Chapter 23: The principles of laser surgery

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It has been said that when the time in which we live is finally named, it will be known as the 'laser age' rather than the atomic or space age. However, we are still only at the dawning of this age. The first laser was not produced until 1960, but since that time a large number of laser systems have been developed with a vast range of scientific, industrial and military uses. Astronomers have measured, to within centimetres, the distance to the moon; huge numbers of telephone calls can be transmitted by way of flexible glass fibres; and physicists have probed plasmas hotter than the sun. In addition, the role of lasers in the 'star wars' programme is currently being researched with amazing defence possibilities and an equally amazing and horrifying potential for offence.

These diverse uses of the laser (light amplification by stimulated emission of radiation) are nevertheless all dependent on the basic characteristics of the laser beam: an intense beam of pure, monochromatic light which does not diverge and in which all the light waves are of the same length, travel in the same direction and are in phase, rising and falling together. The beam can be focused to a fine point producing very high energy levels.

The development of lasers

The essential physics of stimulated emission, which produces coherent laser light, was developed by Albert Einstein in 1917. Planck had proposed the 'quantum theory' embracing the principle that systems had to be restricted in the energy which they could attain, that is their energy was quantized. As a development of this theory, Einstein proposed the idea of stimulated emission which was new to science. Until that time, only two interactions had been known to exist between matter and light, namely absorption and spontaneous emission. An atom is normally in the low energy ground state, but it may be excited by the absorption of a photon (a quantum of light) if that photon has the correct frequency and concomitant energy to bridge exactly the gap between the two energy levels. Conversely, if an atom has been excited, for example by collision with an electron, it can return to the low energy ground state with the spontaneous emission of a photon.

Einstein proposed that if an atom in the excited state were struck by a photon with the same energy as that which would normally be emitted spontaneously, it would be stimulated to emit an identical photon travelling in the same direction as the original stimulating photon. From this concept, it was possible to imagine that in a population of excited atoms a series of collisions would result in the release, by stimulated emission, of an increasing number of identical photons.

The first device to exploit this phenomenon was the maser (microwave amplification by stimulated emission of radiation) produced in 1955 by Townes and his students at Columbia University. Three years later, Schawlow and Townes (1958) proposed that the principle of the maser could be extended to the infrared and visible areas of the spectrum. In 1960, T. H. Maiman, working at the Hughes Research Laboratory, produced the first laser using a synthetic ruby as the lasing medium, which emitted deep-red light at a wavelength of 694 nm, but at short pulses of less than a millisecond.
At about the same time, the xenon photocoagulator was introduced into ophthalmology by Meyer-Schwickerath (1956), and early experimental work suggested that the laser was superior to this instrument for the purpose of retinal photocoagulation. However, it soon became apparent that for much clinical work, the pulsed ruby laser was too harsh and uncontrollable, and it was eventually shown (Minton et al, 1965; Ketcham, Hoye and Riggle, 1967) that in the destruction of tumours with the pulsed laser, viable malignant cells were contained in the debris produced explosively by the laser impact, and with the additional significant risk of forcing malignant cells into adjacent, normal tissues.

The helium neon laser was the first continuous wave machine to be developed producing low power red light, and it is still in use both as an aiming beam and in alignment, but is too low powered for therapeutic use, although its role in biostimulation is being investigated.

In 1965, Patel produced the continuous wave carbon dioxide laser which has become the laser most commonly used as a high precision, bloodless, light scalpel and which has unique value in gynaecology and in otolaryngology. Early animal experiments with laboratory bench machines were carried out, and in some studies it was necessary to use moving tables on which to move the anaesthetized animals beneath the fixed, focused laser beam. However, these experiments demonstrated the potential of this laser as a surgical tool and the first clinical CO₂ laser system was developed by the American Optical Corporation in 1969.

At the same time as the CO₂ laser was being investigated, the argon laser was being developed, and this continuous wave device is now widely used for retinal photocoagulation based on the original work of Zweng (1971). The pulsed neodymium glass laser was also investigated and rejected by surgeons in the mid-1960s, but in the early 1970s, the continuous wave neodymium-YAG (yttrium aluminium garnet) laser was developed which produces near infrared coherent light. This is used for thermal tissue destruction and blood vessel coagulation. The pulsed Nd-YAG laser has recently been introduced which delivers nanosecond (10⁻⁹) pulses of energy into the eye. These produce precisely localized lesions in which the temperature is higher than that of the sun, and shock waves from these are used to destroy opaque structures within the eye, such as the posterior lens capsule after the removal of a cataract. Pulsed lasers are also being investigated for the destruction of renal stones and gallstones by photomechanical effects.

These three lasers - carbon dioxide, argon and Nd-YAG - are the three most commonly used in clinical practice, with the krypton laser being widely used for retinal photocoagulation.

The dye laser is under investigation for use in two main areas: first, the photocoactivation of intratumour haematoporphyrin derivative for the treatment of malignant disease by photodynamic therapy and, second, in both pulsed and continuous waveforms, for the selective destruction of blood vessels within the skin in the treatment of the port wine stain and other cutaneous vascular malformations. Pulsed metal vapour lasers are now being evaluated in these areas: copper vapour on the skin and gold vapour in photodynamic therapy.

Within the last few years, the excimer lasers have been developed and these appear to have enormous potential for producing remarkably precise incisions. The name is derived
from 'excited dimer' and the lasing medium is made up of molecules comprising two atoms of the same species (XeF or ArF) which are bound in the excited state but repel on decaying to the ground state.

The laser

Production of coherent laser light

The lasing medium is contained within the laser tube which has a fully reflective mirror at one end and a partially reflective mirror at the other, which allows access to the laser beam.

The lasing medium is pumped or excited electrically, or by a high energy light source, to create a population inversion of atoms in the high laser energy state compared to the low energy laser state, which, in a collection of excited atoms, normally has an excess in the lower state.

The energy of an atom is raised to the high energy laser level and, with the spontaneous emission of a photon, it decays to the low energy laser level and then back to the ground state. For the population inversion to be achieved, the high laser level must have a long lifetime compared to the low level, allowing the high laser level to build up.

As proposed by Einstein, stimulated emission then occurs as atoms spontaneously emit photons which, on collision with other excited atoms, stimulate these to emit identical photons travelling in the same direction as the original stimulating photons. The release of these photons is in all directions, but from time to time a photon will be released exactly in the axis of the laser tube and will then be reflected back into the lasing medium from the mirrors, with further collisions causing the release of increasing numbers of identical photons, all travelling in the axis of the tube. There is a rapid build-up of light energy in the laser tube - the cascade effect - and the beam is then emitted through the partially reflective mirror.

Beam characteristics

The laser beam is an intense, collimated (parallel) beam of pure, monochromatic, single wavelength light in which all the light waves are the same length and travel in phase in the same direction. This beam can be focused by a lens or concave mirror into a small spot producing extremely high energy densities.

Beam transmission

The coherent light from visible and low infrared lasers can be transmitted by fine flexible fibres to appropriate delivery devices. However, as yet, no flexible fibre has been found which will transmit efficiently the far infrared CO₂ laser energy, although a number of fibres are currently under investigation and it appears certain that an efficient fine fibre will soon be available. The CO₂ laser tube of some early models was mounted directly on to the operating microscope and the beam was aimed at the target by a concave mirror on the laser/microscope assembly, controlled by a micromanipulator. This made the system both unstable and cumbersome and, in more modern machines, the laser tube is mounted on the
console or on the microscope stand and the beam is transmitted to the microscope attachment, hand piece or bronchoscope by way of a self-supporting articulated arm which is hollow, with mirrors at the articulations. The length of the arm and the number of articulations and, therefore, range of movements, vary from machine to machine.

The argon laser is used with a slit lamp or operating microscope and both incorporate a shutter, which closes when the laser is fired, to protect the eyes of the operator. It may also be used with a hand piece in dermatology or by means of a delivery fibre for endoscopic work. The Nd-YAG laser may also be used with a microscope or slit lamp, with the operator's eyes protected by filters. Filters or goggles will also be used for protection when an endoscopic delivery fibres is used. The design of the tip of the endoscopic fibre appears to be critical. The laser fibre is surrounded by a metal-tipped Teflon sheath, down which compressed air is blow to keep the fibre tip free from debris and secretions. If these touch the tip they will absorb energy causing thermal damage to the fibre which may have to be removed for cleaning and even for recutting during a long treatment session. In addition, the metal tip may become so hot that it causes the Teflon sheath to swell, making it impossible to remove the fibre from the biopsy channel of the endoscope.

The CO₂ laser is used with the microscope when the operator's eyes are protected by the optics of the microscope, or with the hand piece when the laser is used as a light scalpel. There are a number of different types of hand piece and it must be said that some are far too bulky and clumsy for precise work, particularly in the oral cavity. A rigid bronchoscope may be coupled to the articulated arm, and there are considerable differences in the design of the couplers with particular reference to the beam aiming facilities.

**Beam aiming**

Before the 'working' laser beam is activated, it must be aimed accurately at the target. With lasers operating in the visible wavelengths, an attenuated beam is used to define the beam path and target area; but with the invisible near and far infrared lasers, a coaxial low-powered visible helium neon laser is used for aiming. With the CO₂ laser, a concave mirror may be used to focus the beam, but some use a zinc selenide lens as this is a substance which will transmit both the infrared and red wavelengths.

When used with the operating microscope for laryngology, the focal point of the beam is adjusted to the focal length of the lens, which for most microlaryngeal surgery is 400 mm. However, shorter working distances may be used and Anderson (19810 described the use of a laser focused at 400 mm, with a microscope lens of 250 mm focal length, to give a wide defocused beam of 2 mm in diameter for work on the cervix.

The laser/microscope attachment incorporates a micromanipulator which moves the final focusing mirror enabling the aiming and working beams to be positioned with great accuracy.

With the bronchoscope, the working beam may be 'fixed' into the centre of the distal opening of the bronchoscope with no aiming beam, or static aiming with thumbscrews may be available. Others have full aiming facilities with a small micromanipulator on the bronchoscope coupler.
**Laser beam parameters**

**Beam power**

The power levels vary from laser to laser with milliwatt powers for mid-laser therapy to 100 watts in high-powered CO₂ or Nd-YAG surgical lasers.

**Power density**

For all medical and surgical laser applications, it is essential to know not only the power but also the power density or irradiance measured as power per unit area.

The laser energy will have a greater effect if it is delivered within a small sport rather than if it is spread over a large area. The power density, recorded in watts or milliwatts per square centimetre, is measured by dividing the power by the area of the imprint.

**Energy distribution within the beam**

In spite of the parallel laser beam, there may be profound differences in the energy distribution within the beam resulting from differences within the optical cavity, such as the radii of the mirrors and their spacing.

There are, therefore, a number of different transverse electromagnetic modes (TEM). The commonest is the fundamental or TEM₀₀ mode in which the distribution is circular but the power level does not have a sharp cut-off, and the spot size is measured between points at which the power has fallen to 14% of the central level. This means that in this mode there will be effects on the tissue outside the boundaries of the quoted spot size. With TEM₀₁, the power distribution is doughnut shaped, and with other modes the energy may be distributed in a number of points with the TEM number indicating the number of nodes or points of zero energy.

**Total energy delivered**

This is measured in joules (watts/second) per unit area and is measured by the power, exposure time and spot size.

**Laser/tissue interaction**

The qualitative nature of the laser/tissue interaction is wavelength dependent, as this determines the pattern of absorption of the laser beam by the tissues and its effects on them. The quantitative extent of the interaction will depend on the intensity of the irradiation, the total energy delivered and the rate of delivery of the energy.

**Biostimulation**

In a paper summarizing the work of Mester and his colleagues in Hungary in the 1960s, published after his death by his sons (Mester, Mester and Mester, 1985), it has been
stated that very low levels of laser energy are biostimulative and at higher levels become inhibitory, ultimately having a thermal effect on tissues.

Mid-laser therapy has developed on the basis of this work and is used for improving wound healing and for pain relief in sports injuries and in 'rheumatological' conditions. Much of the early work was uncontrolled and anecdotal and could not be repeated in other centres. It is indeed difficult to define a mid-laser, as in this field the essentially low-powered, red helium neon and infrared gallium arsenide lasers and therapeutic CO\textsubscript{2}, argon and Nd-YAG lasers at very low subtherapeutic power levels have been used. However, some controlled studies have recently been reported which do show some value in these lasers for the purpose of pain relief and in the promotion of wound healing. Dyson and Young (1986) have shown that both wound contracture and cellularity are affected by mid-laser treatment. Further results from carefully constructed studies must be awaited with interest.

**Thermal effects**

When tissues absorb laser energy, the temperature rises. No changes in tissue structure are evident between 37 and 60°C, but above that temperature tissues begin to coagulate. The protein in the collagen fibres denatures owing to a randomization of the protein chains, and this results in contraction. This contraction of collagen in both the blood vessel wall and in perivascular tissues accounts for the haemostatic properties of laser energy.

When the temperature of soft tissues is raised to 100°C, intracellular water is boiled and this conversion into steam with a thousand-fold expansion results in almost instantaneous vaporization. Once the water has been removed from tissues in this way, residual cellular debris is burnt at a temperature of 400-500°C, but as there is poor thermal contact between this debris and residual tissues, this burning should not cause any significant damage to normal tissues adjacent to the laser wound.

**Non-thermal effects**

The non-thermal effects may be photomechanical or photochemical. An example of the mechanical effects is the use of the pulsed Nd-YAG laser for destruction of opaque bodies within the eye. Nanosecond (10\textsuperscript{-9}) pulses create minute balls of plasma in which the temperature is higher than that of the sun, and shock waves from these are used to destroy the lesions. This laser, using longer pulses, is being investigated for the photomechanical destruction of renal stones and gallstones.

A direct interaction between laser photons and molecules is responsible for photochemical effects in, for example, the photoactivation of haematoporphyrin derivative within a malignant tumour for photodynamic therapy, and in the ultraviolet laser tissue interaction with excimer lasers in the reshaping of the cornea or in the removal of atheroma from arteries.
Surgical lasers

The name of each laser is taken from the lasing medium, which also determines the wavelength of coherent light produced by that laser. The wavelength determines the absorption of the laser beam by body tissues and this defines the clinical role of the laser. As each laser produces essentially one wavelength of coherent light, it has one main clinical role, and to change role, one must change laser. There is, however, considerable overlap in the roles of the three lasers most commonly used in clinical practice, as can be seen in Table 23.1.

Table 23.1. The most commonly used roles for lasers

<table>
<thead>
<tr>
<th>Laser</th>
<th>Tissue destruction</th>
<th>Vessel coagulation</th>
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<tr>
<td>Carbon dioxide</td>
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<tr>
<td>Argon</td>
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<td>Neodymium-YAG</td>
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The CO₂ laser is used as a high precision, bloodless, light scalpel with an ability to seal blood vessels of up to 0.5 mm in diameter. The role of the argon laser is in blood vessel coagulation and, at higher power levels, slow and relatively imprecise thermal tissue destruction can be performed. The Nd-YAG laser is used for slow, imprecise, but adequate tissue destruction, with better haemostasis than is possible with the CO₂ laser.

The carbon dioxide laser

The carbon dioxide (CO₂) laser produces continuous wave, far infrared, coherent light at a wavelength of 10.600 nm which is absorbed by water and, therefore, by body soft tissues which contain 70-90% water. Intracellular water absorbs the energy and is boiled, causing a thousand-fold increase in volume and sudden, almost instantaneous, cell vaporization, which releases the cell contents into the beam where they are carbonized and fall as carbon soot around the laser wound.

It has been shown in several studies that there are no viable cells or cell components in the debris released by cell vaporization. Mihashi et al (1976) studied the debris following vaporization of the tongues of dogs and found that, although some epithelial cells were recognizable, they had lost their 'functional vitality'. Oosterhuis et al (1982) vaporized Cloudman mouse melanomata and found no viable tumour cells on culture in vitro or on intramuscular or intraperitoneal implantation in vivo, whereas controls of cells mixed with debris and smoke remained viable.

There is no shock impact when the beam strikes the tissues and, therefore, no tendency to force cells into adjacent normal tissues.

Cell vaporization takes place at the relatively low temperature of 100°C (the boiling point of water) and, as tissues conduct heat poorly, there is a very thin layer of damaged cells adjacent to the laser wound which may be as little as 50 µm wide. It has been shown by
Kiefhaber, Nath and Moritz (1977) that the CO_2 laser energy is 90% absorbed in a depth of 100 µm. This laser, therefore, removes a layer of cells by vaporization, exposing subjacent layers which are then vaporized, so deepening the wound as with a scalpel.

Two methods are available for the removal of tumours with this laser. First, after a representative biopsy has been taken, the laser is used to vaporize the whole lesion and adjacent normal tissues until a tumour-free defect to appropriate margins has been achieved. This technique destroys the greater part of the lesion, thus making it unavailable for microscopic assessment. The second, and better, method is to use the laser beam where possible as a scalpel to excise the lesion with appropriate margins. The anterior border is first cut to an appropriate depth, and then the lesion is undercut. The specimen must be kept under tension to prevent heat contracture, and with this technique the final defect is no larger, and is more precisely cut, and the whole specimen is available for histological study.

As a result of this method of tissue removal, the features of CO_2 laser surgery, in appropriate fields are:

1. immediate tissue destruction
2. bloodless dissection
3. minimal instrumentation
4. precise dissection
5. minimal damage to adjacent normal tissues.

**Immediate tissue destruction**

Tissue destruction by instantaneous vaporization is an obvious advantage over cryotherapy, in which a period of many days is needed to allow the tissue destroyed by freezing to separate. This period is accompanied by pain, oedema and slough which are minimal or absent after CO_2 laser surgery.

**Bloodless dissection**

The focused CO_2 laser beam will seal blood vessels of up to 0.5 mm in diameter, and if a defocused beam with lower power density is used, larger vessels may be controlled. As with the monopolar diathermy, if high cutting power is used, coagulation is less efficient, and for all work a 'compromise' power will be used which provides both rapid cutting and good haemostasis. Surgery within the larynx is essentially bloodless, but if extended endoscopic resections are performed, some vessels will be encountered which will require diathermy coagulation. In surgery to the mouth and tongue, some diathermy will be required with ligatures for control of the major vessels.

The beam also seals lymphatics and it has been suggested that this may reduce the spread of malignant cells by the route. Oosterhuis (1978) studied the lymphatic spread of labelled Cloudman S91 melanoma cells after scalpel and laser incisions, and found significantly higher spread after a scalpel incision, with the spread after laser incision no higher than in the controls in which no incision had been made.
The beam also seals nerve endings. Holzer and Ascher (1979) studied severed peripheral nerves and showed that the ends were smooth with a sealing of the endoneurium and that there was no incidence of neuroma formation.

**Minimal instrumentation**

When a CO₂ laser is used with the operating microscope, no instruments are needed to deliver the beam to the tissues, but a sucker is needed at the point of surgery to remove the steam produced by tissue vaporization, both for visual access and to prevent damage to adjacent normal tissues by the scalding steam. This relative lack of instrumentation is vitally important when access is limited, as in paediatric laryngology.

The CO₂ laser beam cannot, at present, be transmitted by way of a fine flexible fibre and the target area must be accessible to a rigid, straight endoscope. However, stainless steel mirrors equipped with suction are available to reflect the beam to treat lesions in inaccessible areas, such as the undersurface of the vocal cords, laryngeal surface of the epiglottis or nasopharynx.

**Precise dissection**

In otolaryngology, almost all the work is done under the operating microscope, although some resections in the anterior part of the mouth may be carried out with the hand piece. The microscope provides a well-illuminated, magnified operative field in which the bright-red helium neon aiming beam spot is positioned with great accuracy using the micromanipulator on the laser/microscope attachment.

The amount of tissue destruction produced by each activation of the laser with the foot switch can be 'preset' by selecting an appropriate power of the beam and its exposure time on the tissues. The power is continuously adjustable to a maximum of about 40 watts in most clinical machines and a mechanical shutter controls the exposure, permitting exposure times of 0.1, 0.2, 0.5 and 1 second, and 'continuous' when the exposure time will be controlled by the foot switch.

A large number of techniques have been described for removal of tissue in various sites. For much of the early work on the larynx, low power levels of 5-10 watts or even lower were used. For removal of mouth or tongue lesions, 20-25 watts with continuous exposure was often used as this permitted rapid cutting with good blood vessel coagulation. However, many modern machines offer 'super pulsing' of the beam with a high peak power and exposure times measured in milliseconds. Both the theoretical evidence provided by McKenzie (1983) and early clinical evidence indicate that the use of a super pulsed beam with a 'short, sharp' dissection technique may reduce damage to adjacent normal tissues and reduce charring in the wound.

In addition, no instruments or blood are present in the wound and, as the beam does not significantly denature the tissue adjacent to the wound, the progress of dissection can be followed with great accuracy under the microscope.
Minimal damage to adjacent normal tissues

The absorption of the far infrared CO\textsubscript{2} laser beam by intracellular water causes an instantaneous explosive destruction of cells by vaporization, but at the relatively low temperature of 100\textdegree C. As tissues conduct heat poorly, there is an extremely thin layer of damaged cells, only a few micrometres in width, between the laser wound and adjacent normal tissues. As a result, there is minimal postoperative oedema.

Healing of skin incisions cut by CO\textsubscript{2} laser would appear to be slower, with a reduced tensile strength after seven days, compared with an incision cut by scalpel, although the final strength is the same (Cochrane et al, 1980).

In the healing of CO\textsubscript{2} laser wounds of the larynx, reported by Tranter, Frame and Brown (1985), little inflammatory response and few myofibroblasts with little collagen formation in the wounds were found, which meant that minimal scarring or deformation of tissues would result. Similar findings were reported in the case of wounds of the oral mucosa by Fisher et al (1983).

These findings suggest that there are no particular advantages to cutting skin incisions with the CO\textsubscript{2} laser, except in patients with a haemorrhagic tendency where better haemostasis will be achieved, but that it is essentially a mucosal tool of value in gynaecology and otolaryngology, and also in neurosurgery for the performance of precise, atraumatic ‘no touch’ surgery.

Carbon dioxide surgical lasers

A number of CO\textsubscript{2} surgical lasers are now available, and the majority deliver up to 40 watts of power at the tissues by way of an articulated arm system. The power level is relatively meaningless unless the area of the laser imprint is also known, enabling the power density to be calculated in W/cm\textsuperscript{2}.

With the hand piece, very small spot sizes of a fraction of a millimetre can be produced; but at a focal length of 400 mm, which is commonly used with the operating microscope, spot sizes of between 0.9 and 1.7 mm diameter are commonly found, although in some machines the spot diameter can be changed over a wide range of sizes and with this are associated changes in power density.

All machines are supplied with a hand piece for use as a light scalpel, although in otolaryngology these are of limited value as they tend to be somewhat bulky. Many machines supply a coupler for use with a rigid bronchoscope, and a number of trials are in progress to compare the role of the CO\textsubscript{2} laser with that of the Nd-YAG laser in endobronchial tumour destruction.

In the selection of a clinical machine, a number of features must be considered including: power and spot sizes available; length, number of articulations and range of movement of the articulated arm; ease of use of micromanipulator; availability of hand piece and bronchoscope with distal suction and good beam aiming facilities; reliability and quality of service; and, inevitably, price.
The argon laser

The argon laser produces continuous wave coherent light at a number of wavelengths, but most of the energy is at 488 and 514 nm which can be transmitted by way of a flexible fibre.

Coherent light at these wavelengths will pass through water and clear colourless structures without absorption and without causing thermal damage. The light is selectively absorbed by tissues which have its complementary colour red.

In skin, the beam is scattered but absorption by chromophores, such as blood, is significant; it has an absorption depth of about 230 µm whereas in blood it is 170 µm. The selective absorption pattern of argon laser energy means that it is predominantly used for the photocoagulation of both normal and abnormal blood vessels. Jain (1983) compared the use of the laser for blood vessel coagulation in neurosurgery with the bipolar coagulator. He commented that the laser could perform photocoagulation by delivering a precisely calculated dose of energy to create discrete lesions with no spread of energy to adjacent tissues and without contact with the vessel. He commented further that the coagulator had to touch the vessel, with a risk of dislodgement of the clot when the instrument was removed; the amount of energy delivered was imprecise, and there was electrical current leakage and diffuse vessel wall damage. However, he pointed out that the coagulator is simple and cheap whereas the laser is complex and expensive.

In the field of photocoagulation, the argon laser was first used on the retina where, attached to a slit lamp, avascular areas of retina in diabetic retinopathy were photocoagulated to reduce the stimulus to new vessel formation. This treatment can be carried out through, and without damaging, the clear anterior parts of the eye, and it is still widely used in this field, alongside the krypton laser. It is also used in dermatology to treat the hitherto untreatable port wine stain by photocoagulation of the abnormal capillaries in the outer dermis through, and without damaging, the clear overlying normal epidermis. Another unique advantage in this field is the potential to coagulate small vessels lying on vital structures such as the vasa nervorum as suggested by Di Bartolomeo (1981).

The absorption pattern of this laser means that slow and relatively imprecise thermal tissue destruction can be carried out. Some early work on the photodestruction of bronchial tumours was performed with this laser by Hetzel et al (1983). However, for tumour destruction it has largely been replaced by the Nd-YAG laser, although it is still used on occasion to 'gut' tumours which are small, adjacent to vital structures and inaccessible to the CO₂ laser.

Early machines required a continuous flow of water for cooling the laser tube and this, plus the requirement for three-phase electricity, made it necessary to plumb and wire in the machine giving a fixed and relatively immobile installation. Recently, air-cooled machines have been introduced which are readily movable, and even portable, and which are, therefore, much more suitable for multidisciplinary use, appearing not to overheat if used continuously. A majority of machines produce about 5 watts of power but 20-watt lasers are available; these more powerful machines will be necessary only for the control of haemorrhage from upper gastrointestinal ulcers and for some tumour work.
Transmission of the beam is by way of a single flexible fibre of approximately 100 µm in diameter embedded in a protective sheath; at the distal end, the diverging beam is refocused by a lens. When used with a slit lamp or microscope, spot sizes of 50-100 µm are available and aiming is provided by an attenuated beam controlled by a micromanipulator. With the hand piece used in dermatology, a spot size of about 1 mm diameter is used. With the CO2 laser, the optics of the microscope would absorb the laser energy in case of reflection of the beam and, as such, the operator is not at risk of eye damage. However, the operator could be at great risk of suffering retinal damage with lasers of visible wavelength, and both slit lamp and microscope incorporate a shutter which closes when the main beam is activated; this mechanism is fail safe in that the beam cannot be activated unless the shutter is closed.

The Nd-YAG laser

The Nd-YAG laser is the only one of the three most commonly used lasers in clinical practice which does not have a gas as its lasing medium. It has a crystal rod, 100 mm long and about 6 mm wide, of yttrium aluminium garnet with dopant neodymium ions embedded in the lattice. The exciting energy is provided by a powerful light source which is usually a krypton arc lamp focused on the crystal rod. This is the most powerful surgical laser currently in use, as more neodymium ions can be contained in a given volume compared to a gas, and power levels of up to 100 watts are available.

The near infrared coherent light at a wavelength of 1060 nm can be transmitted by way of a flexible fibre and it is aimed by a visible low-powered helium neon laser. The beam at this wavelength is deeply absorbed in the tissues without colour or tissue specificity. Early work suggested that the absorption length of this wavelength could be as long as 90 mm and there was concern that damage could be caused to subjacent tissues even beyond the organ being treated. However, more recent work by Kiefhaber, Nath and Moritz (1977) showed that the beam is absorbed in tissue within a few millimetres. The beam is scattered and diffused by tissue inhomogeneities and so great is the scattering/absorption ratio that a near infrared photon may be scattered many times before it is absorbed.

This pattern of absorption means that the beam affects a far larger volume than the CO2 laser and that at a given power level the temperature rise is far less. The Nd-YAG laser is used at high power levels to perform relatively slow, but adequate, tissue destruction with better control of bleeding than is possible with the CO2 laser. Kelly et al (1983) have states that the Nd-YAG laser can control vessels of up to 1.5 mm in diameter compared to 1.0 mm with the argon laser, and it has been estimated that vessels of up to 0.5 mm in diameter can be controlled with the focused CO2 beam.

In the thermal destruction of tissue with the Nd-YAG laser, it would appear that there are three distinct layers of damage. First, a layer which has been vaporized; second, one which has been coagulated and will subsequently slough; and third, one in which death of cells occurs, these then being replaced by fibrous tissue without loss of physical integrity. This means that, in the treatment of a tumour involving the whole wall of the oesophagus or trachea, there is only a small risk of perforation.

Tissue removal with this laser lacks the precision which is obtainable with the CO2 laser, but recently the Nd-YAG laser has been coupled to a synthetic sapphire 'blade' and this
is used as a laser scalpel. The performance of a wide range of general surgical procedures using this system has been described indicating good healing and low patient morbidity. Results from controlled clinical trials with this laser scalpel must be awaited with interest.

The laser tissue interactions produced by the pulsed Nd-YAG laser which are used to destroy opaque lesions in the eye, and renal stones and gallstones have already been described.

**The dye laser**

The dye laser is under investigation in two main clinical areas: for the photoactivation of intratumour haematoporphyrin derivative for the treatment of malignant tumours by photodynamic therapy, and for the selective destruction of blood vessels within the skin, for which both continuous wave and pulsed lasers are being evaluated. Early work was carried out with laboratory bench machines which required the constant attention of a laser physicist. Recently, however, more stable and, clinical 'hand off' machines have been introduced.

The dye laser uses an organic rhodamine dye as the lasing medium and this is continuously circulated to avoid heating. The dye laser is excited either by a flash lamp or by an argon or copper vapour laser. as each dye molecule is composed of many atoms, it gives rise to a spectrum of laser lines and each dye can be made to lase over a range of about 50 nm. By changing the dye, coherent light in almost all parts of the visible spectrum can be obtained. The required laser line is selected from the available spectrum by the insertion of a birefringent filter which allows only one wavelength of light to pass through it depending on its angle in the beam.

The ability to tune a dye laser is an important feature, of potential value for the photoactivation of other tumour sensitizers which will be developed in the future and which may be photoactivated at different wavelengths. However, a disadvantage is that the power available is, at best, only 25% of that of the exciting laser.

The light from the dye laser can be transmitted by way of flexible fibres, and a number of delivery fibre tips for surface irradiation of tumours are available, together with a cylinder for implantation into tumour tissue and for the treatment of a circumferential lesion, and also a diffusing bulb tip for the irradiation of the whole of the inside of a hollow viscus such as the bladder.

**Metal vapour lasers**

A wavelength of approximately 630 nm is required for the photoactivation of an intratumour haematoporphyrin derivative, and an alternative light source for this is the gold vapour laser. This machine can produce much higher power levels and is more stable and easier to use than many dye laser systems. It is, therefore, more suited to clinical practice as shown by Carruth and McKenzie (1986).

This laser produces red light at a fixed wavelength of 628 nm which is pulsed at a rate of 10 kHz, meaning that for practical purposes it is a continuous wave beam. However, it has been suggested by Hisazumi et al (1985) that the pulsed beam penetrates the tissues better
than the continuous wave dye laser beam, but this work has not been confirmed elsewhere and McKenzie's investigations (1986, personal communication) do not support these findings.

It might be thought that when other tumour photosensitizers are developed, which are excited at different wavelengths, this gold vapour laser would become obsolete. However, it appears certain that for the next five years at least, haematoporphyrin derivative, or one of its components, will be the only sensitizer in clinical use. Furthermore, when other sensitizers are developed, it is reasonably easy to change the metal in the laser from gold to copper, and the copper vapour laser could be used to drive a tunable dye laser.

Safety

The lasers used in medicine and surgery are, obviously, much less powerful than many of those used in science and industry, but all the therapeutic lasers are in the highest power class (class 4) and 'their use requires extreme caution'.

A wide range of national and international safety codes, pertaining to the safe use of lasers, are in existence. In the UK, the relevant codes are the British Standards Code BS4803, Radiation Safety of Laser Products and Systems 1983, and BS5724, for electrical safety of laser equipment. In addition, the document Guidance on the Safe Use of Lasers in Medical practice has recently been published by the Department of Health and Social Security (DHSS).

Safety administration

The local health authority has overall responsibility for the implementation of health and safety advice, and it is stated by the codes of safe practice that a laser safety officer should be appointed who will advise on all aspects of this problem and produce a code of safe practice for each laser in each clinical situation.

The laser safety officer is usually a medical physicist with a wide experience of lasers, and may be responsible for several hospitals within a district or region. Therefore, a local laser protection supervisor will be appointed who may be a doctor or a member of the operating theatre staff, and he/she will be responsible for the implementation of the safety codes when lasers are being used clinically.

It is suggested that a list of 'nominated users' should be drawn up and access to the machine by the key control should be limited to doctors on this list. It is essential to ensure that lasers do not fall into the wrong hands, and the problem of identifying those who have had appropriate training in medical laser techniques and safety remains unsolved. The British Medical Laser Association, founded in 1982, has introduced the idea of accreditation for suitably trained doctors and a mechanism has been set up whereby the curriculum vitae of those wishing to be accredited is studied by the appropriate specialist representative on the committee of the Association and by one or two others appointed by the appropriate national specialist body. However, the concept of accreditation has not been widely accepted and remains a topic of regular and often heated debate.
It would be both impossible and inappropriate to discuss all aspects of laser safety, but some of the more important points must be mentioned.

The machine

The machine must comply with the British Standards codes for electrical and laser safety and a number of specific features have been recommended in the DHSS guide.

Key control

All class 3A, 3B and 4 lasers must incorporate a master key control.

Emission warning

A visible or audible warning should be provided when the laser is switched on and operating.

Remote interlock

This should be available to lock the operating theatre doors electrically when the laser is operating.

Aiming beam

An aiming beam must be fitted and it must not be possible to operate the laser if this beam fails.

Emergency shut-off switch

An instant switch must be fitted.

Beam transmission system

The fibre or articulated arm should be securely fitted and a tool required for detachment.

Warning labels

Appropriate labels must be fitted.

Environmental

The room in which the laser is operated must be designated a 'laser controlled area' and access to this area must be strictly limited to those essential to the procedure, and to specified visitors. Warning signs must be displayed outside and, ideally, these should be illuminated when the laser is switched on. Remove door interlocks which are activated when the laser is working should be used, particularly if there is a significant risk of accidental entry to the controlled area.
The eye hazard

The part of the eye which could be damaged by laser radiation depends on the wavelength of the coherent light. Far infrared light produced by the CO\textsubscript{2} laser would be absorbed by the cornea and a retinal injury could not occur until the beam had penetrated the whole globe. However, the near infrared laser light produced by the Nd-YAG laser and visible wavelengths would be focused on the retina with an increase of power per unit area of $10^5$ times the energy incident on the cornea.

The maximum permissible exposure has been calculated and, for wavelengths transmitted on to the retina, this is a factor of 10 below the level of exposure for which there is a 50% chance of detecting a retinal injury. Maximum permissible exposure tables are available in the British Standards code, and DHSS Code states that these levels should be used as a guide on the control of exposure and should not be regarded as precisely defined lines between safe and dangerous levels.

Eye protection

Adequate eye protection must be provided for the patient and for all the staff in the laser controlled area if the maximum permissible exposure level for the particular laser can be exceeded. It is obviously extremely unlikely that a member of staff could be exposed to the direct beam, but it is possible that the laser beam could be reflected back into the operating theatre from an instrument or retractor. The design of and specifications for the 'laser proof' eye wear which should be provided are clearly defined in the safety codes. The eye wear must be marked to indicate the wavelengths against which protection is provided and the absorbance of the filter at these wavelengths. The glasses must attenuate the laser beam to below the maximum permissible exposure, even if direct exposure occurs, and must not shatter or puncture if exposed directly to the maximum power of the laser.

Different eye wear will be required for use with each laser, and glasses which conform to these specifications are available and must be provided. The eyes of the patient will be protected by glasses or by appropriate, carefully fixed pads which, in the case of the CO\textsubscript{2} laser, must be soaked in water - as described by Colman and Conway (1985) - to absorb the energy should the beam miss the target. Argon laser goggles or eye shields are available; and if work is to be performed close to the patient's eyes, stainless steel contact lenses are available and must be used.

When using the operating microscope, the surgeon will have the optics to protect his eyes against CO\textsubscript{2} laser radiation when the microscope or slit lamp is used with the argon laser, shutters which operate when the laser is activated are used for protection. With the Nd-YAG laser, filters on the endoscope will be used to protect the eyes of the surgeon and goggles or pads are provided for the patient. However, for all other usage, particularly with hand pieces, the surgeon must wear appropriate laser-proof glasses.
**Skin injury**

Unless accidental exposure to the direct beam occurs, skin injury from a reflected beam would be insignificant, and protective clothing is not thought to be necessary for operating theatre personnel.

**Anaesthetic safety**

A hazard unique to otolaryngology is the danger of anaesthetic tube combustion when the CO₂ laser is used, particularly in laryngology. A number of endotracheal fires have been recorded with some fatalities.

If an endotracheal tube, made of combustible material, is struck by the CO₂ laser beam, it will ignite. Research has shown that a continuous beam, at normally used power levels, will cause a rise in temperature of the tube of approximately 5000°C per second (A. C. Wainwright and J. A. S. Carruth, unpublished results).

A number of 'laser-resistant' tubes have been developed and several will not ignite if surrounded by a gas mixture with low oxygen and nitrous oxide content, or if used with a flow of carbon dioxide or nitrogen around the upper part of the tube above the cuff. However, all the tubes tested to date will ignite if surrounded by oxygen, and the use of nitrous oxide does not ameliorate the situation as this gas supports combustion as well as oxygen.

A very large number of materials have been tested which could be used to produce a smooth, flexible anaesthetic tube and these have been plated with a number of metals using a variety of techniques. It has been found that all these materials, when surrounded by oxygen or nitrous oxide, will ignite and burn if struck by the laser. After metal plating the tube appeared to be entirely smooth with a complete coating of metal, but microscopy showed that 'peaks and troughs' on the surface of the tube allowed islands of plastic to appear in the metal coat and these could be ignited. When a thick metal plate was applied the tube became rigid and when flexed the coating cracked.

However, in spite of the lack of a totally laser-proof disposable, soft, flexible anaesthetic tube, a number of 'laser-safe' anaesthetic techniques have been developed, either without an endotracheal tube or using a protected plastic or metal tube. It is essential for the laryngologist to work as a team with an anaesthetist who is fully conversant with this hazard and the techniques to overcome it.

**Anaesthetic techniques for microlaryngeal laser surgery**

**Jet ventilation with no endotracheal tube**

The Venturi ventilation principle, first suggested by Bernoulli, has been known since the eighteenth century. With this technique, the patient is anaesthetized routinely and a fine endotracheal tube is inserted. When the patient has been positioned on the operating table, a laryngoscope is inserted and appropriately fixed. The tube is then removed, a 'jet ventilator attachment' is fastened to the laryngoscope and the paralysed patient is oxygenated by intermittent jet ventilation of oxygen.
There are a number of disadvantages to this technique which, nevertheless, is totally laser safe as there is no combustible material in the airway. First, some patients are not suitable for the technique, particularly those who are grossly obese or who have severe chronic obstructive airways disease. Secondly, the cords abduct and vibrate on each injection of gas, and surgery has to take place between injections. However, when working with the same anaesthetist, the surgeon soon learns the rhythm of injection and surgery can be carried out easily when this technique is employed. Thirdly, the subglottis cannot be protected with a wet swab, although there have been no reports of problems from injuries to this area from the defocused laser beam. Fourthly, it has been suggested that jet ventilation may blow viable particles of papillomata into the lower airway with a risk of seeding the disease. However, this risk, which could also be present with malignant disease, would appear to be theoretical only and there is no clinical evidence to support it.

Other jet ventilation techniques employ metallic catheters inserted into the trachea, but it is considered by some that the risk of causing a pneumothorax with these catheters, particularly in children, is significant.

**Nasopharyngeal airway with spontaneous respiration**

With this technique, described by Vivori (1980), a nasopharyngeal airway is inserted and kept well out of the operative field. Steward and Fearon (1981) suggested that the technique should be supplemented by topical analgesia to lighten the depth of anaesthesia. It is essential to ensure that there is a constant flow of gas down the airway as, without it, there could be a chance, in the expiratory phase, of incandescent carbon particles being blow into the catheter with a risk of fire.

The technique appears to be particularly appropriate for children with recurrent respiratory papillomatosis.

**Protected endotracheal tube**

If an endotracheal tube is in place, it is easier to control and maintain adequate ventilation in difficult patients and it is also possible to protect subglottic structures with wet swabs. The tube may be protected by a wrapping of metal foil, which must be relatively thick as it will absorb some of the laser energy if hit and must, to some extent, act as a 'heat sink'. Narrow 0.5-1 inch (1.3-2.6 cm) adhesive aluminium tape is wound up the tube from the proximal edge of the cuff to a point where the tube is well outside the operative field. The wrapping must start distally to avoid spaces appearing in the wrapping when the tube is flexed, as these might allow passage of the laser beam to strike the tube and cause ignition. The cuff cannot be wrapped and must be protected with a wet swab in the subglottis.

However, this wrapping makes the tube rough and rigid and can cause soft tissue damage to the larynx and pharynx; the tube must never be passed through the nose. It has been suggested that tubes can be protected with wet gauze, but this is generally difficult to apply and to keep in place and it must be kept very wet.

When work is to be carried out in the mouth or pharynx, the upper end of the tube is wrapped and the distal end protected with an appropriate wet throat pack.
Metal tube

Norton and de Vos (1978) developed a flexible metal tube which is totally laser proof, but it has some disadvantages. It is somewhat rough and a little traumatic for the patient and to seal the airway a cuff must be attached for each procedure which, even though it is filled with saline, must be protected. The inside diameter of these tubes is small in relation to the outside diameter when compared with similar sized plastic tubes, and many use these metal tubes with some form of jet ventilation. A malleable copper catheter has also been described by Herbert, Berlin and Eberle (1985) and by Benke et al (1985).

Other techniques

A number of other techniques are being evaluated including high frequency positive pressure ventilation by way of a metal cannula and the use of a metal cricothyrotomy cannula has also been suggested.

Conclusions

With further research, it seems likely that a soft, flexible, disposable, endotracheal tube will be developed which will not ignite in any gas mixture and will, therefore, be totally laser- and foolproof.

Clinical use of lasers in otolaryngology

In all medical and surgical laser usage, it is not sufficient to show that a laser can be used to perform a specific task; it must also be shown why a laser, rather than conventional instruments, should be used. A laser should be used only when it can be clearly demonstrated that it can perform a specific medical or surgical task better than established, conventional techniques, and the words of one of the fathers of laser surgery, Dr Leon Goldman, must never be forgotten - 'If you don't need a laser, don't use one'.

In all clinical situations, it must be demonstrated that a safe machine is being used in a totally safe manner by fully trained medical personnel in appropriate clinical conditions.

The carbon dioxide laser

Instrumentation and technique

For work in the larynx, a rigid laryngoscope with an appropriate support system will be used.

With standard microsurgical instruments, work at the somewhat awkward standard distance of 400 mm can pose some problems for the surgeon, particularly during a prolonged procedure, and some employ an arm rest to avoid fatigue and to prevent shaking of the instrument. However, many laser micromanipulators incorporate a hand rest enabling the aiming beam to be positioned within the operative field with 'shake-free' accuracy.
It has already been stressed that, where possible, lesions should not be vaporized totally after biopsy, but should be excised using the laser as a scalpel, thus enabling the whole lesion to be studied under the microscope. This is of great importance for leucoplakic lesions of the oral cavity and larynx which may show a different histological pattern in various areas, making a single biopsy unrepresentative.

To enable the surgeon to excise laryngeal lesions, special instruments are required. The lesion must be retracted medially with microlaryngeal forceps to enable the pedicle to be divided with the laser; the beam must be aimed with the micromanipulator and suction must be provided at the point of surgery to allow visual access, and to prevent the steam from damaging the normal laryngeal structures with the production of oedema. The only instrument which could be used by an assistant is the suction tube, and this is not practical as there would be a significant risk of hitting the assistant's hand with the direct beam. A number of instruments have been designed for laser laryngeal microsurgery including those described by the author (Carruth, 1985b).

Microlaryngeal suction forceps are available with a fine suction catheter built into an angled cupped forceps as is a malleable adjustable suction tube which can easily be clamped into any size or type of laryngoscope to provide adequate distal suction without encroaching significantly into the lumen of the laryngoscope. Rhys-Evans has designed a double-suction tissue holding device which enables the tissues to be held and retracted with the distal suction hole, with steam aspirated through a more proximal opening.

A number of other retractors and metal 'paddles' are available with built-in suction, both to retract tissues in the exposure of lesions and to prevent damage, by the beam or by steam, to other areas of the larynx. Despite some early evidence to the contrary, it has been shown that it is not possible to remove mucosa from the anterior ends of both vocal cords without a significant risk of webbing.

For work in the mouth, a number of standard mouth gags can be used and the lesion will be kept under tension by sutures. Further retraction and suction will be provided by an assistant who is able to observe the dissection directly and, with the use of a long metallic suction tube, there will be no significant risk of injury.

**Microlaryngeal surgery**

All the features of tissue removal with the CO₂ laser make it an ideal tool for these procedures, which can be performed precisely, with no bleeding and with minimal damage to normal laryngeal structures, resulting in minimal postoperative oedema and contracture of the surgical defect.

**Benign lesions**

**Traumatic vocal cord nodules**

It would be preferable to excise all lesions from the larynx for histological examination, but 'classical' vocal cord nodules lying at the junction of anterior and middle
thirds of the cords are almost invariably smaller than the laser 'spot size' at the microscope's working distance of 400 mm.

Suspicious or atypical nodules should be removed for histology and cupped forceps will be needed for this procedure. However, if there is no doubt about the diagnosis, the lesions may be destroyed using the CO₂ laser. A suitably protected anaesthetic tube is inserted and the cuff and subglottis are protected with wet swabs. The CO₂ laser beam is then aimed at the wet swab, turned on and moved towards the lesion, allowing the edge of the beam to shave the nodule off the vocal cord edge without damaging the underlying fibrous cord. Postoperative speech therapy will then be given, as appropriate.

**Polyps**

Localized polyps can be drawn medially with microlaryngeal suction forceps and excised by division of the pedicle. If more sessile lesions cannot be excised, then they can be readily vaporized after representative biopsies have been taken.

**Vocal cord oedema**

It has been shown by Moesgard-Nielsen, Højslet and Karlmose (1986) that if, after surgical vocal cord stripping, the patient continues to smoke there will be a high chance of recurrence. In their series of 120 cases treated by a standard microsurgical technique, only six stopped smoking with a recurrence rate of 58%, although 81% had persistent voice problems.

The vocal cord mucosa and oedematous tissue may be vaporized and, under the microscope, this can be done without causing damage to the fibrous cord. However, a number of more detailed, sophisticated techniques have been described in the literature, including the submucosal enucleation of polypoid cords performed by Yates and Dedo (1984). They made an incision in the mucosa of the superior part of the vocal cord following the arcuate line. The mucosal edge was then retracted medially and the submucosal oedematous tissue vaporized until the fibres of the thyroarytenoid muscle could be seen. The mucosa was then turned back and laid on the denuded cord. This technique is essentially similar to that described by Kolle, Iverson and Paulsen (1985) who, where possible, removed the oedematous tissue by suction and then fixed the mucosa to the surface of the vocal cord with intermittent pulses of laser energy.

In the Yates and Dedo short series of 11 patients, nine had good or excellent results and, in the Paulsen series, the results were better than in previously reported series in which routine microsurgical techniques had been used.

**Laryngeal stenosis**

It was hoped that the minimal tissue reaction adjacent to the CO₂ laser wound might make it possible endoscopically to 'core out' both congenital and acquired stenoses in which the cartilaginous support of the airway was maintained, without recurrence or with a much reduced rate of recurrence compared to conventional endoscopic techniques. A study of the literature shows that this hope has, in part, been realized and, if laser vaporization of the
stenosis is combined with the endoscopic insertion of a 'stent', a majority of patients can be 'cured', if a cure is defined as an adequate voice and airway with no tracheostomy.

**Vocal cord webs**

Vocal cord webs may be congenital or posttraumatic following external trauma or the endoscopic stripping of the mucosa from the anterior ends of both vocal cords.

Using the CO₂ laser, it is extremely easy to divide the web. However, if such a division is carried out, many webs will recur, as this procedure, in itself, denudes the anterior ends of both cords of mucosa. Nevertheless, recurrent web is almost always smaller than the original and, in many cases, one or two laser procedures will reduce the web to insignificant proportions.

Several techniques have been described to overcome the problem of recurrence. The first technique is to open only the anterior end of the web, leaving a bridge at the posterior edge of the web which is divided when the anterior opening has epithelialized. The second technique is to remove the fibrin endoscopically from the healing cords at regular intervals to prevent reformation of the adhesions, and the third technique, is to provide cover for one cord, using either an absorbable gelatin sponge or a plastic splint. The fourth and most commonly used technique is to insert and endoscopic 'keel' into the anterior commissure, but debate continues on the length of time that the keel should be left in place.

Division of the web alone will be more successful in this diaphragmatic webs, and a keel or another technique will almost always be needed to prevent recurrence after laser division of thick, post-traumatic webs.

**Subglottic stenosis in children**

This condition may be congenital or acquired from prolonged endotracheal intubation. Traditionally, it was managed by performing a tracheostomy with a fenestrated tube which incorporated a speaking valve, this allowed the child to breath out through the larynx, enabling normal laryngeal growth to occur and the child to speak. However, in a series of 25 children reported by Fearon and Cotton (1974), six (24%) died of causes related to their tracheostomy. In contrast, in a similar series of 85 children who required a tracheostomy, described by Hollinger et al (1976), 10 children died, but only five from causes related to the tracheostomy.

Evans and Todd first reported their technique of laryngotraceoplasty in 1974, and since then a number of surgical procedures have been developed to correct the stenosis, but all are associated with a significant morbidity.

In a series of 13 patients reported by Kaufman, Thompson and Kohut (1981), 11 were children under the age of three years. These patients with subglottic stenosis, predominantly from prolonged intubation, were managed by injection of steroids into the lesion before laser vaporization. Stents were used in three patients, but did not appear to be of benefit in this series. Kaufman et al suggested that circumferential removal of the subglottic mucosa should not be performed as it would encourage scar formation and would interrupt the mucocilliary
cleansing system of the tracheobronchial tree. They considered that dilatation and both antibiotics and steroids given systemically or by injection into the lesion, had a part to play in the management of these cases. At presentation, eight patients had a tracheostomy; of these, three could be decannulated and two had normal airways, but were not decannulated for various reasons. However, two other patients needed tracheostomies during the course of treatment, but a satisfactory airway was achieved in 10 of the 11 children treated.

Holinger, in a preliminary report in 1982, described the use of the laser in the management of six children with severe subglottic stenosis who would have needed a tracheostomy but could be managed without one. The children needed from one to 11 endoscopic resections (average 6.5), but a successful outcome was achieved in all cases. He concluded that an infant with subglottic stenosis who, while needing a tracheostomy, was able to breathe spontaneously and undergo a general anaesthetic, was a suitable candidate for management with the laser. However, in the paper, mention was made of a further five children with the same problem who, for logistic or timing reasons, could not be treated with the laser, and of one child who needed an urgent tracheostomy for very severe obstruction. A further requirement for this management technique is that the child should be in, or should be safely transportable to, a centre in which there is a paediatric laryngologist with experience in the use of the laser.

Post-traumatic stenosis

This may be caused by external trauma, prolonged endotracheal intubation, by an imperfectly performed tracheostomy or it may follow laryngeal surgery. Each case is unique and it is difficult, therefore, to compare series and results.

Management has always posed serious problems; many endoscopic procedures are followed by a disappointingly high rate of recurrence and open surgical procedures are associated with a significant morbidity.

A number of experimental animal studies on the role of the CO₂ laser, in the management of post-traumatic laryngeal stenosis, were performed by McGee, Nagle and Toohill (19981), Healey (1982) and Toohill, Campbell and Duncavage (1984). These studies suggested that in cases of severe stenotic lesions, partial or complete resection of the obstruction alone would both be followed by recurrence, but the use of a stent with antibiotics would improve the results.

In 1980, Lyons et al reported the use of the CO₂ laser in the management of six patients, five of whom had had previous treatment. After a relatively short period of follow-up, the tracheotomies in four could be ‘plugged’ and two patients had been decannulated. For the treatment of supraglottic and isolated glottic stenosis, Lyons et al excised the false and true cords on both sides and one arytenoid, and for other causes excised the stenosis on one side and combined this with an injection of steroids. They concluded that the technique appeared promising but further follow-up was needed.

Shugar, Som and Biller (1982) described the management of 16 patients with the laser. Seven had redundant supraglottic soft tissues following hemilaryngectomy; after this was removed, six could be decannulated and in one a tracheostomy was avoided. However only
two of the other cases could be decannulated; one had a web which was excised and a keel inserted for two weeks, and another suffered postradiotherapy scarring which recurred nine months after decannulation following laser excision of the stenosis. A further resection in the same case had been successful in maintaining the airway but for only three months.

In a comprehensive paper, Simpson et al (1982) described the management of 60 patients with a wide range of stenotic lesions of the larynx and upper trachea. In 39 of them, soft Silastic stents were used. Success was defined as an adequate voice and airway without a tracheostomy, and this was achieved in 41 patients. However, it is somewhat difficult to compare exactly results for laser surgery alone with results for laser surgery followed by stenting. Simpson et al concluded that features indicating a poor prognosis were circumferential scarring, stenosis longer than 1 cm, posterior inlet scarring with arytenoid fixation and bacterial infection of the tracheostomy.

Duncavage, Ossoff and Toohill (1985), in an elegant review paper, reported a successful outcome in 11 out of 20 patients treated with the CO\textsubscript{2} laser. Seventeen were managed by laser excision of the stenosis alone and, in the remainder, 'supplemental treatment' was given with dilatation, intralesion steroids, grafts and, in three patients, the use of a stent. They concluded that success could be anticipated with small thin scars and redundant soft tissues and they shared the views expressed by Simpson et al (1982) on poor prognostic features. They felt that the use of submucosal 'micro-trapdoor flaps', stents and steroids should improve results.

The micro-trapdoor flap was described by Dedo and Sooy (1984) for the management of stenosis in the posterior glottis, subglottis and trachea. They made an incision on the superior surface of the scar and the submucosal tissue was then removed with the laser. Incisions with a knife or microscissor were then made on either side of the trapdoor, enabling it to be laid on the raw area. Suturing was not necessary as the mucosa readily adhered to the denuded area. They achieved success in eight of nine patients.

It would appear appropriate and ethical to attempt to treat stenotic lesions of the larynx and upper trachea with the CO\textsubscript{2} laser, ideally carrying out a submucosal dissection of the stenotic area rather than a simple vaporization. A careful follow-up will show whether improvement is being achieved and, if so, surgery with the laser should continue until decannulation is possible. However, if there is no significant improvement, a stent should be employed after the stenosis has been resected and, in this way, it should be possible to manage many patients endoscopically and avoid the morbidity of an open procedure.

There is recent anecdotal evidence that the use of a super pulsed laser for the treatment of laryngeal and upper tracheal stenosis may produce results which are superior to those achieved with the standard continuous wave models. It has been suggested that the super pulsed beam may cause even less damage to adjacent, normal tissues, and this may be significant in reducing the rate of recurrence. Further work with these machines must be awaited with interest.
**Bilateral vocal cord paralysis**

In the past, this condition was managed by endoscopic arytenoidectomy, with standard microlaryngeal instruments, or by an external approach, such as Woodman's operation.

A number of techniques have been described to perform endoscopic cordectomy with the CO₂ laser with, in some, either partial or complete removal of the arytenoid in the treatment of this condition.

In all reported series, excellent results have been obtained and it would seem that the CO₂ laser is now the preferred treatment modality for this problem.

The technique was first introduced by Strong et al in 1976 (1976a), and Croft presented a series of cases (1984) in which a wide resection of the true cord was performed with good results in a short series. Shaheen (1984) described his own procedure for the removal of the posterior third of one cord, with 'enhanced effects' if the arytenoid were also removed.

Ossoff et al (1984) updated their 1983 paper and reported success in 10 of 11 patients treated by laser arytenoidectomy, in which the cartilage was exposed and vaporized with the laser. They concluded that the use of the laser offered refinements over the operation performed by conventional instruments. Prasad (1985) also reported a successful outcome in a short series of 10 patients who had been subjected to CO₂ laser vaporization of part of the cord and of the vocal process of the arytenoid.

It has been stated that the use of the CO₂ laser to vaporize the 'non-water-containing' arytenoid cartilage is time-consuming and creates very high-temperatures. Further series will show whether it is significantly better to excise rather than to vaporize this cartilage.

**Recurrent respiratory papillomatosis**

This condition, thought to be caused by the human papilloma virus, often begins between the ages of 2 and 5 years and was once known as 'juvenile laryngeal papillomatosis' in the expectation that a remission would occur at about the time of puberty. However, in many patients the disease may continue into, or even begin in, adult life and the newer name of 'recurrent respiratory papillomatosis' has been suggested.

In the past, the disease has been treated by a number of surgical techniques to remove the papillomata in order to preserve the airway and by a number of 'medical' techniques in an attempt to prevent or reduce the rate of recurrence.

Routine surgical excision of papillomata is accompanied by significant nuisance bleeding, and diathermy techniques cause significant thermal damage to normal tissues with postoperative oedema and the risk of late scarring with contraction. Treatments given to prevent a recurrence have ranged from antibiotics to antimetabolites, and from ultrasound to radiotherapy, but no technique has given consistently good results and some were either harmful or had an unacceptable morbidity. It was hoped that vaccines would be of value but only one series, reported by Professor C. Freche (personal communication), regularly gave
good results, but his vaccine required 2 grams of papilloma tissue and a high pressure press, and his results have not been repeated elsewhere.

Several papers have suggested the use of interferon (Haglund et al, 1981; Goepfert et al, 1982; McCabe and Clark, 1983; Saito et al, 1985). All series showed a significant regression of the papillomata while the administration of interferon continued, but there was a rapid recurrence of the disease in most patients when the drug was withdrawn. This drug has to be given by intramuscular injection and toxic side-effects were reported. However, treatment appeared to be well tolerated by most patients and had to be discontinued in very few. All state that the drug is of obvious value in this condition, but that they found it hard to define the optimum treatment programme. In the author's series of six patients treated with inosine pranobex (Immunovir), five showed significant improvement, and one child, aged two years, who had needed the removal of papillomata every three weeks to maintain his airway, has had no evidence of disease for almost two years while on treatment. The drug has low toxicity and can be given by mouth.

Further studies will determine whether these drugs may be used to reduce the recurrence rate in patients with this condition and, if so, how this may be done; however, until further evidence is available, children will be managed by surgical removal of the papillomata. As children often require dozens of operations, the CO₂ laser should be used as it reduces the morbidity of each procedure.

With the CO₂ laser, complete removal of all visible disease can be performed without nuisance bleeding and with minimal damage to underlying, normal laryngeal tissues; there should, therefore, be no postoperative oedema and less contracture of the mucosal defects.

McCabe had pointed out that the laser can, if used inexpertly or excessively, cause significant damage with webbing and scarring, particularly to the posterior and anterior commissures, and he has suggested that a debulking rather than a total extirpation of disease should be carried out.

With the use of the laser, it should be possible to avoid a tracheostomy which, in itself, has a significant morbidity in small children, and which has been followed in some cases by the development of papillomata in the trachea and in the tracheostome. In 109 patients treated by laser and by the application of podophyllum, Dedo and Jackler (1982) reduced the need for a tracheostomy from an average figure reported in the literature of 25% to 1.8% and the mortality from 7% to 0.

Two methods of managing the patients have been described, and some maintain that by debulking the papillomata at regular intervals, a prolonged remission can be obtained. Strong (personal communication) maintains, however, that in his large series he has not been able to achieve this and advocates an 'on-demand' technique. This technique requires intelligent, alert parents and an every-ready surgical team, but, in practice, 'out of hours' procedures are extremely rare and the child has the least number of operative procedures.

The CO₂ laser is, undoubtedly, the instrument of choice for the surgical removal of papillomata, but it must be used with care to take advantage of its minimal damage to normal tissues and to avoid excessively deep damage with webbing and scarring. It is to be hoped
that one of the new 'antiviral' agents will reduce the need for any form of surgical intervention in this distressing condition.

**Intubation granuloma**

Vocal cord granulomata may follow intubation, and surgical removal is often followed by recurrence. The CO₂ laser is an ideal tool for their removal as the lesion can be excised to the point of exposing the arytenoid cartilage. However, as shown by Benjamin and Croxson (1985), its use does not seem to produce improved recurrence rates.

**Malignant granuloma**

The larynx may be involved in one of these unpleasant conditions with complete obstruction and the need for a tracheostomy. Obstructing tissue may be removed with the laser to provide both an airway and a voice, but the ease of surgery and the rate of recurrence will depend on the activity of the disease. If the disease is active and not under control, surgery will be accompanied by significant bleeding and recurrence will be rapid; on the other hand, if the disease is inactive, surgery will be bloodless and recurrence will be slow or may not take place.

**Leucoplakia**

Histology of a leucoplakic patch may vary from a simple hyperkeratosis to an invasive carcinoma and different patterns may be seen in different parts of an individual lesion. It is essential, therefore, to excise these lesions with the laser, thus enabling the whole specimen to be examined histologically, as a single biopsy taken before the lesion is vaporized may be unrepresentative.

Further management will depend on the histology, but almost all patients will be advised, where relevant, to cut down or, ideally, to stop smoking. If the lesion is found to be a carcinoma *in situ*, which has been excised with adequate margins, then the patient should be regularly and carefully followed up. The management of early invasive lesions is discussed in the next section, but, at present, if an invasive carcinoma is found, the patient should be considered for a course of radiotherapy.

**Malignant disease of the larynx**

It is difficult to write authoritatively about the management of carcinoma of the larynx as treatment varies between clinics and countries. However, in a majority of centres in the UK, T1N0 carcinoma of the vocal cord would be treated by radiotherapy, with the expectation of a 'cure rate' of 80-90% and without any significant incidence of complications or of radionecrosis. The course of radiotherapy has a significant morbidity with, where relevant, the risk of radiation-induced malignant change after several decades. However, after a well given, successful course of radiation, the voice should essentially return to normal.

In 1975, Strong introduced the idea of treating early vocal cord carcinoma by laser excision and the experience of the Boston group was updated by Blakeslee et al in 1984.
In Strong's first series of 11 patients, three had failed radiotherapy, all had free margins at excision, and no patient had a recurrence. In one patient, a tumour was removed from the other cord one year later. Strong commented that if margins were found to be involved by tumour, other treatment by radiotherapy or surgery would be necessary, and that the voice was 'as good as the remainder of the larynx would allow.

In 1984, in the updated paper by Blakeslee et al and in the paper by Ossoff, Sisson and Shapshay (1985), a total of 113 non-irradiated patients were treated in essentially the same way: the lesion was excised with appropriate margins and biopsies taken from the edge of the defect, which were then studied by frozen section. The removal of tumour was continued until either the margins of the defect were shown to be tumour free or the thyroid cartilage was reached when it was considered that further resection was inappropriate and radiotherapy should be given.

Blakeslee et al defined the criteria for a successful treatment by excision biopsy as follows. The lesion must be completely exposed at laryngoscopy, it must not extend to the vocal process of the arytenoid or anterior commissure, and it should be confined to the mucous membrane. No residual tumour should be evident at high magnification and frozen section from the defect should be tumour free, as must be the margins of the specimen when examined by multiple routine sections. If these criteria were met, then excision was considered to be curative; but if the excision extended to the thyroid cartilage, or if the specimen margins showed involvement by tumour, then further therapy with radiotherapy or surgery was considered to be essential. The results from the two series are shown in Table 23.3.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No</th>
<th>Free at 3 years</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excision biopsy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blakeslee</td>
<td>50</td>
<td>46</td>
<td>92</td>
</tr>
<tr>
<td>Ossoff</td>
<td>17</td>
<td>17</td>
<td>100</td>
</tr>
<tr>
<td>Excision + radiotherapy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blakeslee</td>
<td>34</td>
<td>29</td>
<td>85</td>
</tr>
<tr>
<td>Ossoff</td>
<td>6</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Excision + surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blakeslee</td>
<td>4</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>Ossoff</td>
<td>2</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>113</td>
<td>103</td>
<td>91</td>
</tr>
</tbody>
</table>

In Blakeslee's paper, reference is made to 15 patients who had failed radiotherapy, only six of whom were disease free after a period of three years. These findings were confirmed in the series of Annayas et al (1984), who obtained good results in non-irradiated patients and poor results when laser salvage surgery was attempted for radiation failures.

With regard to the effect on the voice of laser excision, Blakeslee et al reported the voice to be serviceable following the removal of small lesions, and breathy and rough when
larger tumours had been resected. Ossoff et al (1985) found the voice after laser excision to be good to excellent; and in a study of patients after unilateral laser cordectomy, Vecerina and Krajina (1983) stated that the vocal function was good.

The advantages of excision biopsy were summarized by Blakeslee et al as: the ability to establish the diagnosis and stage, and to provide an adequate treatment for 'mini' and 'micro'-tumours and squamous carcinoma if the margins were found to be clear. The technique is very appropriate for radiotherapy-resistant tumours and for exploring recurrent lesions after unsuccessful radiotherapy. This treatment technique offers several advantages. If the excision is found to be complete, the patient will have been spared the short- and long-term problems of a course of radiation and will have had treatment carried out under one anaesthetic. The treatment can be repeated as often as necessary, but the voice will not be as good as after a well given, successful course of radiotherapy. In the long term, it appears that 'cure rates' will be as good as those obtained by radiation.

Some cases have been reported by Motta (1985) in which more extensive tumours were resected endoscopically until the sphincter function of the larynx has been threatened in some cases. The period of follow-up is too short to draw significant conclusions, but early results are encouraging.

In the management of advanced tumours, the laser offers three potential advantages, but trials have not yet shown whether these will prove to be significant. The tumour can be debulked at the time of biopsy, enabling more accurate staging and reporting of results. It also presents the radiotherapist with a reduced tumour bulk to treat, which may possibly improve results. In the past, if a patient has presented with laryngeal obstruction from a tumour, only two treatment techniques have been available: urgent laryngectomy after frozen section confirmation of the diagnosis, or, alternatively, a tracheostomy, but with this there is a risk of tumour seeding around the stoma. Using the CO₂ laser, it is possible to vaporize sufficient tumour to restore the airway allowing further treatment to be planned at leisure.

**Tongue and oral cavity**

From the early work of Strong et al (1979b, c), it has been evident that the CO₂ laser can be used to remove lesions from the tongue and oral cavity with advantages over conventional instruments. Much of the work has been carried out under the operating microscope which provides a well-illuminated, magnified view of the operative field. However, the system is a little 'rigid' and it is important to check regularly the lines of resection. The hand piece can also be used for work in the anterior part of the mouth but many hand pieces are rather bulky for intraoral work. As in all other areas, lesions should be excised where possible rather than vaporized.

In the removal of lesions from the mucosa of the oral cavity, underlying soft tissues on the floor of the mouth, fauces and cheek may be removed en bloc with the lesion, and as the healing of laser wounds is associated with a low number of myofibroblasts and little collagen in the defect, it appears that there is significantly less contracture of laser cut wounds, and large defects may be left open and ungrafted.
If the lesion involves bone, it may be exposed during the dissection if radiotherapy has not been given, and bone may be removed slowly and at a high temperature. However, if radiotherapy has been given there is a significant risk of osteoradionecrosis if bone is exposed or damaged.

Benign, premalignant and malignant lesions may be removed without significant bleeding and with low postoperative morbidity. Rhys-Evans et al (1984) reported the management of 51 lesions, 44 of which were leucoplakia in 34 patients, and their series confirms the advantages of the CO₂ laser in this field.

Lesions of the tongue can also be removed transorally and the limitations of transoral surgery apply, namely that the lines of resection must be visible at the outset or become visible during the course of the dissection. The lines of resection are first marked out and then cut using the laser at about 25 watts, which gives both good cutting and coagulation of vessels. Bleeding should be minimal and haemostasis can be achieved with a few points of diathermy and ligatures on the lingual artery.

Standard 'cancer margins' must be observed for malignant lesions as the CO₂ laser does not, in itself, cure cancer and the ability of the surgeon to control malignant disease will depend on the removal of a specimen with histologically free margins. However, it has been suggested that the limited tissue manipulation and sealing of lymphatics may lead to improved 'cure rates', but confirmation of this from controlled trials is needed.

It has been shown that muscle in the mouth epithelializes rapidly and defects may be left ungrafted and unsutured. This enables residual tongue muscle to hypertrophy and, untethered by sutures, the tongue regains maximal residual function.

Healing appears to be relatively rapid, although it has been shown that laser defects heal rather more slowly than scalpel cut wounds. There is minimal postoperative oedema and postoperative pain is also slight. Patients can resume their normal diet in the evening on the day of surgery and nasogastric feeding is rarely, if ever, needed.

In the author's series (Carruth, 1985a) of 100 major tongue procedures performed by laser, 45% needed no analgesics, 32% mild oral analgesics and 85% could be discharged on the first or second postoperative day.

The management of carcinoma of the tongue has not changed significantly, except that slightly larger lesions may be removed by laser for cure by excision biopsy and, occasionally, larger lesions will be excised in the elderly, infirm patient in whom a laser excision has a lower morbidity than a course of radiation. Primary excision may also be performed in young patients where radiotherapy is relatively contraindicated. In all other cases, the laser will be used to resect residual or recurrent tumour after radiation failure.

In the author's series, in which the majority of patients have been followed up for two to three years, 100% of T1N0 tumours treated by excision biopsy are disease free, and for larger T2 and T3 tumours a 'cure rate' of more than 60% has been achieved, which compares favourably with historical controls.
**Pharyngeal pouch**

The pharyngeal pouch or hypopharyngeal diverticulum may be treated either by external excision, followed by cricopharyngeus myotomy, or by an endoscopic technique based on the procedure described by Dohlman (1949).

In a recent update of their earlier paper by van Overbeek, Hoeksema and Edens (1984), the endoscopic treatment of 377 patients is described, in which 308 were treated by electrocoagulation and excision and 69 were treated by laser excision of the 'party wall' between pouch and oesophagus. With the laser technique under microscopic control and with the use of a specially developed endoscope, the bridge is excised with accuracy and with minimal bleeding.

It might be thought that the lack of tissue reaction adjacent to the laser wound would not encourage adhesions between pouch and oesophagus and might, therefore, lead to leakage and the development of mediastinitis. Although three cases of mediastinitis were reported in 69 laser cases, compared to five in 308 cases treated by the standard technique, van Overbeek considered that this was acceptable and that the final results were better without any of the circumferential scarring which was found on occasions with the electrocoagulation and excision technique.

**Endobronchial surgery**

Both the CO$_2$ and Nd-YAG lasers are in use for the removal of lesions from the tracheobronchial tree, and in some of the early work described by Hetzel et al (1983), the argon laser was used although, for fibreoptic work, this has now been almost totally replaced by the Nd-YAG laser.

The use of the CO$_2$ laser in this field was first described by Strong et al (1974), and since that time bronchoscopic adaptors have been developed for use with almost all CO$_2$ surgical lasers. There are considerable design differences in the adaptors, as described previously, and in particular the aiming facilities vary from a fixed beam through a static readjustment with thumb-screws, to continuous aiming with a micromanipulator. Almost all bronchoscopes provide adequate distal suction.

Nd-YAG laser energy can be transmitted by a flexible fibre and it can, therefore, be used with a fibreoptic bronchoscope. In theory, it could be used to remove more peripherally placed lesions which are inaccessible to the rigid instrument that has to be used with the CO$_2$ laser. However, in practice, palliation can be achieved regularly only by the removal of tumour from the trachea or main bronchi, and this may be done through either bronchoscope. Much of the work with the Nd-YAG laser is done using a rigid bronchoscope to enable fragments of necrotic tumour to be removed with forceps and to provide better suction.

A relatively small number of cases using the CO$_2$ laser have been reported in the literature, and McElvein and Zorn (1983) described the management of 43 patients with malignant disease of the trachea and bronchi, treated for palliation which was achieved immediately in 39.
Several series of cases of carcinoma of the bronchus treated for palliation with the Nd-YAG laser have been reported by Toty et al (1981), Dumon et al (1982), Hetzel et al (1983) and McDougal and Cortese (1983). The series all include between 22 and 50 patients, and in at least 50% of these considerable palliation could be achieved, but not in cases where there was total obstruction of a bronchus with collapse of the lung. In these, although re-expansion could, on occasions, be achieved, the risk of pneumonia appeared to be extremely high.

Benign tumours may be removed and the recurrence rate will depend on the histology and natural history in each case. Stenoses may also be ‘cored out’ and the chance of cure depends on the integrity of the cartilaginous support of the airway, the thickness of the stenosis, the amount of the circumference of the airway which it occupies, and carinal involvement, as reported by Ossoff et al (1985) who successfully treated eight of 14 patients.

The CO\textsubscript{2} laser produces better and more precise tissue destruction and the Nd-YAG laser better haemostasis, although severe problems with bleeding have not been regularly reported with the use of the CO\textsubscript{2} laser.

**The oesophagus**

A number of series have been reported by Fleischer and Kessler (1983), Mellow, Pinkus and Frank (1983), Krasner and Beard (1984) and Swain et al (1984) to show that obstructing tumours of the oesophagus may be treated for palliation by removal of the tumour by means of the Nd-YAG laser. Many treatment sessions may be needed initially to relieve the dysphagia, but prolonged palliation may be achieved by repeating the procedure as often as is necessary. As mentioned previously, this laser produces three layers of thermal tissue damage: the first, a vaporized layer; the second, a coagulated layer, which will subsequently slough; and a third layer in which cell death occurs and which is replaced by fibrous tissue but without loss of physical integrity. This means that the risk of perforation, even if the tumour involves the whole thickness of the oesophageal wall, is slight.

It is not possible to palliate untreatable tumours of the postcricoid region by the passage of an indwelling tube and, in such cases, where cure is not possible, the laser may be of great value in providing palliation.

**Otology**

The role of lasers in otology is currently being evaluated, and although the argon laser offers some potential advantages, these await confirmation by controlled trials. The value of lasers in this field is not widely accepted.

Some work has been carried out with the CO\textsubscript{2} laser to perform myringotomies and to vaporize the stapes footplate in experimental animals. However, many believe that this laser is not suitable for otological work.

The argon laser has been used to perform atraumatic ‘no touch’ stapedectomies in the hope that the lack of manipulation might lead to less inner ear damage. Critics suggest that when the argon laser beam has penetrated the footplate of the stapes, it could pass through the perilymph and be absorbed by a vascular structure on the saccule. However, as yet,
neither the advantages nor the potential hazard have been shown clearly in the reported clinical work.

The argon laser is coupled to the operating microscope which incorporates a safety shutter which closes when the laser is fired. An attenuated beam is used for aiming, guided by a micromanipulator, and spot sizes of 50-100 µm are used.

Perkins (1980) reported a series of argon laser stapedectomies and suggested that the atraumatic technique might result in better preservation of high tone hearing and less vestibular disturbance. In his technique, the laser was used for haemostasis during the tympanotomy and for dividing the stapedius and the posterior crus of the stapes, and partially dividing the anterior crus. A rosette of perforations was then made in the footplate, enabling a small piece to be removed to accept a prosthesis.

McGee (1983) compared 100 small fenestra stapedectomies with 100 performed with the argon laser and found that the postoperative course in the laser cases was smoother, but he could not find any significant difference in audiometric results.

The argon laser has also been used for the removal of granulation tissue, for the removal of dense fibrous tissue from the mastoid in revision procedures, and to spot weld a graft of fascia on to the drum remnant in myringoplasty.

Otoneurosurgery

Glasscock, Jackson and Whitaker (1981) reported the use of the argon laser in the removal of 25 acoustic neuromata in a series of 48 tumours. They exposed the lesion and then, by applying a power of 3-3.5 watts, used the laser first to 'gut' the tumour and then to remove the capsule. At these power levels, tumour removal was slow, but they found the laser to be of value in the management of small inaccessible lesions which were difficult to remove with forceps.

Gardner, Robertson and Clark (1983) used the CO₂ laser in 15 cerebellopontine angle tumours in a series of 105, and found it to be of value for the rapid atraumatic removal of tumour tissue. However, Powers et al (1984) initially used the CO₂ laser and then changed to an argon laser, which they found to be more suitable for the removal of acoustic neuromata.

Nasal surgery

The CO₂ laser can be used to perform precise 'dermabrasion' for the treatment of rhinophyma, whereas the argon laser is of great value in the management of cutaneous vascular abnormalities of the skin of the nose. In addition, the argon laser can be used to coagulate the telangiectatic spots of Osler's disease, but, as with all other techniques, there is a tendency for the lesions to recur elsewhere.

With regard to the nasal cavity, Simpson et al (1982) reported on the use of the CO₂ laser for the removal of a wide range of lesions including papillomata, nasal polyps, adhesions and granulomata. The series also included one malignant case treated for palliation through
a lateral rhinotomy. The use of both the CO$_2$ and argon lasers for the performance of turbinate reduction has also been reported.

If adequate access is possible then the CO$_2$ laser can be used to remove lesions from the nose, but its advantages in this field are limited.

However, Healey et al (1978) reported that the CO$_2$ laser can be used transnasally to resect the obstructing partition in choanal atresia; and Williams (1983) has suggested that in the performance of a vidian neurectomy for intractable rhinorrhea, the CO$_2$ laser may be used to destroy the contents of the vidian canal after a standard bony approach, and has stated that the operation could be performed as a day case procedure with improved patient comfort.

The CO$_2$ laser can undoubtedly be used to ablate untreatable fungating tumours for palliation, as reported by Rontal and Rontal (1983).

Photodynamic therapy

This technique represents a new and exciting approach to the management of many forms of localized, malignant disease.

Research is concentrated, at present, on the identification of an ideal tumour sensitizer which should be selectively taken up or retained by malignant tissues, giving a high tumour/normal tissue ratio. Such a sensitizer should be non-toxic in clinically useful doses; it should have a high level of photochemical activity; and it should be activated by a wavelength of light which provides adequate tissue penetration.

To date, the only tumour sensitizer which has been developed to a point at which clinical trials are appropriate, is the haematoporphyrin derivative which is activated by red light at a wavelength of 630 nm produced by either a tunable dye or gold vapour laser.

The tumour sensitizer

Although many substances have been investigated, most of the work has been on the porphyrins and on haematoporphyrin derivative in particular, which was first used by Lipson, Baldes and Olsen (1964) for the identification of malignant tumours. Recently, Dougherty, Potter and Weishaupt (1983) have reported the identification of the active component from the mixture of porphyrins as dihaematoporphyrin ether, but others consider that further work on the identification of the active component is appropriate.

Much of the research into the development of a new sensitizer is concentrated on the phthalocyanines and these appear very promising. Uroporphyrin I was also hailed as the ideal sensitizer by El Far and Pimstone (1983), but their results have not yet been confirmed.

It seems certain that other better sensitizers than haematoporphyrin derivative will be developed, but it will be several years before another is ready for clinical trials.
**Light sources**

The laser is somewhat peripheral to the technique of photodynamic therapy and many early studies were carried out with a wide range of both filtered and unfiltered light sources. However, it became apparent that lasers provided the ideal source of pure light, and, of sufficient power, which could be transmitted via a flexible fibre.

The first laser to be used was the tunable dye laser, described previously, which has the advantage that the wavelength can be changed to activate other sensitizers which may be developed in the future, but has the disadvantage that the power output is limited to, at best, 25% of the power of the driving argon laser. The gold vapour laser produces pulsed, red light at a fixed wavelength of 628 nm and high power levels are available. It has been suggested that the pulsed light might penetrate more deeply into tissues than the continuous wave light produced by the dye laser, but subsequent work has not confirmed these findings. As this laser has a fixed wavelength, it cannot be tuned to activate other sensitizers. However, it is relatively easy to change the metal in the tube to copper and the copper vapour laser could be used to drive a tunable dye laser.

Haematoporphyrin derivative is activated best by ultraviolet light but this does not adequately penetrate tissues. Therefore, the 'compromise' wavelength of 630 nm is used which activates haematoporphyrin derivative and, with surface irradiation, penetrates most tissues to a depth of up to 1 cm.

A number of delivery fibres are now available with a straight cut or microlens tip for surface irradiation, a diffusing cylinder to treat circumferential lesions or for implantation into tumours, and a diffusing bulb to irradiate the whole of the inner wall of a hollow viscus.

**Mode of action**

Much of the credit for the development of this technique must be given to Dr Tom Dougherty and his colleagues at Roswell Park Memorial Institute, Buffalo, USA. It has been shown that after an intravenous injection, haematoporphyrin derivative is widely distributed in body tissues and is then selectively retained by malignant tumours. The mechanism for this retention remains uncertain, but it is thought to be related to the abnormal tumour circulation.

It has been shown by Weishaupt, Gomer and Dougherty (1976) that when haematoporphyrin derivative is exposed to red light, singlet oxygen is produced by energy transfer from the excited porphyrin molecule. This highly reactive, transient state of the oxygen molecule is cytotoxic by oxidation of sensitive bonds.

There appears to be photodynamic activity within the vascular stroma, as shown by Henderson and Dougherty (1983), and also at cellular level, as shown by Moan et al (1982).

**Diagnosis**

When a tumour which contains haematoporphyrin derivative is exposed to ultraviolet light, it will fluoresce. Some exciting work has been reported on the diagnosis of early lung tumours by a fluorescent bronchoscopic technique, which uses a krypton laser as the source.
of ultraviolet light, and an image intensifier used with a fibreoptic bronchoscope to identify the areas of fluorescence. Some of these tumours have been treated when surgery was refused or deemed inappropriate and there have been some exciting early results. The technique is also used to diagnose malignant areas in multifocal disease of the bladder.

**Treatment technique**

In all the clinical studies, essentially the same technique has been used. On day one, the patient is given haematoporphyrin derivative or dihaematoporphyrin ether by intravenous injection, in a dose of 3 mg/kg body weight for haematoporphyrin derivative (dihaematoporphyrin ether, 1.5-2 mg/kg). No significant side-effects have been reported from the injection, but all patients develop severe skin photosensitization which lasts for three to four weeks.

After 72 hours, the tumour is photoirradiated using a laser and delivery fibre. Subcutaneous disease is treated to a dose of 25 joules/cm² which will destroy the tumour but preserve the overlying skin; whereas ulcerated lesions are treated to a total dose of 100-200 joules/cm² which will cause maximal tumour necrosis to a depth of 1 cm with surface irradiation.

The treatment can be repeated as often as necessary, both to remove further layers of thick tumour or to treat other new lesions.

The time taken will depend on the power output of the laser and the area to be treated, but for large tumours with a low power laser the time may be measured in hours.

**Clinical trials**

It has been estimated that more than 5000 patients have now been treated by this technique, and much of the work has been carried out on primary and secondary skin tumours. Dougherty has estimated that local control can be achieved in 60-80% of patients with multinodular metastatic disease of the chest wall from breast carcinoma. Basal cell carcinoma which has failed other modalities, and in particular multiple lesions, can readily be treated, with excellent results. Several head and neck series have now been reported. These tumours appear ideal for this form of therapy as they are relatively small, remain localized, are accessible, and surgery is always mutilating, either to the cosmetic appearance of the patient or to his ability to talk and swallow.

The largest number of patients has been treated by Wile et al (1982, 1984) who treated 114 tumour sites in 39 patients. In 28 sites, complete tumour response was obtained and 'several' remained tumour free for more than one year. A partial response was obtained in 42 patients but the others were either not measurable or showed no response. They found that patients with persistent or recurrent disease in the primary site benefited substantially from treatment and that tumours of the tongue appeared to be particularly sensitive to this form of therapy.

Other series, reported by Carruth and McKenzie (1985), Keller, Doiron and Fisher (1985) and Schuller, McCaughan and Rock (1985), have shown that in the advanced tumours
which are ethically permitted to be treated in pilot studies, it is possible to produce tumour
necrosis, with the result that palliation can be achieved in many cases and local control in
some.

Basal cell carcinomata have appeared to respond well, and this treatment is particularly
appropriate for multiple lesions which are extremely difficult to treat by other modalities. When, on occasions, small recurrent tumours have been treated where no other modality is
available, for example in the nasopharynx, local control has been achieved, but the period of
follow-up remains short.

Head and neck tumours appear to be most suitable for treatment by photodynamic
therapy and it appears likely that this modality will soon be introduced into controlled trials
of combined therapy.