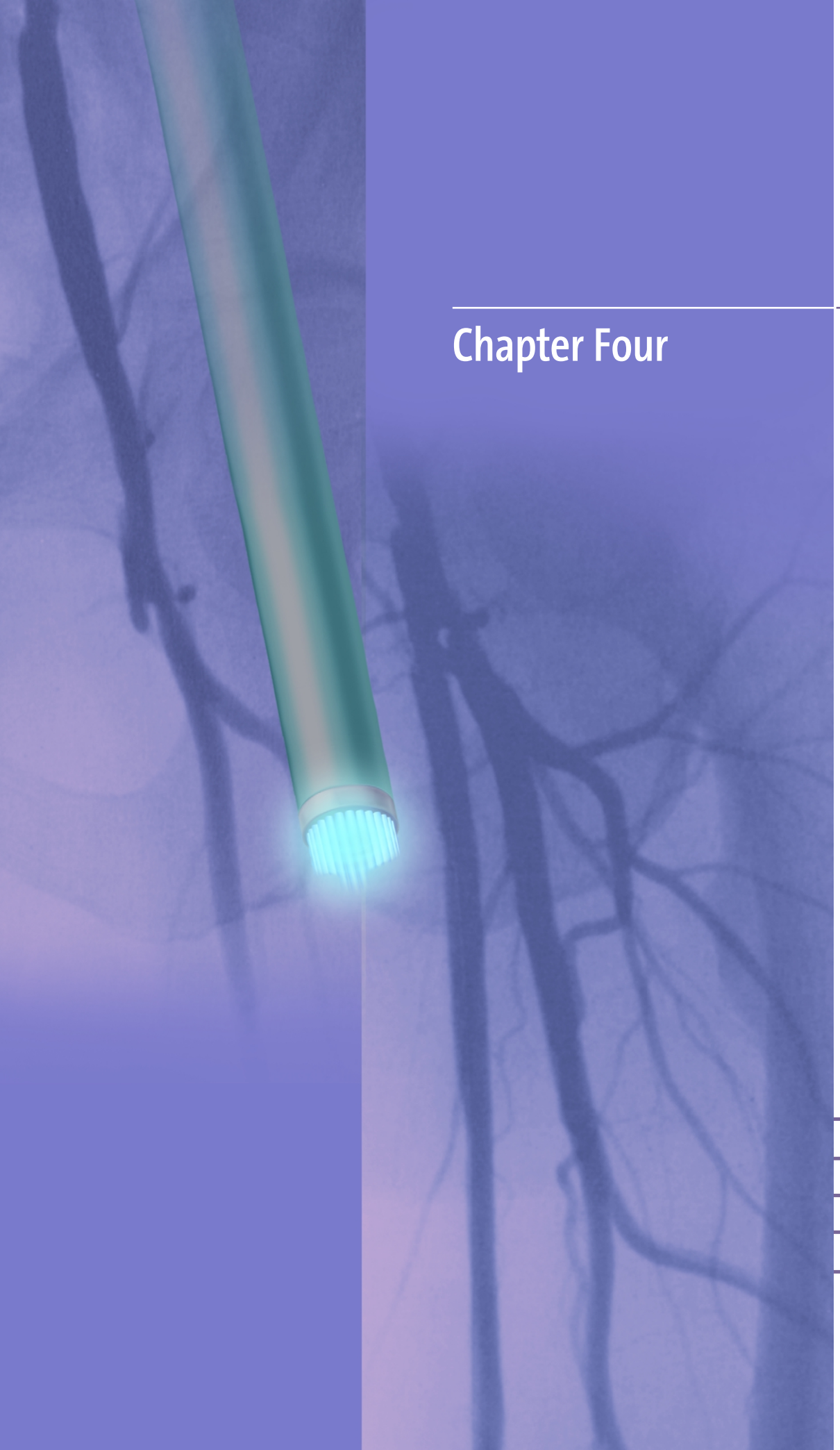


Chapter Four

Laser Physics

The excimer laser has unique properties that make it ideally suited to debulk atheromatous and thrombotic arterial blockages. To understand its effect in the arterial system, it is important to understand some basic laser physics. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. However, there are many types of lasers, distinguished by the wavelength of the emitted light, the effective power of the light beam, and whether the light is pulsed (like a flashbulb) or continuous (like a light bulb). The effectiveness of a given laser for intra-arterial applications depends on how the light interacts with tissue inside an artery.

8

Light
Amplification by
Stimulated
Emission of
Radiation

The basic concept of laser atherectomy is to apply light energy directly to the arterial plaque, thereby altering the plaque in some helpful way, without damaging the surrounding artery. Lasers suitable for intravascular use produce an intense monochromatic light beam that can be delivered through fiberoptic catheters to a small area of tissue with great precision.

The first parameter that defines this laser/tissue interaction is wavelength. Each laser type emits a characteristic wavelength that is determined by the gain medium inside the laser (Figure 4.1).

The most important parameter in determining the biologic effects of the light on tissue is penetration depth, or how deeply the light propagates into the tissue. This parameter, typically expressed as the absorption depth, or the distance over which the tissue absorption diminishes the light to 37% (1/e) of its original intensity, is determined only by the wavelength and the tissue. For precise work, the penetration depth must be as small as possible, to ensure that effects are localized to the point where the beam is applied.

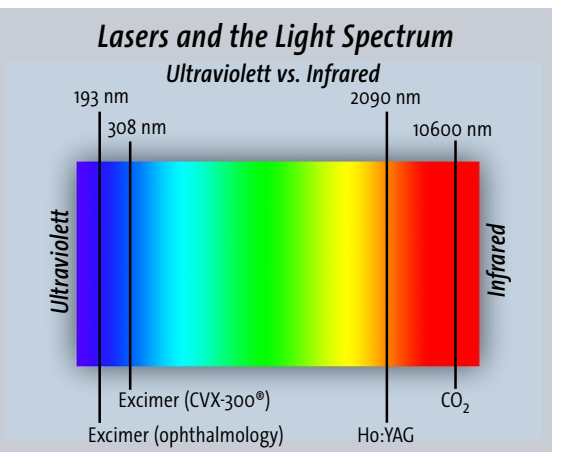
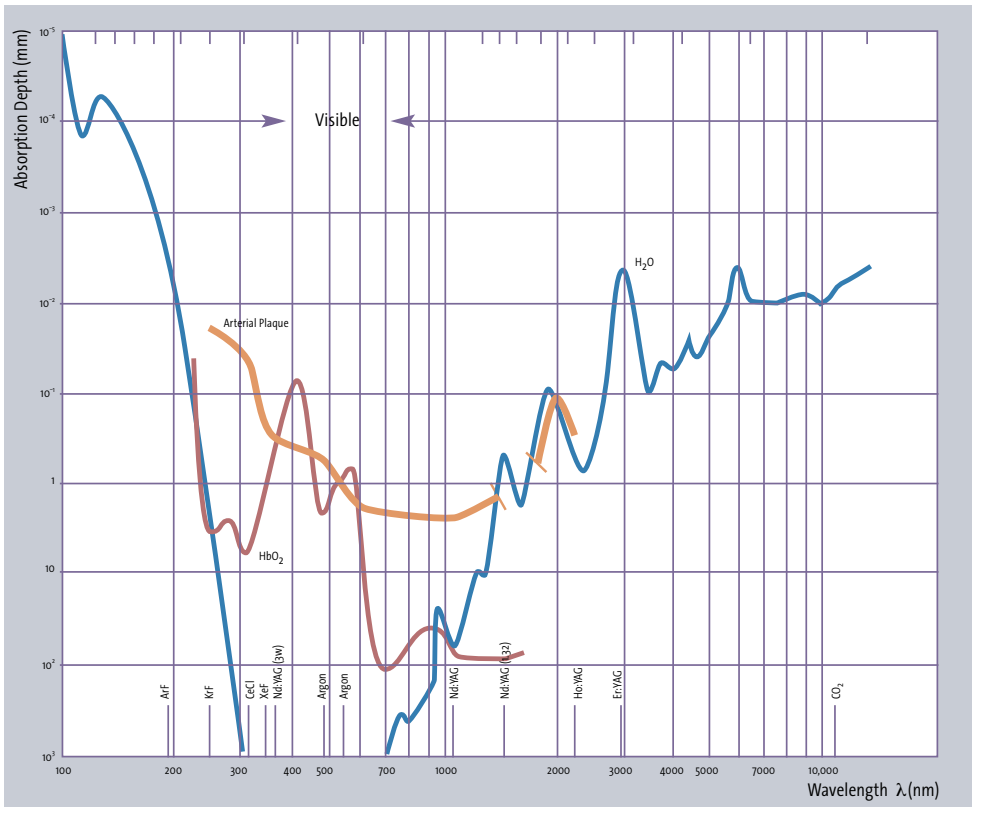


Figure 4.1: Lasers and the Light Spectrum

Figure 4.2: Absorption Depth by Wavelength



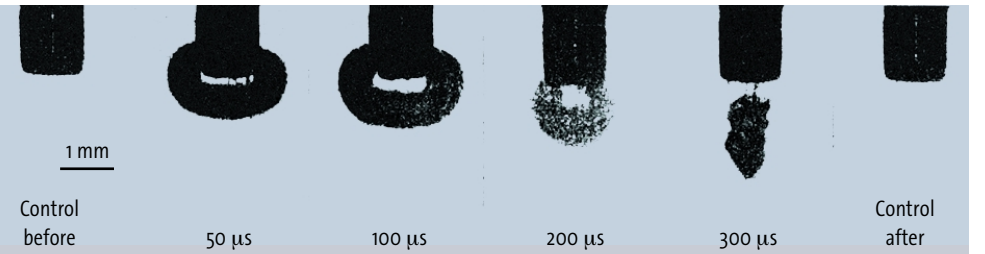


Figure 4.3: Formation of a steam bubble is necessary for pulsed laser ablation. This transient bubble forms on each laser pulse, grows to a maximum diameter roughly 50% larger than the catheter tip in about 150 microseconds, and collapses completely in another 100 microseconds as the steam cools and condenses.

Reprinted with permission from van Leeuwen TG, et al. Intraluminal vapor bubble induced by excimer laser pulse causes microsecond arterial dilation and invagination leading to extensive wall damage in the rabbit. Circulation 1993; 87:1258-1263.

Picking a particular wavelength to use in vascular tissue is fairly straightforward, once the typical absorption spectrum of tissue is plotted. In the near-infrared regions, between 2000 and 3000 nm, water is the dominant absorber; the light penetration depth varies from about 1 mm to .1 mm over this region. At the other end of the spectrum, in the UVB region near 300 nm, the absorption depth is shallow, owing to absorption by cellular macromolecules. At 308 nm, where the XeCl laser emits, the typical absorption depth is about .05 mm (50 micrometers). The further advantage of using UVB light lies in its ability to break molecular bonds directly, by a photochemical process. Each photon of 308 nm light carries enough energy to break a single carbon-carbon bond. Delicate measurements in tissue indicate that about 2% of the UVB photons absorbed by the proteins and lipids in cells actually breaks bonds, which weakens or lyses cellular structures.[1] This direct lytic action is a unique feature of using ultraviolet light. Figure 4.2 illustrates the effect of laser wavelength on absorption depth.

The next parameter in light/tissue interaction is pulse width. For all lasers, most of the light energy absorbed by the tissue is converted to heat almost instantly. To use pulsed lasers, such as the XeCl excimer laser, successfully, the thermal effect must be confined in the irradiated tissue. That is, the laser pulse must deliver its energy in a time span much shorter than it takes for the heat to diffuse away from the tip of the catheter.[2] Once thermal confinement is assured, tissue ablation can be achieved by forcing the tissue to absorb enough energy in one pulse to vaporize the most volatile liquid in the cells – water. This is accomplished by transmitting sufficient energy per pulse, through each fiber in the catheter, to ensure that the water content of the tissue in the thermal confinement zone under each fiber vaporizes. With the XeCl laser, the cell structures are first weakened by photochemical bond breaking, and then the cells explode when their internal water turns into steam. This leaves subcellular debris, and a shallow crater under the catheter (Figure 4.3). The debris washes downstream without embolizing distal capillaries, and the catheter tip advances into the crater. On the next laser pulse, the process repeats, allowing the catheter tip to nibble through the tissue, as each laser pulse removes a thin layer of tissue at the bottom of the crater. For XeCl laser catheters, the layer removed by each pulse is about 10 micrometers thick.

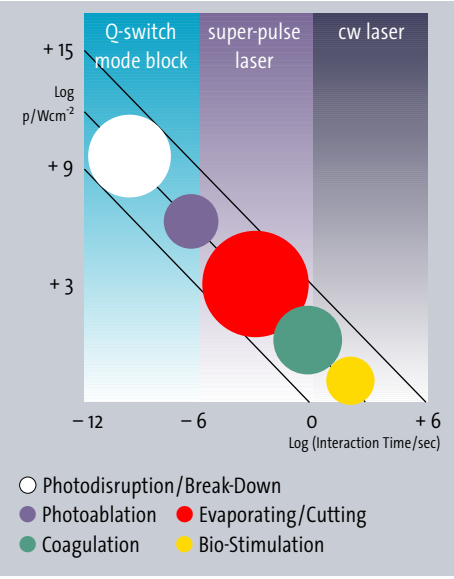


Figure 4.4: Effect of Laser Energy Wavelength by Interaction Time and Energy Density

One last parameter of light/tissue interaction is average power (Figure 4.4). Ideally the absolute minimum of heat would be deposited in the artery, since the typical response of arterial wall to thermal injury includes proliferative healing and restenosis. The minimum pulse energy for a pulsed laser system is determined by the penetration depth of the light and by the need to form a steam bubble on each shot; effectively, this creates a unique threshhold energy density for each laser type. For XeCl lasers the threshhold is about 35 mJ of energy per square millimeter (mJ/mm^2) of optical fiber in the catheter tip. A typical 2 mm diameter excimer laser catheter has about .71 mm^2 of fiber and delivers 25 mJ of energy per pulse at the minimum fluence. Delivering significantly more energy than this creates a more violent reaction in the tissue (which can be advantageous in particularly tough or calcified lesions) but deposits greater heat in the process.

Continuous Wave Lasers

Medical lasers have been evaluated for the treatment of the most complex peripheral disease since the mid-1980's. Early clinical applications of laser angioplasty in severe atherosclerotic stenoses and occlusions utilized continuous-wave (CW), hot-tipped lasers, such as the Argon or the Nd:YAG lasers. In contrast to the pulsed, 308 nm excimer laser, with continous wave laser systems light energy is constantly converted into thermal energy, which diffuses into and injures the surrounding tissue. Total thermal energy is transferred to the metal cap at the end of the probe resulting in temperatures in excess of 450 degrees C (Figure 4.5). Furthermore, the catheter probe becomes covered by a layer of carbonized blood after the first laser shot. The problem is compounded in Argon lasers that employ a wavelength that is actively absorbed by hemoglobin. This layer of carbonized blood absorbs the laser energy and prevents direct

Figure 4.5: Continuous Wave Nd:YAG Laser Probe

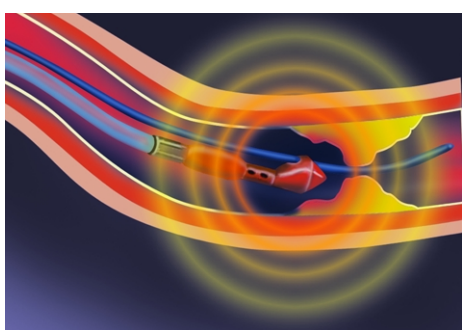


Figure 4.6: Continuous, Hot-Tip Probe Resulted in Vessel Charring

laser tissue interaction. Tissue ablation is achieved by a denaturation of the tissue followed by carbonization and vaporization. CW lasers also failed to ablate or penetrate calcified plaques. Despite a high technical success rate, these early experiments with thermal, continuous wave lasers resulted in significant complications such as aneurysm formation, late perforations and a high restenosis rate (Figure 4.6).[3-7] As a result, continuous wave laser systems have been abandoned for arterial applications.

Xenon Chloride (XeCl) Excimer Laser Operation

Because of the shared acronym LASER, the negative clinical outcomes of continuous wave lasers were associated with the newer excimer laser systems, despite signficant differences. A thorough review of the properties of the excimer laser will eliminate this confusion. Excimer lasers use a mixture of gases to form the lasing medium. One element of the mixture must be a rare gas (Ar, Kr or Xe) and another is typically a halogen (F or Cl). The wavelength emitted by the excimer laser is determined by which rare gas - halogen pair are chosen: XeCl lases at 308 nm, KrF lases at 248 nm, ArF lases at 193 nm, etc. In a typical XeCl laser, Xe and HCl gas are added in small quantities to a buffer of neon. To make the laser emit light, a concentrated pulse of electricity is discharged through the gas in a matter of a few nanoseconds. In a typical medical XeCl laser, the amount of electrical energy discharged per pulse is about 20 Joules, of which approximately 0.3 Joules emerges as ultraviolet light. The rest of the electrical energy is converted to waste heat inside the laser.

When the electrical discharge runs through the laser gas on each pulse, some of the electrons collide with the Xe atoms and form ionized xenon, Xe$^+$. Other electrons collide with HCl, dissociating the molecule into H and Cl atoms. Still more collisions produce the ion Cl$^-$. With a little help from the neon buffer atoms, the Xe$^+$ and Cl$^-$ ions unite to form a unique dimer (two-atom molecule) in an excited state, XeCl*. When an ultraviolet photon strikes the excited dimer ("excimer"), the XeCl* is stimulated to emit its excitation energy as another photon. As each excimer molecule adds more photons to the light field, the laser pulse grows exponentially until it bursts forth from the output end of the laser. Meanwhile, the de-excited molecule XeCl falls apart, into Xe and Cl, which are recycled by the electrical discharge into more XeCl* excimer molecules. This entire cycle takes less than a nanosecond, and continues for as long as the electrical discharge in the laser gas remains strong.

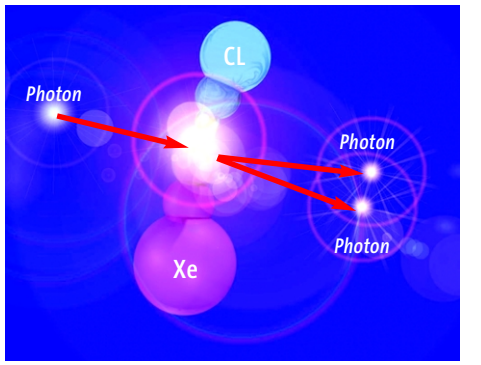


Figure 4.7: Excitation Process

In a typical medical excimer laser system, a metal vessel holds the XeCl gas mixture at several atmospheres of pressure. A high-voltage electrical system directs the discharge through the metal vessel and through a portion of the gas mixture inside. A small computer governs the function of the high-voltage circuit according to inputs from the user, such as how many pulses per second to deliver and how much laser pulse energy to launch into the proximal end of the fiberoptic catheter. Since the catheters are made of insulating materials, such as quartz and polymers, only the ultraviolet light (no electric current or heat) is conducted by the catheter to the target tissue.

Fiberoptic Catheters

From the proximal end (where the catheter plugs into the laser) to the distal end (where the catheter tip contacts the lesion) an excimer laser catheter is about three meters long. The outer skin of the catheter surrounds a flexible fiberoptic cable, made of high-purity silica fibers. A typical 2-mm diameter catheter has 240 individual fibers, each one with a core diameter of 61 microns, approximately the size of a strand of human hair. At the proximal end, the fiber bundle is held in a connector, where the laser beam is launched into the fibers. The fibers conduct the laser light to the distal end of the catheter, where the fibers terminate at the catheter tip. At the distal tip, the fibers are arranged around a guidewire lumen, which is rounded and polished. During tissue ablation, the polished fiber ends are in direct contact with the tissue. The UV laser light emerges from individual fibers, penetrates about 50 micrometers into the tissue and is absorbed by the cells; the light does not deflect to the side or penetrate deeply ahead of the tip.

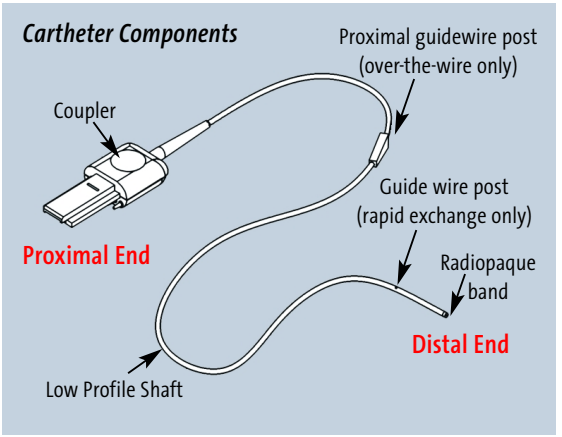


Figure 4.8: Excimer Laser Catheter

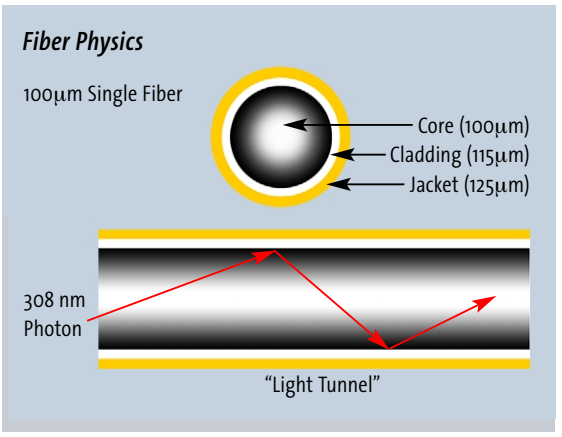


Figure 4.9: The core/cladding interface provides a mirrored surface allowing the photon to travel down the fiber optic strand

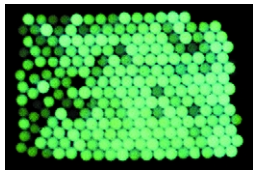


Figure 4.10: Fiber bundle shape at the catheter coupler

Figure 4.11: Catheter Distal Tip

The 308 nm excimer laser facilitates the successful treatment of the most severe peripheral disease by ablating and removing thrombus and other obstructive material. Excimer laser debulking transforms a diffuse, polymorphous lesion into a more easily ballooned stenosis with fewer complications. By removing the thrombus burden common to diffuse disease, the laser reduces the potential for distal embolization. Further, the laser may reduce the number of dissections, resulting in the need for fewer stents.

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