Lasers in Otolaryngology

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Preface

Albert Einstein described the basic physics of stimulated emission of radiation in 1917 but it was not until 1960 that the first laser was produced by T. H. Maiman using a synthetic ruby as the lasing medium.

Since then, a vast number of lasers have been developed producing both pulsed and continuous wave coherent light in all parts of the visible and invisible spectrum. The range of uses of these lasers is now so great and so diverse that it has been suggested that the age in which we live will eventually become known as the laser age rather than either the atomic or space age.

As each laser was developed its effects on body tissues were investigated. In the case of the carbon dioxide laser, which is now the most commonly used laser in otolaryngology, this involved moving the experimental animals on moveable tables beneath the fixed, laboratory bench laser.

However, from the mid 1960s using rather more sophisticated and clinically orientated machines, a considerable amount of research took place on the effects of this laser on a wide range of tissues and its potential value as a 'light scalpel' became apparent.

Much of the credit for the introduction of the carbon dioxide laser into otolaryngology must go to the 'Boston group'. Here a unique and imaginative team of physicists, scientists, instrument makers and surgeons collaborated to define the effects of this laser on laryngeal tissues, first in animals and subsequently in man. They then developed appropriate delivery systems and endoscopes to enable clinical work to begin.

This group identified at an early stage the need for all these workers to collaborate to ensure that laser tissue interactions were fully understood and then translated into clinical practice using appropriate machines and delivery systems. This model has become the standard for all other laser units developed throughout the world.

In 1971, Dr. Stuart Strong and Dr. Geza Jako began the first clinical studies in man and following the development of other laser systems, within America and throughout the world, the use of the carbon dioxide laser escalated in this field and its value has now become fully established.

At present the infrared coherent laser beam cannot be transmitted via a flexible fibre and a hollow articulated arm with mirrors at the angles must still be used. However, it seems certain that a fine diameter efficient fibre will soon be available for use with this laser.

Another interesting and potentially important development with the continuous wave carbon dioxide laser is the introduction of super pulsing of the beam with high peak power and short exposure. Theoretically, and in practice, this results in instantaneous vaporization of tissue with less charring and with less thermal damage to adjacent tissues. There is a small but relatively insignificant loss of haemostasis but time will show if the reduction of tissue reaction will result in a further reduction in the contracture of laser wounds, and if this proves to be the case then it should be possible to achieve better results than at present in the laser treatment of laryngeal stenosis. Future developments will depend on the physicists and scientists defining exactly the tissue response to lasers of different wavelengths with various powers and exposures and surgeons will then marry this information to their clinical needs and laser manufacturers will produce machines capable of delivering the appropriate treatment parameters. It has been said that the laser surgeon must become a 'biomedical engineer' and although this remains true, few if any surgeons can acquire the laboratory expertise to perform both the experimental and clinical work and collaborative groups are essential.

However, in all medical laser applications the words of Dr. Leon Goldman, one of the fathers of laser surgery, must never be forgotten, 'If you don't need the laser, don't use it'. A laser should only be used when it can perform a particular task better than existing conventional techniques. The carbon dioxide laser has proved its worth in otolaryngology, especially in microlaryngeal surgery particularly on children. The evidence for the value of the argon laser in otology is increasing but at present the case for its use remains 'unproven'. The Neodymium YAG laser has established its role in endobronchial surgery and it will be interesting to compare this laser with the carbon dioxide laser in this field, especially when a delivery fibre is available for the infrared carbon dioxide laser beam.

Photodynamic therapy represents a new and exciting modality for the treatment of many forms of malignant disease. A photosensitive tumour localising drug is given and then activated within the tumour by laser light of the appropriate wavelength. Using haematoporphyrin derivative and red laser light produced by either a tunable dye or gold vapour laser, some exciting preliminary results are being obtained. The head and neck tumour is particularly suitable for this form of treatment as it is relatively small, accessible, metastasises late and surgery is always mutilating to either the appearance of patients or to their ability to talk and swallow. Within this field control of some advanced lesions has been achieved, and a 'cure' with a follow-up of more than two years in a small number of patients with early lesions, who were unsuitable for other treatment modalities.

It is not difficult to learn to use a laser attached to the operating microscope but it is difficult to use it well. Safety is of the utmost importance and the establishment of required training standards for doctors before using medical lasers, remains a thorny and unsolved problem on both sides of the Atlantic.

Before beginning work with a surgical laser the surgeon must ensure that the machine conforms to all the appropriate national and international standards and that all national and local codes of safe practice are being followed to the letter. The surgeon should also have spent time studying the techniques 'at the feet of an established master' and ideally should have a chance to develop them on the cadaver or experimental animal.

Before beginning clinical work, a team must be formed with one or more anaesthetists who are fully conversant with the hazards of laser anaesthesia and how to overcome them.

Few additional instruments beyond those normally provided for microlaryngeal surgery will be needed, but the surgeon must be fully conversant with the absorptive and reflective properties of the materials from which the instruments are made. He must also ensure that there is no excessive absorption with heating of the instrument, and that surfaces from which the beam could be reflected back into the operating theatre are roughened to ensure that any reflection is diffuse.

It is vitally important to suck away the vapour produced by tissue destruction at the point of surgery, both for visual access and to ensure that the steam does not damage normal tissues. A wide range of suction devices are available which can be attached to the laryngoscope or are combined with mirrors, retractors or microlaryngeal forceps to ensure that adequate suction can be provided in all operative situations.

In the past it has been stated that a lesion has been removed using the carbon dioxide laser but in future this information must be combined with details of the exact excision parameters, including power, power density, fluence etc. In this way optimal treatment parameters for each clinical condition will eventually be defined.

The authors in this volume combine the best from both sides of the Atlantic. This book represents a state of the art account of the current use of lasers in all fields within otolaryngology and, in addition to the full clinical cover, there are sections of physics and safety (written for the clinician) and the extremely important topic of laser safe anaesthesia. This volume should enable laser surgeons of all degrees of expertise to identify those conditions which should be treated by laser and, given the current state of knowledge, how to treat them.

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1 Contents

1 *Lasers – Physics, tissue interaction and safety*

ALAN L. McKENZIE

1.1 Laser physics

1.1.1 INTRODUCTION

If lasers are ever deployed as space weapons, it will be interesting to reflect that both 'Star Wars' lasers and surgical lasers owe their efficacy not to intrinsic high power but to the phenomenon of beam parallelism. Without the ability to deliver a tight beam of radiation across hundreds of miles of space, the high-power laser weapon would be useless, while in the operating theatre, the parallelism of the surgical laser beam allows it to be focused to cut effortlessly through tissue using less power than a domestic light bulb.

It would be wrong to say altogether that the generation of high powers is not a requirement in laser surgery, because the ability of lasers to deliver all of their power at a given wavelength can be useful in instances where different tissue absorption properties can be exploited. Broadly speaking, however, in surgery, the key characteristic of laser radiation is its parallelism, enabling the beam either to be focused directly onto tissue or into a narrow optical fibre for endoscopic applications.

1.1.2 STIMULATED EMISSION

How does this beam parallelism arise? The answer is to be found in the phenomenon called stimulated emission, which Einstein predicted theoretically in 1917. Until that time, only two interaction processes were known to occur between matter and light – absorption and spontaneous emission. When a photon is absorbed by an atom, it is completely destroyed, leaving the atom in an excited state (Figure 1.1(a)). Conversely, if an atom has been given energy (by collision with an electron, for example) then it is likely that the excited atom will emit this energy in the form of a photon in a random direction (Figure 1.1(b)). This is known as spontaneous emission. Einstein envisaged such an excited atom being hit by a photon of the same energy as that which normally would be emitted spontaneously. In this case the atom is stimulated to emit its energy not in a random direction, but in the very same direction as the incident photon (Figure 1.1(c)). The picture then, in stimulated emission, is of a photon interacting with an excited atom and producing as a result a copy of itself, identical in every respect. Since an atom can be excited to certain discrete energy levels only, there is a limited number of wavelengths which the stimulated photon can possess, and, by the same token, only those wavelengths can be candidates for stimulated emission.

In order to see how stimulated emission accounts for beam parallelism, imagine that a large number of excited atoms have been collected into a long, narrow cylinder with highly reflecting mirrors stuck on each of the two flat ends (Figure 1.2). When these excited atoms lose their photons by spontaneous emission, the light is generally lost out of the curved sides of the tube. Occasionally, however, a photon will be

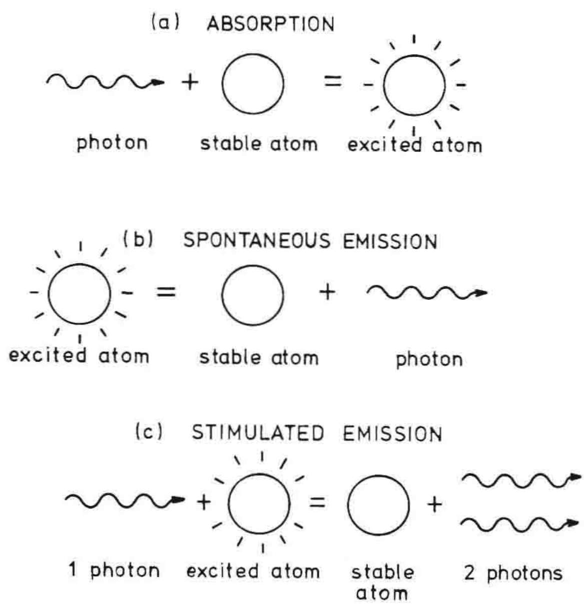

Figure 1.1 Of the three interactions, absorption, spontaneous emission and stimulated emission, the latter is the process which is responsible for laser action.

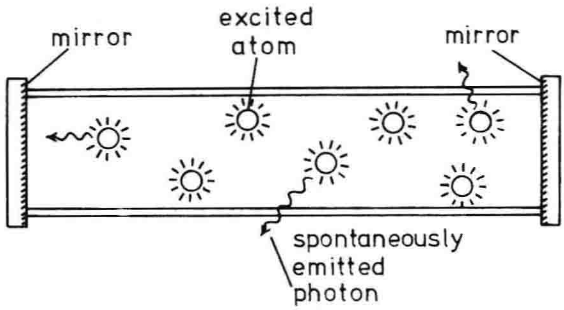

Figure 1.2 The lasing process begins when a spontaneously emitted photon is reflected along the axis of the tube, so that other photons are produced by stimulated emission.

emitted parallel to the tube axis and so it will be reflected back into the volume. Such a photon has a high chance of encountering another excited atom and stimulating it to emit another photon in the same axial direction. These two photons go on to produce another two stimulated photons, and so an avalanche builds up, with virtually all the stimulated photons travelling parallel to each other in the axial direction.

Because the original axial photon has been amplified in numbers by stimulated emission, the process gives rise to the phrase 'Light Amplification by Stimulated Emission of Radiation', from which the word 'laser' is derived as an acronym.

1.1.3 A PARALLEL BEAM OF LIGHT?

It is easy to extract a useful output beam from such a device: one of the end mirrors is simply made partially transmitting, so that some light leaks outside. This light will be emitted in a beam of about the same diameter as the volume, and all of the photons will be travelling in the same direction, which accounts for the characteristic parallelism of the laser beam.

In the nature of things, it is not possible to produce a beam which is perfectly parallel. For one thing, such a beam physically could not exist, because there would always be a tendency for it to diffract at the edges. For another, it is easier to confine the radiation within the laser tube using concave mirrors rather than flat ones, and this is frequently done in practice. But this effectively imposes a curvature upon the beam which is manifest by a divergence of the beam as it leaves the laser (Figure 1.3). A red He-Ne laser beam, used for aiming invisible surgical laser beams, could be directed straight at the moon, but the

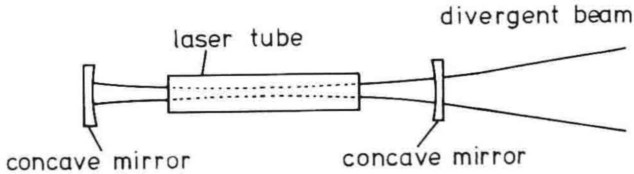

Figure 1.3 Laser beams are not absolutely parallel in practice, but diverge slightly. The degree of divergence is exaggerated here for clarity.

beam would cover a circle on the moon's surface several hundred miles across. This imperfection means that, in practice, a converging lens placed in the laser beam will not focus the radiation into an infinitely small point, but will, nevertheless, be capable of focusing a visible argon laser beam into a spot diameter of 100 μm, or a CO_2 laser beam into a circle only a millimetre or so across, depending upon the lens characteristics.

1.1.4 POPULATION INVERSION

I was once asked at a meeting of head and neck oncologists what would happen if a surgical laser beam struck a metallic instrument and was reflected directly back into the laser – would this cause the laser power inside the tube to build up without limit?

Although the conditions necessary for such an accident are unlikely, the question may be restated to ask what would happen if, instead of radiation leaking through the output mirror, suppose that both mirrors were 100% reflecting? Intuitively, of course, the radiation power inside the tube could not increase indefinitely – nature abhors infinities. But what is the actual mechanism preventing such a runaway catastrophe?

To answer this, consider the excited atoms inside the laser tube being stimulated to emit their energy in the form of laser photons. What happens to these atoms? They do not, of course, disappear, but remain in the laser tube as before. The difference is, now, that when a photon encounters the 'spent' atom, it can no longer stimulate the emission of another photon. Now the tables are turned, and the photon is liable to be absorbed by the atom, promoting it to its former excited state, called the upper laser level (Figure 1.4). If both the end mirrors were suddenly made totally reflecting, the laser power inside the tube would grow to begin with, and more excited atoms would be hit by laser photons as a consequence. This in turn, would increase the number of 'spent' atoms (called the lower laser level – Figure 1.4), and these would begin to mop up the excess laser photons by absorption. Soon an equilibrium would

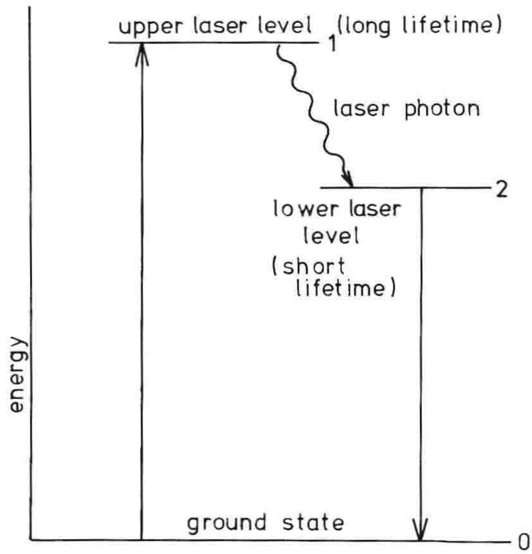

Figure 1.4 Lasing occurs when there is a greater population of atoms in a high energy state than a lower energy state. This condition is called 'population inversion'.

be reached where the numbers of upper-laser-level atoms and lower-laser-level atoms were equal, and the laser power will increase no further.

Notice that the rôle which the lower-laser-level atoms play in the production of laser light is crucial – ideally, the number of such species should be kept to a minimum, and certainly the upper-laser-level population should be greater than the lower; otherwise laser light would be absorbed as fast as it was created. This imbalance of numbers in favour of the upper laser level is called 'population inversion', because it is contrary to the normal state of affairs in a collection of excited atoms. Conditions necessary for achieving population inversion are shown in Figure 1.4. In this diagram, atoms with no excess energy are considered to be in the 'ground' state, i.e. at level 0. An atom may be excited to the upper laser level by collisions with electrons or other excited atoms in a gas discharge, or by light from outside the tube, which is termed 'optical pumping'. In order for the upper laser level (level 1) to build up, the atom in that state must have a long natural lifetime against decay by spontaneous emission or collisions with other laser atoms. By the same token, the lower laser level (level 2) will be kept small in size if the atoms there have a short lifetime against decay back