Electric and Laser Energy for Endoscopic Surgery

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───── Abstract ─────

Improvements in surgery have focused on refinements in the ability to dissect and limit blood loss. The electrosurgery unit (ESU) and laser (light amplification by stimulated emission of radiation) have been widely used in recent endoscopic surgery. ESU is a form of surgery in which high-frequency (100 kHz − 5 MHz) electric currents are used to incise, destroy, and remove tissue and to seal blood vessels in order to maintain hemostasis. The use of lasers in surgery has added a new dimension to operative technique through increased precision, improved hemostasis, and less tissue manipulation. This paper aims to explain the basic principles and applications of electrosurgery and lasers.

Key Words: Electrosurgical unit, laser, endoscopic surgery, physics

MODERN ELECTROSURGERY

All surgeons use electrosurgery but hardly any of them know the general principles, therefore many mistakes are made and the full possibilities of electrosurgery are almost never used.[1] The first half of this paper aims to explain the basic principles of electrosurgery and to apply the principles to laparoscopic surgery.

Modern electrosurgery is often called high frequency surgery, in reference to the frequency of the electricity. The frequency of the electricity in Korea is 60 Hz. This frequency cannot be used for the application of electrosurgery to humans as it interferes with neuromuscular synapses throughout the body and can cause ventricular fibrillation.

A safe frequency level, which does not interfere directly with the (neuro) physiologic responses in the human body, is above 10,000 Hz. Some types of electrosurgery need a specific frequency, this being in general from 350 kHz to 3,300 kHz (Fig. 1). More detailed information can be found later.

The first electrocautery units using vacuum tubes were developed in the 1920s by Cushing and Bovie.[1]

These tubes could generate a specific waveform which gave the so-called sparking effect of fulguration, but it was impossible in those days to contact-coagulate or to cut tissue. The current electrosurgery generators are all solid-state generators with a wide array of surgical possibilities.

Electrosurgical techniques

There are several modern electrosurgical techniques which have their own special applications as shown in Fig. 2. It is remarkable that these effects are hardly known and that most surgeons only use one or two of them. It should be recommended that electrosurgery be incorporated into the training curriculum for surgeons.[2]

Pure electrosurgical cutting is characterized by cutting the tissue without any lateral thermal damage. This can be done by using a very small and thin contact electrode, e.g. a needle electrode, and using a very high current density with sinusoidal waveform. This energy is transformed at the contact surface into so much heat that the cells are heated to a temperature of more than 100°C, and they subsequently explode and vaporize. In this way, tissue can be separated with precision. As the generated heat is absorbed by the water released from the cells, there is hardly any thermal damage; however, coagulation does not occur.

If coagulation is necessary, the electrode can be moved more slowly through the tissue and a thicker
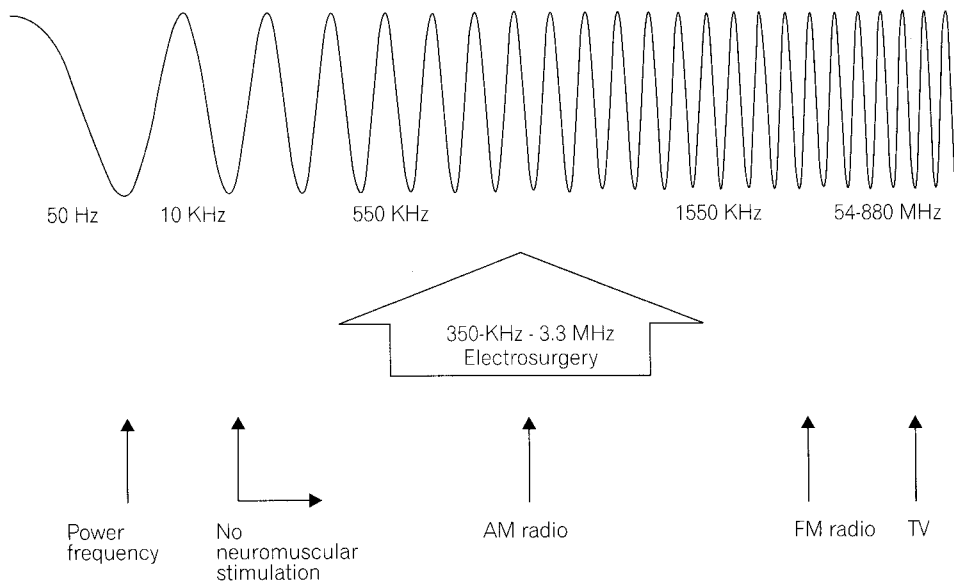
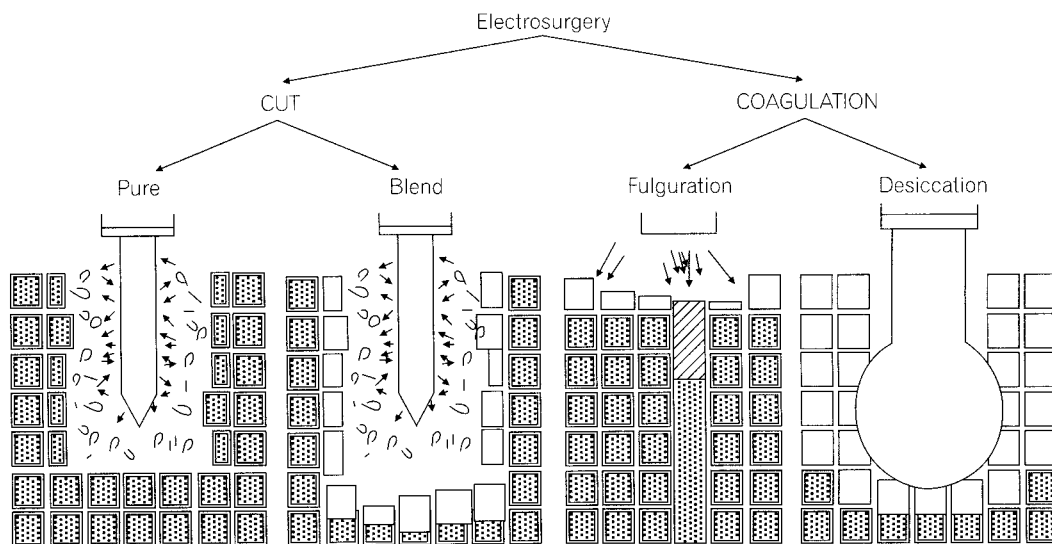Fig. 1. The place of electrosurgery in the frequency spectrum.

Fig. 2. Several modern electrosurgical technique. The white rectangles mean denaturation of proteins.

electrode can be used with the wave modulated or pulsed. With this method, the heat can penetrate deeper into the tissue and generate heat of less than 100°C in the surrounding tissues, which causes desiccation of the cells and promotes coagulation.

To obtain coagulation, it is necessary to restrict the current density so that just enough warmth is developed for the cell fluid to diffuse through the cell membrane and cause denaturation of the proteins. The cells are in fact dried out and can be recognized

by their white color, while the cell membrane remains intact. For this process, direct contact between electrode and tissue is necessary and all types of waveform can be used depending on the surface of the contact electrode and the current density.

An important factor for desiccation is the time it takes for the heat to penetrate into the tissue adjacent to the electrode. The heat distribution is more effective at low power for a longer period than at high power for a short period. Moreover, during the latter
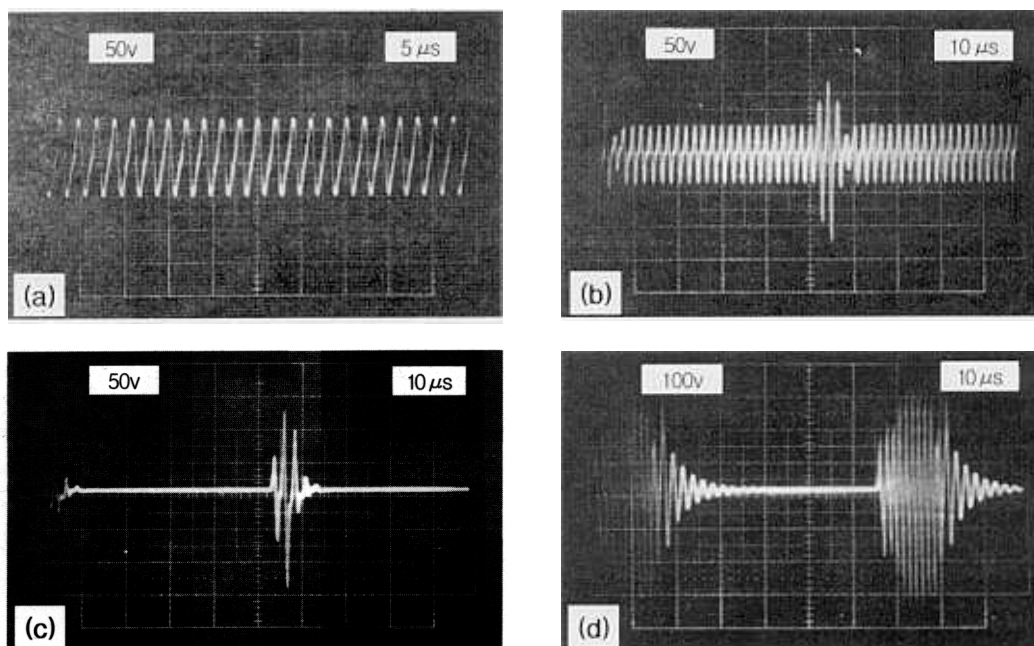
Fig. 3. Electrosurgical generator output waveforms. (a) Pure cutting waveform, (b) Blended cutting waveform with coagulation, (c) Low-duty-cycle coagulation waveform, (d) Open-circuit coagulation waveform for fulguration.

the tissue will only be superficially heated and will carbonize at the contact electrode. The tissue will stick to the electrode and be torn when the electrode is removed.

Fulguration is another type of coagulation, also called spark coagulation. It differs from desiccation in that the electrode does not make contact with the tissue and subsequently cauterizes the tissue. Fulguration can be created by high peak voltage with low power, the advantage being that the sparks jump from the electrode to the tissue sites with the lowest resistance, the open (bleeding) capillaries, which are coagulated. This makes this method very suitable for a large oozing surface, e.g. in liver surgery. During fulguration there is always carbonization (necrosis) of the tissue, which is advantageous in that it prevents heat conduction and subsequent coagulation of the deeper tissue layers.

A separate form of desiccation is bipolar coagulation. In this technique a patient plate is dispensed with by using an isolated bipolar coagulation forceps consisting of an active electrode and a patient plate electrode, one in each arm of the forceps. The advantage of this technique is that, while using very low power, one can obtain very precise coagulation without damaging the surrounding tissue. Fig. 3 shows
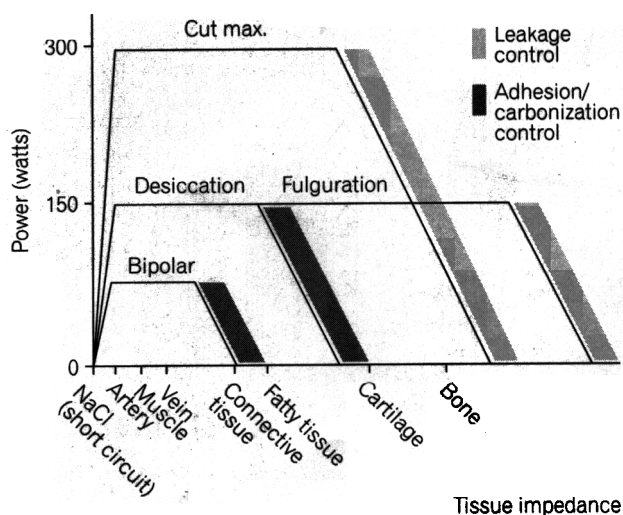

Fig. 4. The various effect by applied power and specific tissue impedance.

the various waveforms for cutting (a), blended cutting with coagulation (b), coagulation (c), and fulguration (d).

Optimal operation mode

Electrosurgery is based on handling a certain quan-

tity of thermal energy which is determined by the following factors: contact time between electrode and tissue, chosen power, active electrode surface, waveform, and specific tissue impedance.[2] The effects of all these factors are shown in Fig. 4. It should be understood that factors such as a layer of carbonized tissue on top of the electrode or the presence of some blood may decrease the effectiveness of electrosurgery. A thorough knowledge of the basics of electrosurgery and experience in its use are the factors for successfully choosing the correct type of electrosurgery and correct adjustment of the right power level.

Minimally invasive surgery

The use of electrosurgery is even more essential during minimally invasive surgery than in open surgery. Using electrosurgery during laparoscopic surgery has some potential hazards[3,4] but these can easily be prevented if the laparoscopic surgeon is fully aware
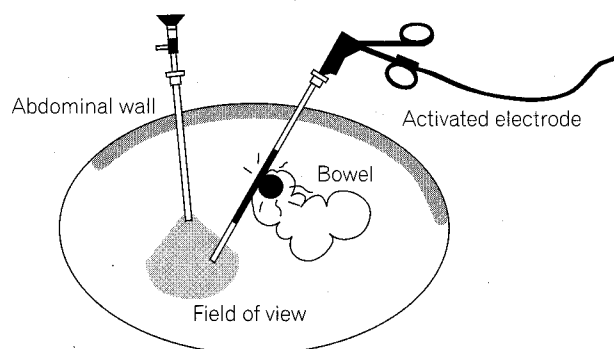

Fig. 5. Risk of internal burn by invisible insulation failure of the activated electrode.

Fig. 6. Risk of burn due to direct contact of the activated electrode with metal instrument.

of them. The main hazards are isolation damage of the instrument and direct coupling.

As illustrated in Fig. 5, isolation damage of the laparoscopic instrument can cause dangerous burn wounds to tissue which comes into contact with such an instrument.[2] As this part of the instrument is usually not in view the damage is often not recognized until the postoperative period when the patient develops peritonitis due to bowel perforation.

Direct coupling occurs when one touches another instrument, which is in contact with the intestines, with the active electrode as shown in Fig. 6. If this happens (mostly out of view), the surgeon does not recognize it and it can also result in perforation of the bowel or other serious complication.

Recommendations for the use of monopolar electrosurgery during laparoscopy:
● Always carefully inspect the isolation of the instrument, visually and electrically.
● Use low voltages.
● Use the cut or desiccation signal.
● Do not activate the electrode without it being in contact with tissue.
● Prevent direct contact with other metal instruments.
● Use only metal trocars and trocar grips.

If these recommendations are followed, electrosurgery can be safely used during laparoscopic surgery.

LASER ENERGY IN ENDOSCOPIC SURGERY

Physics of laser

An atom as a fundamental element of all substances is composed of a central nucleus and surrounding electrons which turn around the nucleus at a constant distance. When a certain atom absorbs energy ($h\nu$), the energy makes the electron move to an excited orbit (E_1) from a stable orbit (E_0) as shown in Fig. 7. The excited electron returns to the stable orbit and radiates energy the same as that received in the form of a photon. In 1917, Albert Einstein introduced for the first time that there are two possible ways of returning the excited electron to a stable orbit.[6] In other words, one is a spontaneous emission and the other is a stimulated emission by
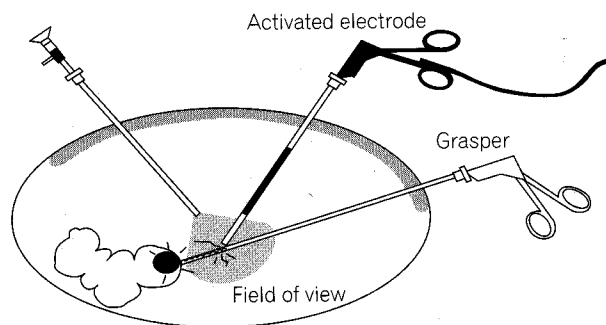
the collision of one photon with another photon as shown in Fig. 7. In the case of spontaneous emission, various types of photons are radiated, while in the simulated case, only the same photon as the one received is emitted. Therefore, a high intensive light consisting of a single photon can be amplified through repeated collision of the stimulated photons with each other. Townes et al. called this phenomenon LASER (Light Amplification by Stimulated Emission Radiation).

Since Theodore Maiman[7] introduced the first application of laser using man-made ruby, several versatile lasers have been developed for clinical surgery such as CO_2, Neodymium-Aluminum-Garner (Nd:YAG), and Argon, and their wave lengths are 10600, 1060, 488–514 nm, respectively. The characteristics of the three major surgical lasers including absorption, reflection, and penetration in tissue are shown in Table 1.

From the aspect of laser tissue penetration, CO_2 laser is the weakest, Argon laser is in moderate, and Nd:YAG laser is the strongest. Depending on the penetration capability, the laser accuracy and hemo-

stasis can be determined. A further important difference is in their own delivery system as shown in Fig. 8. The CO_2 laser is delivered to the target through mirrors inside the articulated arm.

Argon and Nd:YAG laser are transmitted through a flexible fiberoptic wave guide. The absorption of the CO_2 laser is not related to the tissue color, but is proportionately dependent on the moisture contained in the tissue. In addition, the reflection and scattering are almost nonexistent, and a thermal effect to the ambient tissue is also feeble. Therefore, CO_2 laser has been widely utilized for precise cutting and vaporization, but it is not suitable for blood coagulation. Argon laser can be permeated through transparent fluid such as a crystalline lens, and has a strong absorption in tissue with a pigment such as hemoglobin and melanin. Therefore, Argon laser is useful for photocoagulation of tissue containing pigments and/or vessels, and it is also used in microsurgery by minimizing the irradiative area by virtue of its very short wave length. Nowadays, Nd:YAG laser has become the standard instrument in surgery by compromising the disadvantages between CO_2 and Argon lasers.

Structure of laser

A laser system is composed of a main and peripheral compartments. The main compartment consists of a resonator tube containing a laser medium, excitation source, and aiming beam. The peripherals include a power amplifier, cooler, and delivery
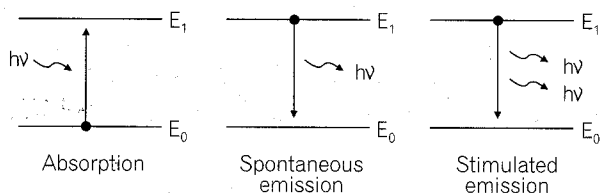
Fig. 7. *Spontaneous and stimulated emission.*

Table 1. Characteristics of the Three Major Surgical Lasers

	Lasing medium		
	CO_2	Argon	Nd:YAG
Type	Gas	Gas	Solid
Excitation	Electric	Electric	Optical
Wavelength	10,600 nm	500 nm	1,064 nm
Spectrum	Infrared	Visable	Infrared
Aiming beam	HeNe	Argon	HeNe
Absorption	Water, glass	Heme, melanin	Proteins
Penetration	0.1 mm	2 mm	4-6 mm
Delivery	Rigid mirrors	Fiber	Fiber
Max power	100 Watt	20 Watt	100 Watt
Coagulation	+	++	+++
Precision cut	+++	+	+
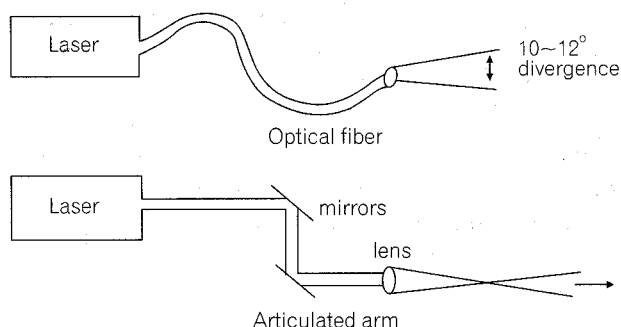
Fig. 8. Delivery system: optical fiber and articulated arm.

Fig. 9. Three laser effects depending on the pulse duration and power.

system. According to the selection of a laser beam medium, either an electric discharge, electron beam, or glitter lamp is selectively utilized as an excitation source. A glitter lamp such as Krypton or Xenon arc lamp is suitable for a solid laser, while an electric current for a gas laser and a coherent light source for a liquid laser (variable pigment laser) is used. Since an infrared laser such as CO_2 and Nd: YAG is invisible, an additional laser beam is utilized to ascertain the target and focus size of the laser beam. As for an aiming beam, a white visible light or a red HeNe laser is used. In general, the latter is more frequently used since the HeNe has the advantage of checking the path of the transmittant beam.

Throughout the whole system from the energy source to laser beam generation, the system efficiency is quite low. Therefore, the power current should be amplified for charging the excitation source. A high energy power source, 3 phase 208 V, is necessary for the higher output of an Argon or YAG laser. As the laser system is very inefficient, an air or water cooler is inevitable to dissipate the generated heat. A water cooler is suitable for higher output or less efficient lasers, but an air cooler is sufficient for lower output lasers. A delivery system plays a role in delivering the beam from the laser head to the target. For this purpose, two methods are available: an articulated arm using a mirror or a fiberoptic transmitter as shown in Fig. 8.

Tissue interaction

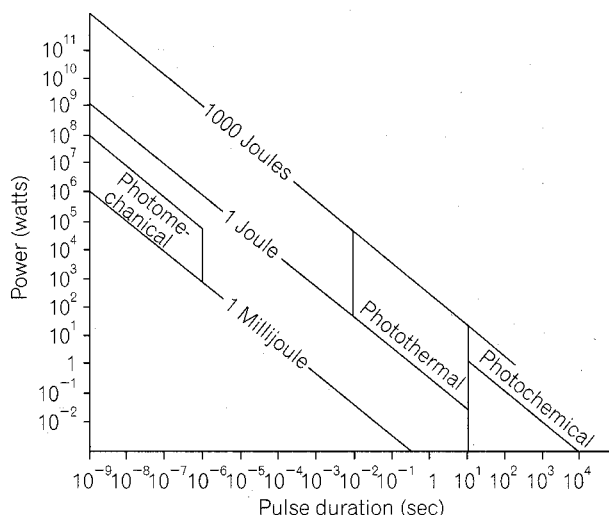When a laser beam penetrates live tissue, three typical reactions can be observed as shown in Fig. 9.[5]

In a very low output intensity laser beam, a specific chemical and metabolic reaction occurs without any destruction of cells (photochemical). Under a moderately high output intensity, the beam destroys some tissue by increasing tissue temperature (photothermal). Finally, with a very high output intensity, the laser explodes tissue before its destruction by heating (photomechanical).

Chromophores are present throughout tissue. Different chromophores absorb light at different wavelengths. Water, for example, has a high absorption in the ultraviolet and infrared portions of the spectrum (Fig. 10). Tissue color is due to absorption of light in the visible spectrum. A red lesion for example absorbs light of a complementary color (green) and reflects red light, thus causing it to appear red in color. The advantage of this property is that one can tailor a laser beam (by choosing the appropriate lasing medium) to be absorbed by a lesion, yet be reflected by surrounding tissue, thus minimizing 'collateral' tissue damage.[8] The ideal laser system would incorporate a spectrophotometer to analyze both the target tissue and the background tissue, select the wavelength of light where the difference between the two was greatest, and deliver that particular wavelength from a 'tunable' source.

Occasionally, one wishes to achieve deep tissue penetration. This is achieved by choosing a laser whose wavelength is poorly absorbed by surrounding tissue chromophores. Given the fact that water and
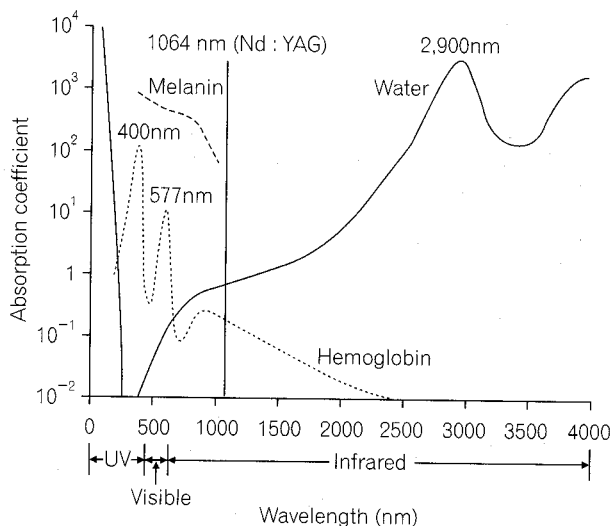
Fig. 10. Absorption coefficients of water, hemoglobin, and melanin.

hemoglobin are predominant chromophores within tissue, laser wavelengths which are poorly absorbed by these tissue elements will promote the greatest amount of light scattering. This results in the greatest width and depth of tissue heating. The Nd:YAG laser generates laser light in the near infrared spectrum, which is also the lowest point of water and hemoglobin absorption (Fig. 10). This proves to be useful in palliative obstruction gastrointestinal malignancies where deep uniform heating allows for maximal tissue destruction and coagulation.

Laser-tissue interaction can be either photomechanical, photothermal, or photochemical. Most uses of lasers in medicine cause tissue injury by heating (photothermal). Pulsing parameters affect the type of laser-tissue interaction. A long low power pulse will cause a photothermal interaction, spreading heat from the application point to surrounding tissue. A common application of a photothermal tissue interaction is photocoagulation of peptic ulcers. Numerous studies have demonstrated that laser coagulation is an effective method for controlling ulcer bleeding and/or rebleeding.[9,10]

Shortening the pulse time and dramatically increasing the power will cause tissue disruption by a shock wave mechanism without significant thermal damage to adjacent tissue (photomechanical interaction). Energy is derived from a pulsed-dye laser and is delivered through a flexible quartz fiber 320 to 550 nm in diameter. The light energy at the tip of the fiber

against the stone wall results in a massive transfer of energy, shattering the stone with very little effect on the surrounding tissue.[11]

Conversely, a long duration and low power laser beam may act as a catalyst for a chemical reaction without appreciable thermal or mechanical tissue damage (photochemical interaction) as shown in Fig. 9. The basic mechanism of photodynamic therapy is discussed below.[12]

Photodynamic therapy

Photodynamic therapy (PDT) utilizes the photochemical effects of low power, long duration pulsing (e.g. 3–10 W for 3–10 sec) of a laser beam to catalyze chemical reactions of photoactive drugs. Tumor-localizing agents such as hematoporphyrin derivative (HpD) of photofrin II are injected intravenously into patients and subsequently concentrate within the tumor. Light of a specific wavelength in the drug's absorption spectrum is then used to initiate the release of oxygen free radicals which destroy tumor cells without causing surrounding tissue damage since very little heat is generated from oxidative tissue injury as shown in Fig. 11. PDT is currently limited by the lack of light delivery to deeper tissues, and the lack of HpD delivery to relatively ischemic regions within the tumor. These two problems limit the effectiveness of PDT to lesions confined to the mucosa and submucosa. The third problem with PDT is that lingering chemical levels after injection force patients to remain in dim lighting for approximately 4 weeks after therapy to avoid activating the cutaneous HpD.

Laser tissue welding

A variety of laser-welding techniques has been developed.[13] The advantages of welded anastomosis include the absence of a foreign body, water-tightness, and the ability to grow. The actual mechanism of action is not completely understood. Some believe the weld is a result of high structural proteins. Another theory suggests that hydrogen resulting from disulfide bonding between heat-denatured proteins is responsible for creating the weld. Laser-welded anastomosis has been shown to give patency rates of 70% in 4.5 year follow-up studies.[14]
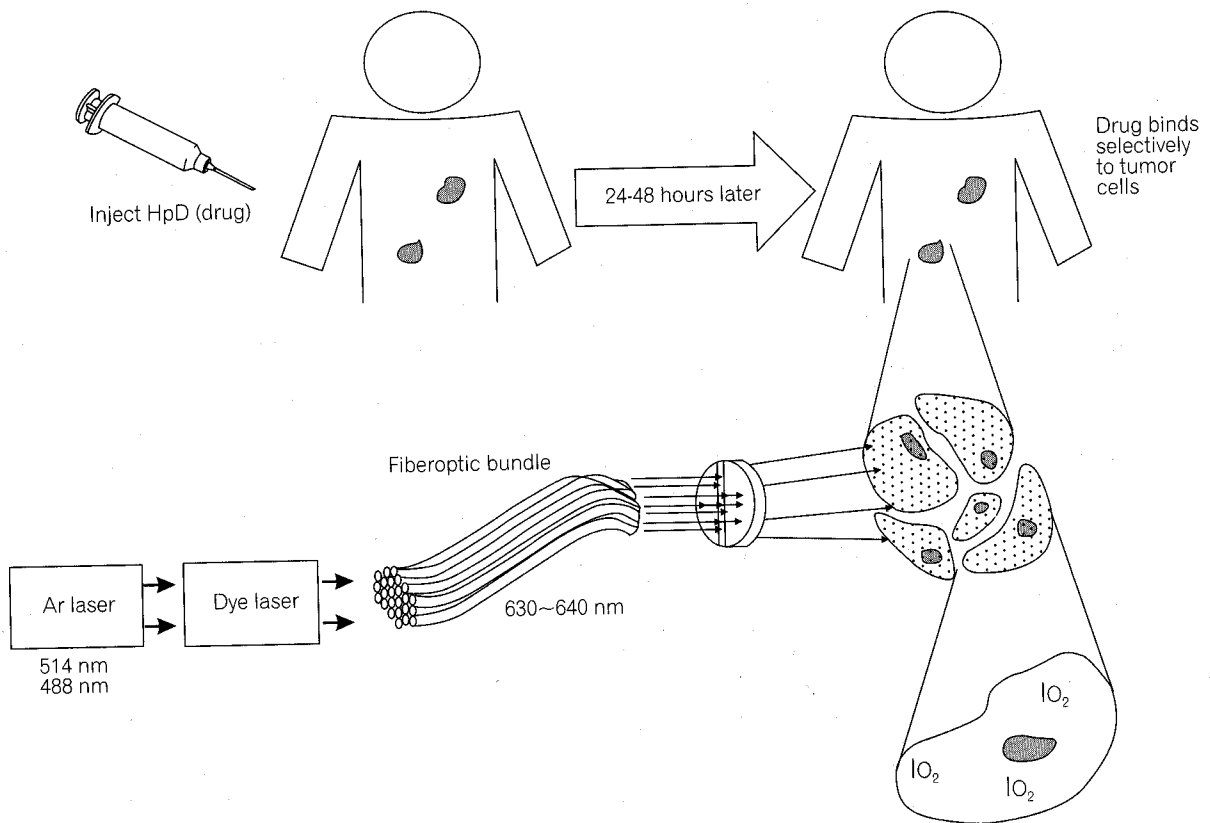
Fig. 11. The procedure of photodynamic therapy.

Argon beam coagulator

The argon beam coagulator (ABC) (Bard-Birtcher Medical Systems, Englewood, CO) is a noncontact, monopolar electrocoagulation device which delivers radiofrequency electrical energy to tissue across a jet of argon gas. The argon gas jet aids in even distribution of electrical energy and clears the target tissue of any pooled blood. Transmitted energy is only marginally higher than standard monopolar electrocautery (40−150 W vs 10−120 W respectively). It has been used primarily as a hemostatic tool for solid organ bleeding, such as in the liver, spleen or kidney. Its efficacy has been documented in both clinical and animal studies.[15,16]

It is now available for use in laparoscopic and flexible endoscopic surgery. The high pressure, large volume argon gas jet must be vented from the abdomen to avoid overdistension. Gas embolism from solid organ resorption is also a theoretical risk.

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