LASER'S USE IN BONE AND JOINT SURGERY

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The use of lasers in podiatric and orthopedic surgery has been delegated routinely to the treatment of soft tissue pathologies in which they have proven to be the preferred treatment compared with more conventional techniques. Beginning with the carbon dioxide (CO_2) laser, medical researchers and practitioners alike have been trying to develop a laser that could cut bone efficiently and precisely in a way that afforded minimal damage to peripheral structures. No one laser has accomplished this task; each has its own advantages and disadvantages. This article explores the various types of lasers used for bone and joint applications.

BONE COMPOSITION AND LASER EFFECT

The clinician should have a basic understanding of bone composition before performing any osseous procedure with a laser. Bone consists of compact (substantia compacta) and spongy (substantia spongiosa) types. Bone substance is comprised of two major components—organic matrix, consisting of 95% type I collagen, which is embedded in a ground substance made up of glycosaminoglycans, and inorganic salts, comprised of calcium phosphate, citrate, and carbonate ions. Water is also a common constituent of both components, making up between 17% to 34%.[20a]

It is important to have a basic understanding of bone composition when using various types of lasers, because each laser has its own individual absorption qualities in the infrared region of the electromagnetic spectrum (Fig. 1). With regard to laser ablation of bone, laser energy can be absorbed by water molecules in both organic and inorganic areas of bone, by organic collagen matrix or inorganic salts, or by optical breakdown and the plasma-cutting phenomenon, producing bone ablation at sufficiently high laser irradiance.[16]

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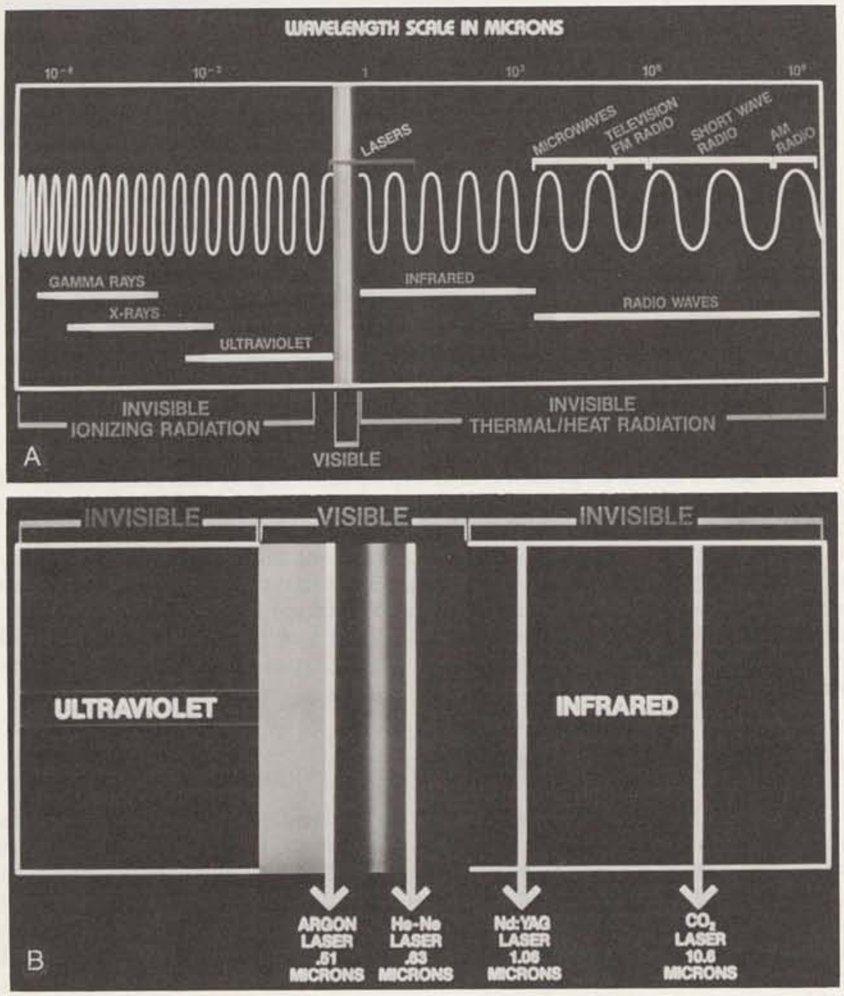

Figure 1. *(A)* Electromagnetic spectrum. Note the wavelength of lasers falls within the visible and invisible (both ionizing and thermal) spectrum. *(B)* Enlarged section of laser's spectrum.

These three mechanisms of ablation are generally the accepted means by which lasers cut bone.

Optical breakdown is a nonlinear phenomenon occurring when laser energy condenses at extremely high levels of irradiance and is seen most commonly with the pulsed neodymium (Nd)-YAG laser (1064 nm).[24] When breakdown is achieved, a spark and audible snap occur as the electrons dissociating from their atoms create plasma (ionization). Once formed, plasma is capable of decreasing energy transmission by shielding the deeper underlying structures from the beam of the laser, resulting in increased laser irradiance and decreased target ablation. This is termed *plasma-cutting* and is seen with the use of the Q-switched Nd-YAG laser for bone ablation.[26] Because bone tissue absorbs very little of this wavelength, plasma-cutting is the mechanism of ablation and a narrow zone of peripheral thermal injury occurs. The irradiance of this type of laser (10^9–10^{12} W/cm^2) makes it a viable choice for osseous structures.

Although the irradiance of the holmium (Ho)-YSGG (yttrium-scandium-gallium garnet, 2100 nm) and erbium (Er)-YAG (2940 nm) lasers (10^5 W/cm^2) are not in the range to cause optical breakdown and plasma formation, they are able to vaporize bone tissue but cause much more thermal damage. With pulsed lasers (Nd-YAG, Ho-YSGG, Er-YAG), the dissipation of energy occurs through a process called *spallation*, whereby energy is dissipated through the expulsion of pieces of target tissue as part of vaporization.[20] The Er-YAG laser is absorbed at higher levels per volume measurement of tissue and, therefore, has less thermal damage and greater ablative properties associated with it compared with the Ho-YSGG laser. This occurs because with the Ho-YSGG laser, deeper penetration is attained but with a greater energy expenditure necessary to reach vaporization.

According to Nuss, the Q-switched Nd-YAG laser ablates bone in a plasma-cutting manner with minimal thermal damage, the Er-YAG laser is the most effective bone ablater due to its being highly absorbed by bone, and the Ho-YSGG laser is the least effective due to its lacks of absorption, thereby creating greater thermal damage (Figs. 2 A–E).[16] Overall, pulsed lasers are associated with decreased amounts of thermal damage to contiguous structures.

BONE HEALING

The constituents of bone contain high amounts of minerals and little water. This relationship retards vaporization; therefore, when using a CO_2 laser (10,600 nm), temperatures may rise in excess of 4000°C. The high amounts of minerals present increase the necessity to prolong laser exposure to afford vaporization. This increased exposure results in extended on-time for completion of a bone cut, causing increased para-incisional damage.[6] Therefore, by decreasing exposure time the surgeon could decrease para-incisional damage. Clayman and colleagues introduced superpulsed lasers in bone surgery to achieve this effect and found healing time did decrease when a superpulsed laser was used.[7] Their work was substantiated by Small and colleagues who found significant reduction in the delay in healing of laser osteotomies using rapid superpulsed (RSP) lasers.[22]

Nitrogen cooling systems and mechanical assistance of the laser handpiece also have been used to allow reduction in beam scatter that can decrease heat transmission. Decreased beam scattering also is efficacious in affording more precise cutting by decreasing exposure time and subsequently juxta-incisional necrosis.

The work of Callahan has provided insight into the effect that CO_2 lasers have on osseous healing. He found that comparing osteotomies created in the ulna bone of rabbits by CO_2 lasers and oscillating saws, bone healing was comparable in both groups but that healing was delayed in the laser group because inert-appearing bone fragments seemed to inhibit the healing process. A 1.5 week delay in complete bone healing occurred (Fig. 3). Radiographically, there was no statistically significant difference, yet histologically these delays were evident by the appearance of necrotic bone fragments throughout the healing process that were almost always surrounded by fibrosis (Fig. 4). There

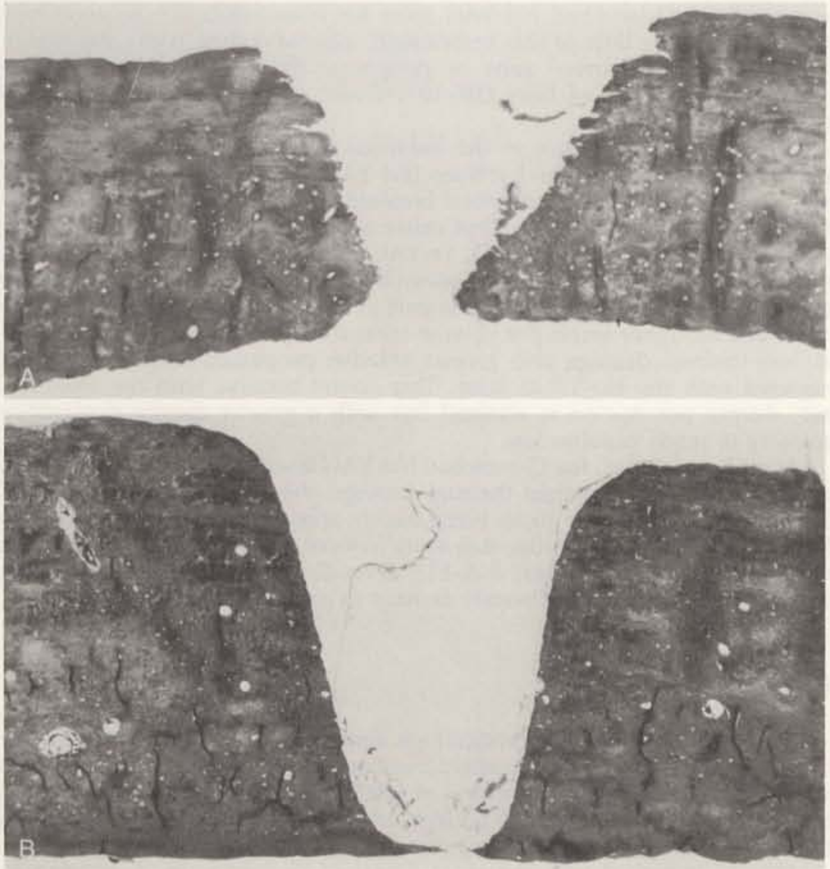

Figure 2. *(A)* Photomicrograph of pulsed Nd-YAG (λ = 1.064 μm) bone ablation. Radiant expressure = 16.5 J/cm^2, 10 nsec pulse width, 130 pulses delivered at 1 pulse per sec. Note smooth lesion edge and narrow (10 to 15 μm) zone of altered staining characteristics (original magnification $\times$4). *(B)* Photomicrograph of Er-YAG (λ = 2.94 μm) bone ablation. Radiant exposure = 46 J/cm^2, 250 μsec pulse width, 8 pulses delivered at 2 pulses per sec. Note smooth lesion edge and narrow (10 to 15 μm) zone of altered staining characteristics (original magnification $\times$4).

was not, however, any evidence of foreign body response, granuloma, or infection when the laser was used. The oscillating saw group showed mild fibrosis, small granuloma formation in one animal, and no infection. Significant findings included the presence of charred bone fragments throughout the healing process in the laser group that were encapsulated by fibrous tissue rather than incorporated into new trabecular or lamellar bone. The delay in the healing process may be somehow attributable to the fact that the charred bone needed to be incapsulated before new bone could form. Because there was no foreign body response, it seems as if the charred bone may remain sequestered inertly in the osteotomy site.

Callahan also hypothesized that the thermal effect of the CO_2 laser may

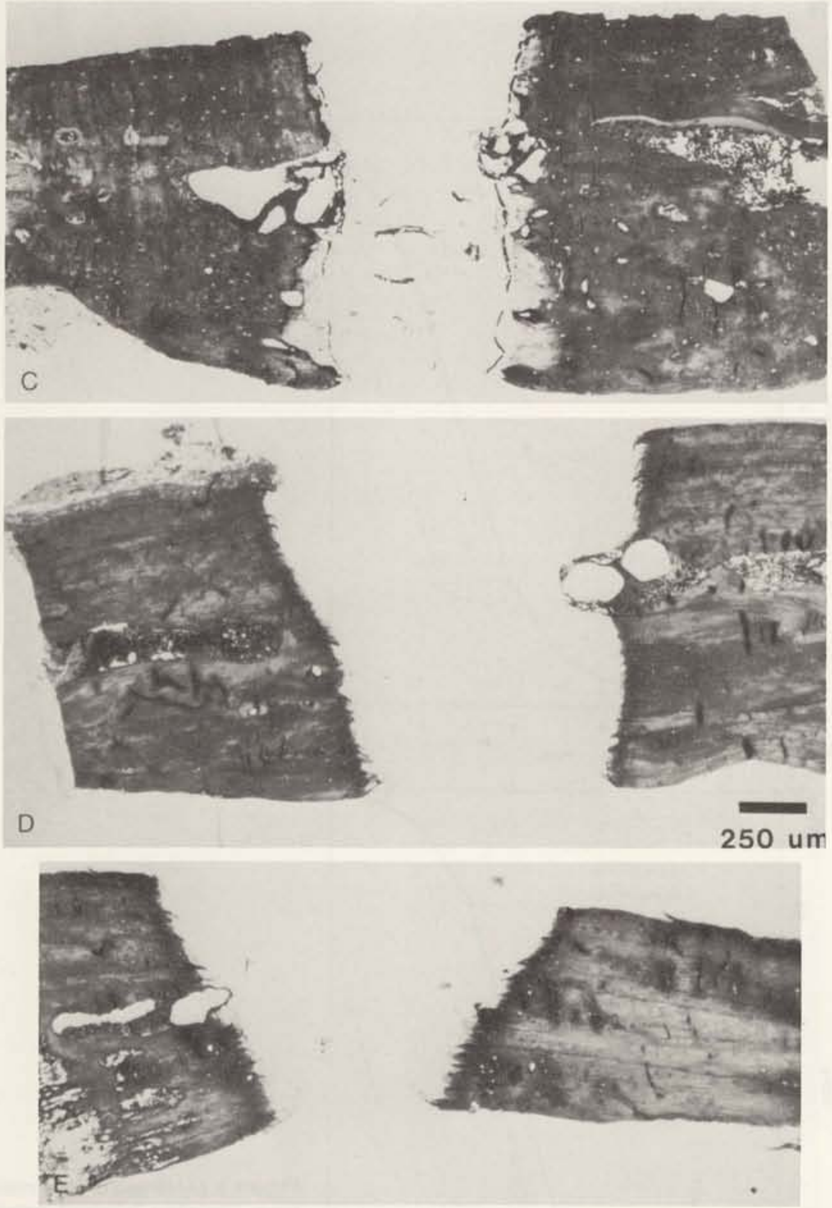

Figure 2 *(Continued). (C)* Photomicrograph of Ho-YSGG (λ = 2.10 μm) bone ablation. Radiant exposure = 44 J/cm^2, 250 μsec pulse width, 25 pulses delivered at 2 pulses per sec. Note rough appearance of lesion edge and wide (60 to 90 μm) zone of altered staining characteristics (original magnification $\times$4). *(D)* Photomicrograph of CW-Nd-YAG (λ = 1.064 μm) bone ablation. Irradiance = 2,700 W/cm^2, 100 msec pulse duration, 5 pulses delivered at 1 pulse per sec. Note jagged, fibrillar appearance of lesion edge and wide (60 to 135 μm) zone of altered staining characteristics (original magnification $\times$2). *(E)* Photomicrograph of CW-CO_2 (λ = 10.6 μm) bone ablation. Irradiance = 880 W/cm^2, 50 msec pulse duration, 5 pulses delivered at 1 pulse per sec. Note jagged, fibrillar appearance of lesion edge and wide (60 to 135 μm) zone of altered staining characteristics (original magnification $\times$2). (*A–E From* Nuss RC, et al: Infrared Laser Bone Ablation. Lasers in Surgery and Medicine, 8:381–391, copyright © 1988, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

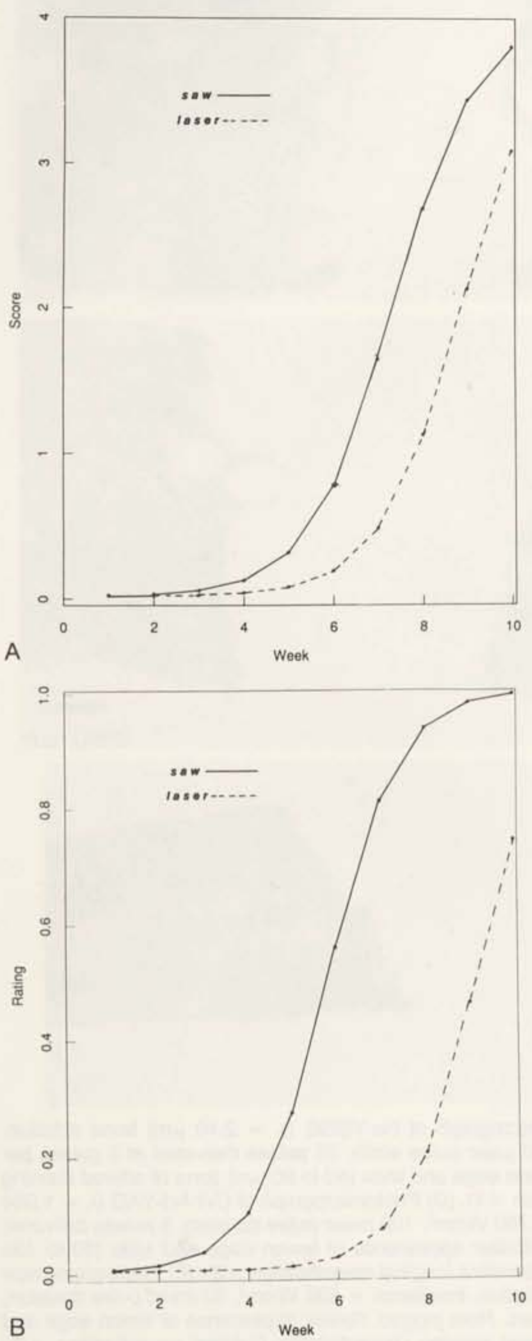

Figure 3. *(A)* Graph of the lamella bone formation following osteotomy, using logistic regression model comparison. *(B)* Graph of the overall healing scores following osteotomy. (*From* DJ Callahan: Osseous Healing after CO_2 Laser Osteotomy. Foot and Ankle 11:146–151, 1990, © American Orthopedic Foot and Ankle Society.)

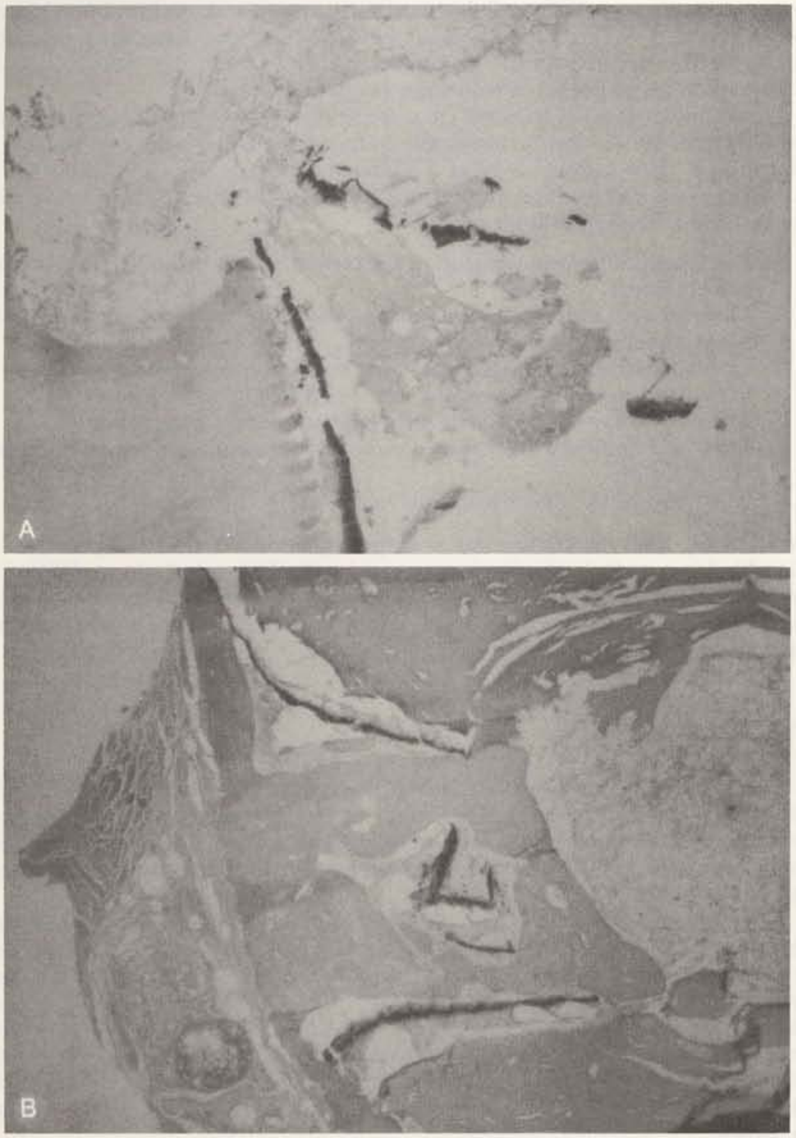

Figure 4. *(A)* Laser osteotomy, week 1 (hematoxylin-eosin and Masson trichrome stain, ×25). Lamellar bone, lower left, with necrotic edge, char debris, amorphous material and organized clot. *(B)* Laser osteotomy, week 10 (hematoxylin-eosin and Masson trichrome stain, ×25). Char debris remains, new bone forming around char remains separated by the char. (*From* DJ Callahan: Osseous Healing after CO_2 Laser Osteotomy. Foot and Ankle 11:146–151, 1990, © American Orthopedic Foot and Ankle Society.)

alter bone substance such that osteoclasts and macrophages are rendered ineffective. Wynn and Lunsford went on to show how, when alkaline phosphatase denatures at 55°C, cellular mechanisms are impaired and local blood flow is reduced.[28] The extreme heat generated by the laser also produces changes in the hydroxyapatite crystalline lattice of bone, but apparently the ultimate strength of healed osteotomies is unaffected.

On a cellular level, Tang and Chai made observations to the effect of low-level CO_2 laser irradiation on surgically induced oscillating saw osteotomies of rabbit radii.[25] They used 18.5 W at a distance of 95 cm, a radiant exposure of 236 mW/cm_2 and a duration time of 10 minutes. Over a 10-day period they observed the following cellular changes:

1. Red blood cells were induced to disintegrate, thus promoting absorption of hematoma.
2. Macrophages emerged early and increased in number so that debridement of necrotic tissue was enhanced.
3. Fibroblasts were more active in producing fibrous callus.
4. Chondrocytes were unusually active in forming bone tissue.
5. The early appearance of osteoclasts favored bone remodeling.
6. Increased capillary formation endowed the healing fracture with rich blood supply.
7. Early deposition of calcium salts occurred.

Overall, CO_2 laser irradiation of a surgically induced fracture produced a noticeable increase in healing rate compared with the control group. With CO_2 laser irradiation, periosteal reactions occurred 8 days earlier, new bone formation in the fracture gap, 4 days earlier, and complete filling of the fracture gap, 5 days earlier.

OSTEOTOMIES

The CO_2 laser has been used, both in continuous wave (CW) and RSP forms, to perform osteotomies in bone. Lasers obviously have the distinct advantage over oscillating saws and burs in that cuts are more precise and less bone is removed. The major drawback seems to be juxta-incisional damage from thermal effects.

Late wound healing has been shown to be comparable following saw and laser osteotomies in canine models.[27] According to Gertsbein and colleagues, the mechanical strength following laser-induced and mechanically induced osteotomies recovers at the same speed.[10] Verscheuren and Oldhoff found, however, that there was a definite delay in healing when CW CO_2 lasers were used.[27] This was due most probably to juxta-incisional necrosis that occurs after prolonged exposure of the laser to the target bone tissue. This is one of the main reasons why the CO_2 laser for osteotomies has not gained overall acceptance.

Clauser used an industrial, high power CO_2 laser to allow comparison of RSP and CW modes of the same laser at average power densities that were chosen to permit rapid incision of bone without reaching the threshold for fat embolism to occur.[11] Results showed that the RSP mode afforded a decreased ability to cut bone at the same average power levels used with the CW mode, but there was a significant reduction in para-incisional damage measured by reduced lateral penetration. CW osteotomies also showed enlargement at deep levels, whereas RSP osteotomies showed a regular decrease in size as depth increased. These results are encouraging because they show that para-incisional damage is minimal at a depth where problems may arise more easily. Unfortunately, both laser modes cut more slowly than drills or saws.

The excimer laser or excited dimer laser (argon fluoride, 193 nm) functions in the UV region (see Fig. 1) and uses ablative photodecompression,[24] whereby organic material is broken up by UV photons into smaller fragments that are removed from the immediate area at supersonic velocities. The subsequent residual energy is removed simultaneously as well, with minimal thermal damage and tissue necrosis occurring peripherally. The excimer laser has been shown by Lustmann and colleagues to produce clean and precise cuts in bone with negligible thermal damage (< 1 μm in width).[15] Trials were performed on both decalcified and nondecalcified bone. The excimer laser is pulsed and produced negligible amounts of adjacent necrosis in both groups. The base of the cuts were evaluated microscopically and found to be perpendicular to the side walls of the initial cut. No debris was found in the remaining osseous defect.

Studies using the Er-YAG lasers have proved promising. Bruhn and colleagues found the most effective energy per pulse to be 150 mJ/pulse at 10 Hz. One problem that occurred, however, stemmed from the fact that blood would extravasate from the marrow, thus impeding the laser's cutting potential. They provide an interesting alternative whereby the Er-YAG and Nd-YAG lasers would be coupled allowing the benefit of the tissue coagulating effect of the Nd-YAG laser to be used. Although histologic assessment of bone healing indicated rapid bone healing with the Er-YAG laser, multiple passes of the laser were needed to cut large bones. This caused a wider and deeper incision in the bone to occur. Hunter and colleagues used a free election laser to osteotomize rat femurs.[12] They found this laser to produce precise cuts through plasma-related thermal-cutting mechanisms. The zone of tissue damage along the para-incisional area was found to be 10 to 20 μm.

BONE TUMORS

The surgical treatment of bone tumors has been enhanced since the CO_2 laser was used for aneurysmal bone cysts, enchondromas, giant cell tumors, and other benign and locally infiltrative bone tumors. Previously, curettage, bone packing, or grafting was used in the treatment of these lesions along with chemical or thermal cauterants to prevent recurrence. These agents, including phenol and liquid nitrogen, were employed to help destroy any remaining tumor cells in the deficit left after excision of the tumor. Although this has decreased the overall rate of recurrence, it has not been very promising due to postoperative infections, fractures, foreign body reactions, and other complications.

The CO_2 laser offers a viable option for this type of surgery because of its inherent ability to vaporize tumor cells and soft tissue structures while decreasing the amount of peripheral damage to bone. Rayan and colleagues found that the changes in cortical bone exposed to CO_2 energy involved only superficial regions of the inner cortex (Fig. 5).[18] No thermal damage was found in the majority of the remaining cortical areas. They concluded that the use of the CO_2 laser as an adjunct modality in dealing with certain types of tumors was promising, because the laser did not affect the remaining bone or cause necrosis and, therefore, cortical reconstitution is possible. These findings are in contrast to those of Cecere and Liebow who found that the CO_2 laser acted

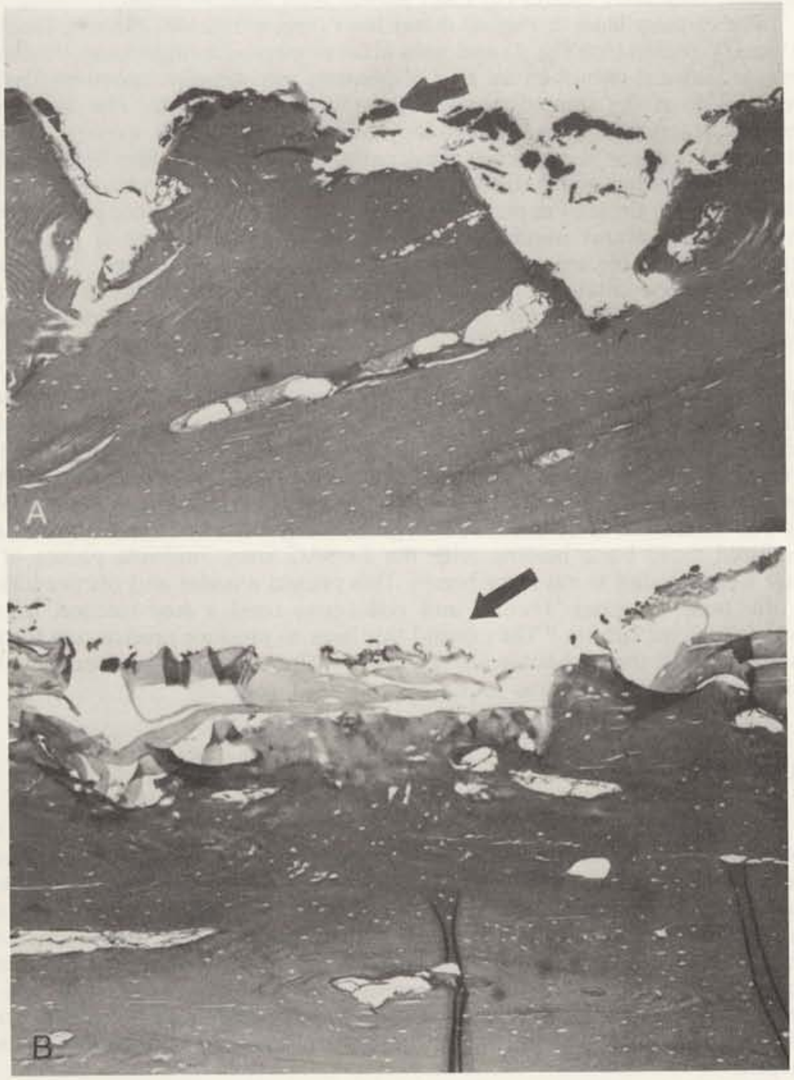

Figure 5. *(A)* Bony changes following CO_2 laser exposure with low-power density. Superficial thin layer of carbonization on the bone surface is present *(arrow)*. The second layer contains for the most part empty lacunae. Viable osteocytes can be seen immediately adjacent to the area of thermal damage (original magnification $\times 150$). *(B)* Bony changes following CO_2 laser exposure with high-power density. Greater thermal damage is seen with excessive fibrillations *(arrow)*, carbon deposits, and empty lacunae without any viable osteocytes (original magnification $\times 150$). (*From* Rayan GM, et al: Effects of CO_2 Laser Beam on Cortical Bone. Lasers Surg Med 11:58–61, Copyright © 1991, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

as a promoter of tumor cells because the laser caused an increased production of growth factor compared with scalpel incisions.[5]

CARTILAGE

Whereas bone contains very little water, cartilage on the other hand is comprised mostly of collagen, which is approximately 80% water. Previously, the use of Kirschner wires for subchondral drilling was shown to relieve pain and restore function in degenerative joint disease.[13, 17] This procedure was 75% successful but lacked histological support. According to Salter, drill holes in articular cartilage of rabbits were repaired with new hyaline cartilage when continuous passive motion of the joint occurred.[19] This was confirmed histologically. More recently, Borovoy and colleagues, using a CO_2 laser, found healing with formation of fibrocartilage and hyaline cartilage in rabbit models.[1] A second group of specimens in which a Kirschner wire was used did not exhibit any areas of fibrous response or chondrogenesis. The CO_2 laser possesses the ability to pinpoint selectively and vaporize cartilage at specific depths with minimal damage to underlying bone. Perforation of the subchondral plate, which is necessary to induce repair, is accomplished but with minimal necrosis and thermal damage. The application of the CO_2 laser for articular degeneration may someday eliminate the need for joint destructive procedures where cartilage regeneration would negate the need for surgery.

The Nd-YAG laser has been used by Schultz and colleagues and shown to cause regeneration of partial thickness cartilage defects in guinea pigs.[21] Lower dosages were effective in producing this effect, whereas higher dosages did not provide for a greater response and actually caused cell death.

The excimer laser has been used by Freedland to provide for the denuding of cartilage from bone due to its having an irradiation range approximately the same as cartilage's absorption pattern. This would allow for the ablation of cartilage with minute amounts of peripheral necrosis or structural change of the adjacent bone (Fig. 6). Buchelt and colleagues found the excimer laser to be of great benefit compared with the CO_2 and Nd-YAG lasers for fibrocartilage ablation. Not only did the CO_2 and Nd-YAG lasers produce great amounts of smoke and unpredictable depths of ablation penetration, they also caused extreme amounts of thermal heat production (201°C and 208°C compared with 65°C for the excimer) (Fig. 7). The excimer laser also enabled ablation without carbonization, whereas the Nd-YAG laser caused massive thermal damage with carbonization, tissue necrosis, vacuolization, and fiber disruption (Fig. 8). They further concluded that the Nd-YAG laser caused earlier and more extensive inflammatory changes due to necrosis and that fibroblastic response was only minimal compared with the fibroblastic reaction from the excimer laser (Fig. 9). Recent studies by Dressel and colleagues have found similar findings in that the excimer laser, when coupled with the xenon-chlorine (Xe-C1) (308 nm) laser in a fiber optic delivery system consisting of fused silica, produced no carbonization and relative temperature increases of less than 40°C in surrounding tissue.[8a] The healing rate of the excimer laser cut was found to be comparable to mechanical cuts, but the cuts themselves exhibited sharp, clean, and smooth edges. This clean removal of bone is cited repeatedly as a significant advantage afforded by using the excimer laser.[3, 8a, 9, 15]

ARTHROSCOPY

For the most part, the CO_2 and Nd-YAG lasers have been used primarily for operative arthroscopy. Recently, the emergence of the Ho-YAG laser for

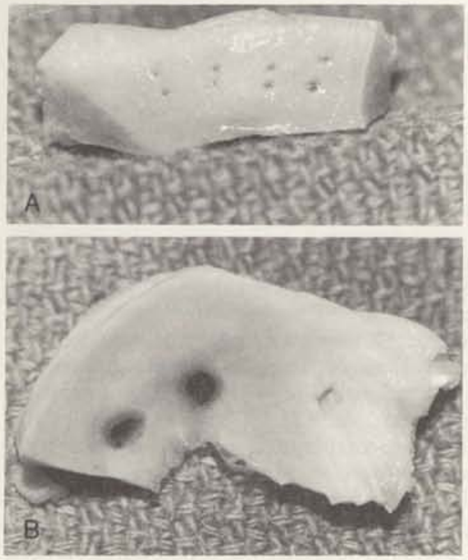

Figure 6. *(A)* Macroscopic appearance following excimer laser irradiation. Round to oval craters with sharp edges are seen. No carbonization is observed. *(B)* Nd-Yag laser-irradiated meniscus. Intense carbonization and irregular crater margins are seen. The right crater is ablated with an excimer laser for direct comparison. (*From* Buchelt M, et al: Excimer Laser Ablation of Fibrocartilage: An In Vitro and In Vivo Study. Lasers Surg Med 11:271–279, Copyright © 1991, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

arthroscopy has caused a reevaluation of the type of lasers used for these procedures. Ho-YAG incorporates the flexibility of the Nd-YAG laser (fiberoptic delivery) and the tissue interaction of the CO_2 laser, without its thermal disadvantages; its wavelength allows absorption by water and water-containing tissues. It also lacks the inherent disadvantages of the CO_2 laser because unlike the CO_2 laser, it is not dependent upon gas distention of a joint in order to be effective.

With the CO_2 laser, the joint must first be distended with liquid for observation, then evacuated and distended with gas because the CO_2 laser cannot function in a liquid environment. Because a gas medium is not required with the Ho-YAG laser, no tourniquet is necessary and it can be used anywhere in the body because the possible risk of subcutaneous emphysema, gas migration, and pulmonary involvement is removed when gas is not used. Therefore, the Ho-YAG laser is associated with quicker relief from postoperative pain, joint inflammation, stiffness, and soreness by its less generalized production of thermal effect and decreased deeper penetration. This translates into decreased postoperative discomfort and a shorter course of postoperative physical therapy. The Ho-YAG laser's ability to coagulate bleeding bones also helps to minimize discomfort.

ADJUVANT PROCEDURES

Percutaneous discectomies, meniscectomies, synovectomies, and tissue-welding procedures all have benefitted from the use of one or several types of lasers. As previously stated, the Ho-YAG laser's introduction for use in discectomies and synovectomies has advanced the benefit of these types of procedures. The decreased pain, swelling, and inflammation afford quicker

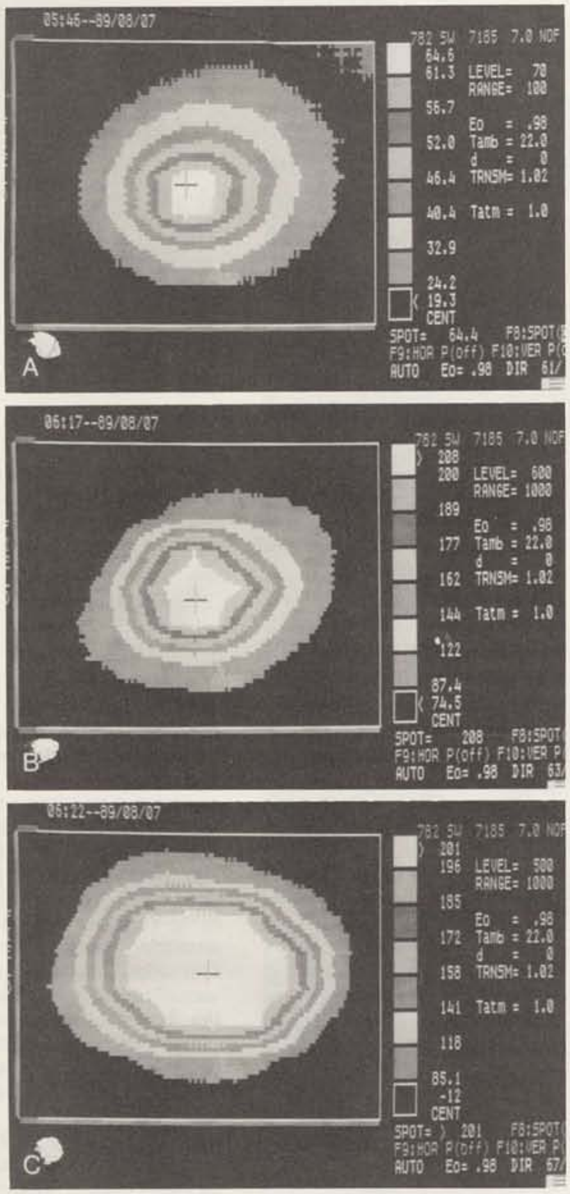

Figure 7. *(A)* Thermographic picture of excimer laser ablation: the hottest spot marked by the cross is 64.4°C. *(B)* Thermographic picture of Nd-Yag laser ablation: the hottest spot marked by the cross is 208°C. *(C)* Thermographic picture of CO_2 laser ablation: the hottest spot marked by the cross is 201°C. (*From* Buchelt M, et al: Excimer Laser Ablation of Fibrocartilage: An In Vitro and In Vivo Study. Lasers Surg Med 11:271–279, Copyright © 1991, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

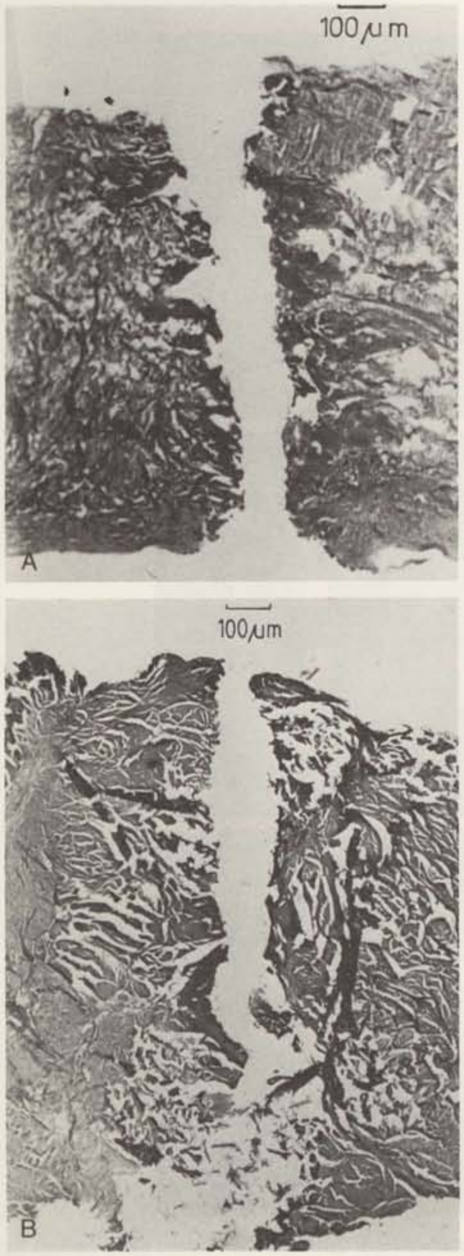

Figure 8. *(A)* Histologic appearance of excimer laser-treated meniscus, showing only a small border zone of thermal coagulation necrosis covering the margin of the crater. The dark spots are in the original stain violet, indicating coagulation necrosis. (original magnification ×90.) *(B)* Histologic appearance of Nd-Yag laser-treated meniscus demonstrating thermal damage with carbonization thermal tissue necrosis, vacuolization, and fiber disruption. In the lumen of the crater, carbonized debris can be seen. (original magnification ×90.) (*From* Buchelt M, et al: Excimer Laser Ablation of Fibrocartilage: An In Vitro and In Vivo Study. Lasers Surg Med 11:271–279, Copyright © 1991, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

rehabilitation. Currently, only the KTP (potassium titanyl phosphate) has Food and Drug Administration (FDA) approval for percutaneous discectomy, which reduces the pressure inside herniated lumbar discs by vaporizing the nucleus pulposus. The CO_2, Ho-YAG, and Er-YAG lasers also have proved to be a viable alternative through investigative trials.

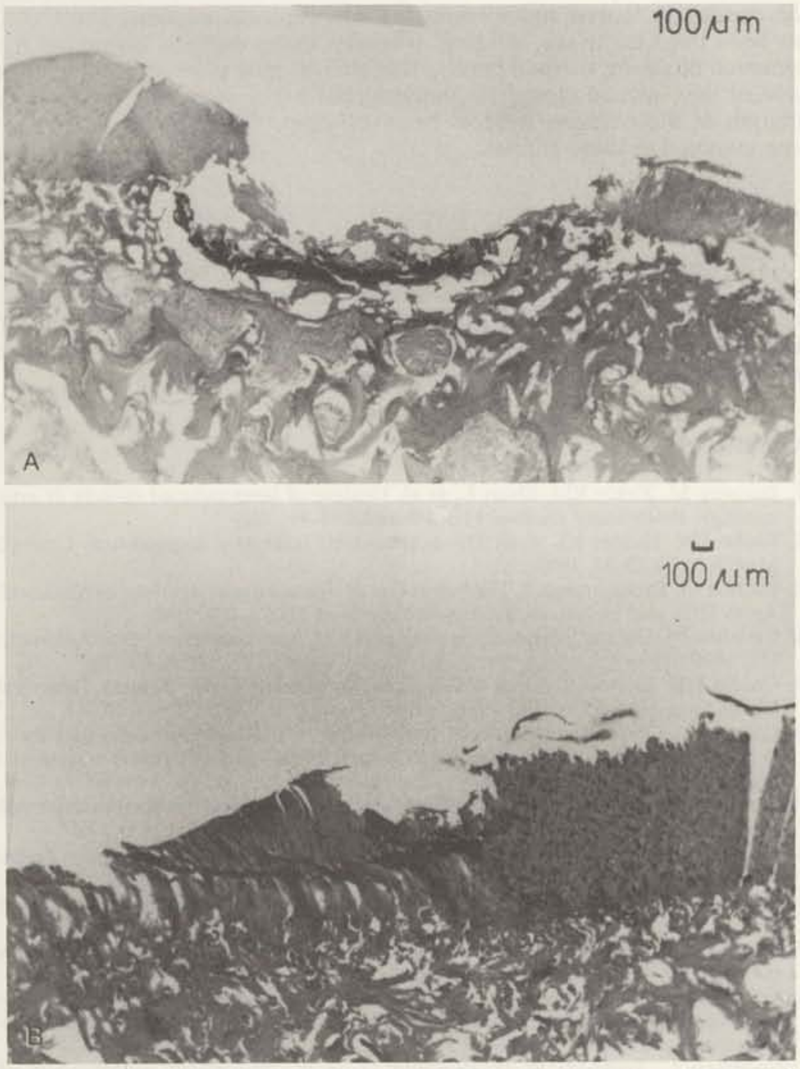

Figure 9. *(A)* Tibial surface after excimer laser ablation showing only minimal degenerative changes and small lesions in the cartilage. (original magnification ×36.) *(B)* Tibial surface after Nd-Yag laser ablation showing severe injury not only to the articular cartilage but also to the underlying bone, which is severely carbonized. (original magnification ×36.) (*From* Buchelt M, et al: Excimer Laser Ablation of Fibrocartilage: An In Vitro and In Vivo Study. Lasers Surg Med 11:271–279, Copyright © 1991, Wiley-Liss, Inc. Reprinted by permission of Wiley-Liss, a division of John Wiley & Sons, Inc.)

Lasers also have been investigated for their use in the removal of polymethacrylate for joint revisions.[14] Previously used surgical instrumentation caused excessive peri-articular damage when the old implant was removed. This tended to loosen and weaken the newly placed implant. The CO_2 laser has been used for tissue welding, whereby living tissue is connected by the formation of strong thermal bonds. This shows great promise for the advancement of new wound closure techniques, but many surgeons have found the strength of the collagen weld to be insufficient.[8] The Er:YAG laser also has been involved in these studies.

SUMMARY

The use of various lasers in medicine and surgery has progressed considerably. Obviously, the sheer number of lasers being used both clinically and experimentally indicates a great potential for further advancement and refinement in technique and surgical outcomes. Although the medical field has come very far accepting and using the laser, there is still a long way to go.

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