removed from the airway and jet ventilation proceeds. This method provides early control of the airway and a smooth transition of ventilation technique [56]. One hundred percent oxygen is used and anaesthesia is maintained with an infusion of methohexitone (e.g. 100 μg kg⁻¹ min⁻¹ during the first 3–5 min, followed by an infusion of 20–40 μg kg⁻¹ min⁻¹), opioids (alfentanil, sufentanil, fentanyl), benzodiazepines (midazolam, diazepam), ketamine or droperidol, or both. An infusion of suxamethonium or a neuromuscular blocking agent of intermediate duration (atracurium, vecuronium) is often ideally suited for these procedures of unpredictable duration. At the end of the laser procedure we often reintubate the trachea with a PVC tracheal tube after the airway is cleared by suctioning. The
trachea is extubated once spontaneous ventilation and appropriate reflexes have returned. Neonates and infants are also managed routinely with this technique, without the complications alluded to by Brummitt, Fearon and Brama [7]. Inadequate ventilation and intraoperative airway obstruction from instruments, debris and obstruction or displacement of the ventilating apparatus require constant vigilance.

In the case of application of the Nd–YAG laser beam to tracheobronchial pathology, a large (≥ 8 mm i.d.) PVC tracheal tube with a swivel port (Portex) is used to allow initial inspection of the process with a flexible fibreoptic bronchoscope under general anaesthesia. However, preoperative evaluation of the airway pathology with the flexible fibreoptic bronchoscope is preferred. If manipulation of a large obstructive process is required to maintain an adequate airway, a rigid bronchoscope is used from the onset. For laser treatment of tumours of the trachea and mainstem bronchi, the rigid bronchoscope is used. General anaesthesia is induced as outlined above. We prefer side-arm bag ventilation for bronchoscopic procedures. Inhalation anaesthetics (halothane, isoflurane or enflurane) are added to oxygen, while helium or nitrogen is used as the diluent gas.

When obstructive pathology is accompanied by (intermittent) hypercapnia or hypoxaemia or both, we utilize up to 100% inspired oxygen or oxygen–helium mixtures. Flare-up of proteinaceous residue in the Nd–YAG laser beam is reduced by curtailing the content of oxygen (and nitrous oxide) and by the stream of cooling gas (nitrogen, helium, helox, air). The inhalation anaesthetics are supplemented with small doses of the short acting opioids or barbiturates. Full muscle relaxation is provided with appropriate agents. At the end of the procedure the trachea is reintubated with a PVC tracheal tube, permitting optimal ventilatory control and cleaning of the airway.

After operation, elevation of the head and the sitting position aid lymphatic drainage and help to open up the air passages [22]. Swelling of the tongue and other oropharyngeal tissues is observed occasionally after suspension laryngoscopy. Nebulization of water in the inspired gas reduces drying of the oropharyngeal structures after laryngoscopy with Venturi jet ventilation [81]. The use of steroids to reduce oedema is controversial, but their anti-inflammatory action may be beneficial. Post-anaesthetic complications of Venturi jet ventilation are usually manifest within the first 2–4 h. Delayed complications produced by the different pathophysiology induced by the application of the Nd–YAG laser beam to tracheobronchial tumours can be encountered during the first 24 h after operation; these include ventilatory depression and obstruction, perforations resulting in haemorrhage, and pneumothorax; fortunately these complications occur only infrequently [76, 96, 98].

Management of intra-tracheal fires

Ignition of the tracheal tube and explosions, in addition to unintended facial burns, are the most common complications of the use of the CO₂ laser [26, 32]. The paucity of reports of tracheal tube fires in conjunction with the use of the Nd–YAG laser may stem, in part, from different application techniques [19]. For an explosion to occur, there must be a source of ignition (the laser beam), a source of combustion (for example an elastomeric tracheal tube or cottonoids) and a medium which supports combustion (such as oxygen or nitrous oxide). A laser-ignited explosion may lead to serious injury to the patient and the experience can devastate the operating room team [74].

A laser ignited explosion can cause a thermal and chemical injury. Thermal injury results from direct exposure to the flame. The severity of the burn depends on the duration of exposure and the heat intensity. The subglottic region, the epiglottis, the base of the tongue and the oropharynx are most likely to be affected. The flame may extend the length of the laryngoscope to burn the lips and face of the patient. Thermal injury can also result from heating of the tracheal tube, while burning tissue can be blasted into the distal airways. Inhalation of smoke may produce a chemical burn. Bronchospasm, intra-alveolar haemorrhage, oedema, and loss of surfactant may occur and lead to respiratory failure. Hydrogen chloride, a pulmonary toxin which produces a severe pneumonitis, is released when polyvinyl-chloride tubes burn [20, 99], while carbon monoxide is a decomposition product of burning rubber [33].

The anaesthetic and surgical team should be well rehearsed in the management of sudden fire and appropriate equipment should be immediately available. Initially, the source of oxygen and nitrous oxide should be disconnected, the tracheal tube removed rapidly and the area flushed...
liberally with sterile water or normal saline. A new tracheal tube should be inserted and ventilation resumed with 100% oxygen as indicated clinically. This assumes that intubation is easy; if this is not the case, a long stylet can be passed through the existing tube before removing it in order to facilitate the passage of a new one. When the fire is extinguished and the airway secured, rigid bronchoscopy with a ventilating bronchoscope can be performed. The extent of injury can then be assessed, foreign bodies (pieces of tube, aluminium foil, pledgets) removed, and the large airways washed to remove carbonaceous deposit. Subsequent management depends on the severity of the burn. The decision to extubate the trachea depends on clinical judgement.

Humidification of inspired gases is essential and a 24-h course of high dose steroids—methylprednisolone 5–7 mg kg⁻¹ or dexamethasone 1–1.5 mg kg⁻¹—is recommended, although their efficacy has not been proven [30]. It may be appropriate to administer a course of antibiotics. Recovery can be monitored by flexible or rigid bronchoscopy and this helps to determine the optimal time for extubation. Supportive measures, such as intermittent positive pressure ventilation and monitoring of pulmonary artery pressures, cardiac output and oxygenation (pulse oximetry), may be necessary. Tracheotomy may also be required.

REFERENCES


38. Knight PR, Kroll DA, Nahrwold ML. Comparison of cardiovascular responses to anesthesia and operation when intravenous lidocaine or morphine sulfate is used as an adjunct to diazepam-nitrous oxide anesthesia for cardiac surgery. Anesthesia and Analgesia 1980; 59: 130–139.


