Section 3
ADVANCED TECHNOLOGY DEVELOPMENTS

3.A Lasers in Angioplasty

The condition known as hardening of the arteries or atherosclerosis is the blockage of the arteries by plaque. When 80-90% of the cross-sectional area of a coronary artery is occluded, the flow of blood is seriously impaired and the risk of cardiac arrest is considerably increased. Figure 20.20 is a photograph of some actual arterial occlusions.

Presently, there are several operations that may be performed to restore blood flow in occluded arteries. One of these—arterial bypass surgery—is one of the most commonly performed operations in the United States today. In bypass surgery, arterial grafts are made to reroute blood flow around blockages. Another procedure, endarterectomy, is used especially to excise blockages from the carotid arteries.[1] In this procedure blood flow is blocked in the area, the artery is opened longitudinally, and the plaque is "peeled" from the artery wall. Then, the artery is reclosed and blood flow is restored.

These are long operations that pose moderate to high risk to the patient, and they are expensive to perform. Postoperative recovery periods are lengthy and often painful. Accordingly, there is continuing interest in developing more attractive alternative treatments for arterial blockages.

In this respect the laser has attracted a great deal of interest recently as the key instrument in a surgical system to treat arterial

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Fig. 20.20
Photograph of cross-sections of human arteries showing various degrees of occlusion due to atherosclerosis.

occlusions. In concept this system channels high-intensity laser radiation through a small optical fiber to burn away the occlusion. The optical fiber is combined with an endoscope for monitoring the process and delivered to the occlusion site through a four-port catheter, introduced into the body through a small shoulder or groin incision and threaded along the arterial passageways. The other two ports will be used for local blood-flow blockage and for suction and flushing. The diameter of the entire catheter device must be less than 2 mm.

Before laser surgery can be performed in a clinical setting, or even on a laboratory animal, it is necessary to determine the effects of laser radiation on arterial plaque and on healthy tissue as well as complete the development of the system described above. We have carried out and documented tissue-irradiation tests here on samples of plaque and healthy tissue. Documentation includes both photographic records and histological analysis. Damage thresholds have been determined for direct irradiation from the laser source and for radiation delivered through an optical fiber.

For direct exposures, laser light was focused onto the specimen with a long focal length lens at an angle of incidence of approximately 60°. For fiber exposures a microscope objective was used to couple the laser light into a 100- to 200-μm-diameter quartz fiber. The fiber output tip was brought to within 2 mm or less of the specimen at an angle of 90° to the surface.

During preliminary direct-exposure tests, we observed that a 514-nm, argon-ion laser operated at a power output of 3-W cw was much more effective on plaque specimens than a similarly focused, 1064-nm, mode-locked, Nd:YAG laser operated at 7-W output. For this reason only the argon-ion laser was used for subsequent testing.

Atherosclerotic plaque is a result of cholesteric deposits on artery walls. Four types of plaque are found in human arteries. Fatty streak plaque is soft and yellowish. Subintimal calcified plaque is a hard deposit under the artery surfaces, the intima. Calcified plaque is a hard deposit on the artery wall. Complicated plaque is calcification on the artery with ulcers and craters and coagulated blood called thrombus underneath the surface.

Damage thresholds were different for the four kinds of plaque. For specimens submerged in distilled water, the focused argon-ion-laser damage thresholds for direct exposure were found to be 9.6×10^3 W/cm^2 for fatty streak plaque, 1.3×10^4 W/cm^2 for subintimal calcified plaque, and 1.4×10^4 W/cm^2 for calcified plaque and complicated plaque. The damage threshold for healthy aortic tissue was 8.5×10^3 W/cm^2.

When calcified plaque was contacted by a 200-μm-diameter optical fiber, the damage threshold was lower—2.5×10^3 W/cm^2. When the fiber tip was pulled back from the specimen, however, the illumination spot spread out, reducing the intensity. As a result, it was necessary to raise the laser power and increase the exposure time in order to damage the plaque.

To evaluate the damage to plaque for different exposure times and conditions, an investigation was carried out on an atherosclerotic aorta which was cut into four longitudinal strips. Two strips were exposed to focused laser light directly, one dry and one submerged in saline solution. The other strips were exposed to laser light delivered by an optical fiber, one dry and one submerged in saline solution. Power was held constant in all cases while time was varied. Each site was photographed and analyzed histologically (Fig. 20.21).

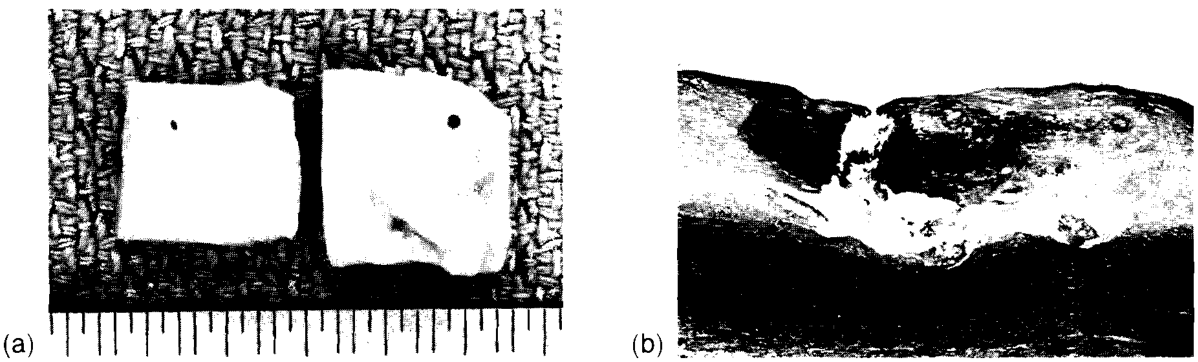

Fig. 20.21
Details of laser tests on atherosclerotic aorta samples:
(a) Photograph of irradiated samples.
(b) Photomicrograph of section of laser crater.

When a fiber was used for delivering light, it was at a 90° angle to the specimen. In actual surgery, unless there is a total, or near total, occlusion, the fiber will be at shallower angles. In order to see the effects of different delivery angles on the plaque, exposures were made at several angles of incidence. Exposure time and power out of the fiber were held constant. Each site was photographed and will be analyzed histologically.

Next, the difference in damage due to light delivered by a cut fiber tip and a rounded fiber tip was considered. Submerged plaque was exposed for times varying from 2-10 minutes. Twelve exposures were done in all, six with delivery by a cut tip and six with delivery by a rounded tip. Each site was photographed and will be analyzed histologically.

Histological slides of dry-state, direct exposures show that much less power is needed to do the same amount of damage in a dry state than in a wet state. For exposure times ranging from 1-60 s, destruction was confined to the plaque layer [Fig. 20.21(a)]. A 60-s exposure showed complete penetration of a 2-mm layer of plaque, but no destruction of healthy aortic tissue underneath the plaque. At an exposure time of 2 min, we began to see penetration of the healthy aortic wall. At 4-6 min there was complete penetration of the artery wall. No further histological analyses have been completed at this time.

When removing plaque from coronary arteries on the heart wall, it may not be possible to maneuver the entire catheter into those arteries due to restrictions on size and flexibility of the catheter. Therefore, the negotiability of coronary arteries with an optical fiber was investigated using the heart of a pig. A pig's heart was chosen as a model because it is similar to the human heart.

To negotiate the coronary arteries, sharp turns of almost 90° must be made by the fiber shortly after entering the arteries from the aorta. A 200-μm quartz fiber was found to be too rigid to make these turns easily. A 125-μm quartz fiber, on the other hand, was found to be very flexible and easily capable of making the sharp turns. Later, negotiation of coronary arteries will be practiced with a new 1.5-mm endoscope. It will only be necessary to maneuver a fiber and endoscope 3-5 cm into the arteries since occlusions occur most frequently at the forks of the vessels and other areas of turbulent flow (Fig. 20.22). Once the fiber has been maneuvered into the coronary arteries, plaque buildups must be identified with the endoscope. When the plaque is identified, the laser will be turned on and the plaque destroyed. Should the endoscope prove to be too large or too inflexible to negotiate the twists and turns of the coronary arteries, the fiber's progress through the coronary arteries may have to be watched using ultrasound imaging.

Although the 125-μm fiber is flexible enough to negotiate the arterial pathways, it is probable that some sort of guidance system will be necessary to accomplish this. A guide wire attached very near the end of the fiber could be used for steering, but this makes the fiber tip rigid and bulky. Another difficulty in maneuvering is the square edges of the fiber which catch and grab the artery walls. This not only makes it much more difficult to maneuver the fiber, but it also increases the danger of perforating the artery wall. To help the fiber maneuver more smoothly, the end was rounded using an oxygen-acetylene torch. The rounded end moves more smoothly through the coronary arteries and also helps focus the emerging light. This makes lesioning plaque more efficient since energy is not wasted doing inadvertent damage to surrounding tissues.

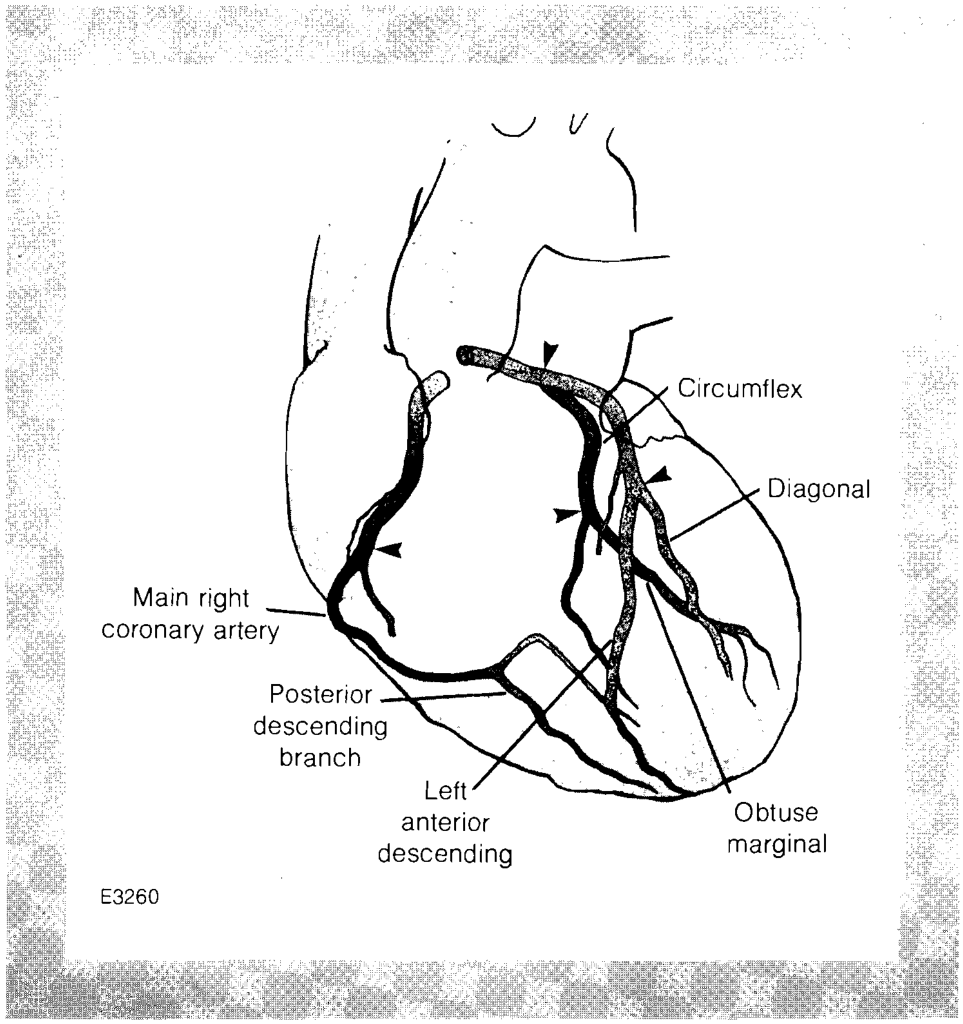

Fig. 20.22
Usual locations of occlusions in coronary arteries.

We conclude that it is feasible to destroy atherosclerotic plaque using an argon-ion laser with an optical fiber for delivery with 3 W or less of laser power. The Nd:YAG laser showed no plaque damage at 7-W output; higher power was not investigated. The wet-state damage thresholds were found to be between 8.5×10^3 W/cm^2 and 1.4×10^4 W/cm^2 at 514 nm. An absorption spectrum of a solution of 1.748×10^{-2} M plaque (dissolved in chloroform) indicates that 450 nm is near the optimum wavelength for plaque destruction. The threshold of damage of plaque was not found to be more than 1.4×10^4 W/cm^2; however, at the same power level, removal of blockages would have taken an inordinate amount of time. The use of higher power as well as shorter wavelengths will be investigated in the near future. Actual laser surgery on animals is also planned for the near future. Once the optimum techniques are found for the removal of arterial plaque, and the patient's safety is guaranteed, this new laser surgical procedure can be performed on humans. At first, procedures will be confined to larger arteries, such as the aorta and the carotid, and femoral arteries. It will not be possible to remove plaque from small coronary arteries until the equipment has been miniaturized. Hopefully, lasers combined with fiber delivery systems will be used clinically to remove arterial plaque in 6-12 months.