Recanalisation of coronary atherosclerotic obstruction by laser radiation


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KEY WORDS: Atherosclerotic obstruction, coronary artery disease, vascular thrombosis, laser recanalisation, fiberoptic laser catheter.

The potential use of lasers to vaporise atherosclerotic plaque obstructions is rapidly becoming recognised. The properties of laser light are unique in that it is coherent, monochromatic and collimated. It can be focused into tiny, flexible optical fibres made of silica which can be inserted into a blood vessel and passed intravascularly to an area of obstruction. The ease of plaque penetration is largely dependent upon the absorptive characteristics of the plaque's substances (i.e., lipid, hyaline or calcium), beam focus, power intensity and duration of laser exposure. Laser radiation of fibrous areas and especially calcified areas causes remnants of charred debris in the irradiated pathway, whereas no debris is found when exposure is focused over a primarily fatty plaque. The laser can also be utilised to canalise the organised thrombus. Since blood clots are comprised of red blood cells which contain haemoglobin pigments, the red clot is readily absorbed and thus vaporised by argon laser energies. Potential complications of recanalising coronary obstructions include perforation, aneurysm formation and red cell damage. Improvements in intravascular laser delivery systems are required before clinical application. The fibre-optic catheter to view and target obstructed sites and the use of the laser cautery cap to vaporise the plaque or thrombus will be helpful in this regard.

The first laser was developed in 1960, and the medical use of this new technology was quickly recognised by ophthalmologists for retinal photocoagulation and by surgeons and dermatologists for destroying cancerous tissue, haemangiomas, and other cutaneous lesions. With the development of fiberoptic endoscopes, the gastroenterologists soon had the ability to use lasers to photocoagulate bleeding ulcer sites, and the pulmonary bronchoscopists could irradiate endotracheal bronchial cancers. Recently the potential of lasers to dissolve atherosclerotic plaque obstructions has been recognised and is under extensive investigation.

Basic principles of laser

The laser emits photons or electromagnetic waves, with properties similar to light from an ordinary light bulb. However, laser light differs from ordinary white light in that it is monochromatic: the laser generates photons with a narrow band of wavelengths. It is also coherent: the photons are in phase with each other and coordinated in time and space. Furthermore, it is collimated, and the light waves are parallel to one another and move in one direction. Thus this highly collimated and coherent light can be packaged and focused into a very tiny but powerful beam, capable of vaporising atherosclerotic plaque obstruction.

The typical laser consists of a resonant cavity which contains the active lasing medium. The latter is bounded by parallel mirrors at both ends; one end fully reflective and the other end only partially reflective, allowing the escape of laser light for medical application (Figure I). The atoms in the active medium can be primed electronically to an excited energy state. When an atom returns to a lower energy state, a photon is spontaneously emitted. When this photon interacts with another atom that is in a high energy state, this...
Figure 1 The lasing medium is bounded by a 100% reflective mirror at one end and a 95% reflective mirror at the other end. Primed by an electric current to high energy states, the atoms in the lasing medium, upon return to a lower energy state, emit photons which result in emission of highly coherent light.

results in the production of two photons having the same frequency and travelling in the same direction. These two photons can stimulate other high-energy atoms, thereby emitting four photons, and so on. Thus the term 'laser' was developed from the acronym fight amplification by stimulated emission of radiation.

There are a variety of different types of lasers; each generates a narrow band of wavelengths specific to the lasing medium. The most common lasers used for medical applications are the argon, carbon dioxide (CO₂) and neodymium and yttrium-aluminium-garnet (Nd: YAG). The first two are gas lasers and the last is a solid-state laser. The argon laser produces wavelengths of 0.488 and 0.514 μm in the green part of the visible spectrum. The Nd: YAG and CO₂ lasers have wavelengths of 1.06 μm (near infra-red) and 10.6 μm (middle infra-red), respectively. The argon or Nd: YAG laser energies can be transmitted by flexible optical fibre made of silica (Figure 2). The use of these lasers upon the atherosclerotic plaque is based on the transformation of light energy into heat, which causes the destruction or removal of plaque by coagulation, carbonisation, and volatilisation.

The coronary atherosclerotic plaque

Since the laser destruction of plaque is in part related to the thermal and optical properties of the plaque, it is important to understand the physical and biochemical composition of the atherosclerotic obstruction. Characteristically, the atherosclerotic plaque is a raised, pearly grey to yellowish grey lesion causing the...
intima to bulge into the vascular lumen. It is comprised of mixtures of three main ingredients: lipid, collagen and calcium. The main cellular components are myointimal cells, myofibroblasts and lipid-filled macrophages. The plaque's dense connective tissue consists mostly of collagen fibres with infiltrations of macrophages and other white blood cells. Deep inside the plaque are debris from dead or dying cells and varying amounts of lipid material. Biochemical analysis indicates that the plaque is composed of heterogeneous mixtures of cholesterol, cholesterol esters, lipoproteins, proteoglycans, phospholipids, glycerol esters, and calcium salts.

While the plaque can totally occlude a coronary artery by itself, more often it predisposes the artery to obstruction by the formation of a vascular thrombus. Acute myocardial infarction is highly associated with a sudden occlusion of a coronary artery by a fresh thrombus, which is a complex aggregation of blood platelets, white cells and red cells in the fibrin network. The absorption of laser energies by each of these different substances in the obstructed vessel may differ according to the wavelength emitted by the laser.

Effects of lasers on coronary atherosclerotic plaque obstruction

Studies demonstrating the effects of laser radiation upon human coronary atherosclerotic obstructions from postmortem hearts have been reported. Laser energies from a variety of commonly used medical lasers, including the argon, Nd:YAG and CO₂, are capable of penetrating and vaporising atherosclerotic plaques. The ease of penetration largely depends upon the absorptive characteristics of the plaque substances, beam focus, the power intensity and the duration of laser exposure.

Due to the plaque's heterogeneity spectrophoto-metric absorption studies to characterise the plaque are difficult to obtain. However, vaporisation is more rapid in plaques containing lipid than in plaques with heavily calcified deposits. Moreover, laser radiation of fibrous areas and especially of calcified areas caused remnants of charred debris in the irradiated pathway, whereas this was usually not the case when exposure was focused over a primarily fatty plaque. In general, the higher the power intensity, the longer the exposure time, and the more focused the laser beam, the greater is the plaque penetration. The total energy (joules) delivered to the plaque is the product of the power (watts) and the duration of exposure (seconds). If power is kept constant, the larger the surface area irradiated, the lower the concentration or power density. Thus, increasing beam diameter twofold will increase the surface area by four times and decrease power density to one-quarter. Conversely, reducing the beam diameter by one-half will decrease surface area to one-quarter and increase power density by a factor of four.

Laser radiation penetrated plaque better under dry than wet conditions. Under dry conditions CO₂ laser produced plaque damage with just 2-5 joules of total energy. However, it took more than 5 joules to reproduce identical plaque damage when the vessel was immersed in saline solution. Furthermore, the application of certain dyes and pigments (e.g., fluorescein, sudan black, haemoglobin) may increase laser absorption and enhance plaque damage. Should these or other substances prove to bind or stain plaque, a lower-power beam can be utilised, lessening the risk of thermal injury to the adjacent normal vascular wall.

The arterial response to laser radiation was studied in animals fed a hyperlipidemic diet to induce atherosclerosis. Laser energies of less than 10 joules (exposure times of 0.1-0.5 s at 1-20 W) produced vaporised craters of approximately 1 mm in depth and 2 mm in diameter in surgically exposed atherosclerotic vessels. The animals were followed for 2 days to 8 weeks. Early after laser exposure, the crater was covered with platelet–fibrin thrombi. The surface of the crater had re-endothelialised with some fibrin and platelets remaining by 2 weeks, and was still visible as a re-endothelialised crater by 8 weeks. Moreover, no significant thrombogenic complication was observed.

Effects of laser on thrombotic obstruction

Since blood clots are comprised of red blood cells which contain haemoglobin pigments, they are readily absorbed by argon energies. The argon laser is capable of vaporising and penetrating thrombus in a linear dose–response fashion. The longer the clot, the higher the power intensity or beam exposure time needed to canalise the organised thrombus.

The thrombus can be further separated into red (whole blood plus fibrinogen plus thrombin) and white clot (fibrinogen plus thrombin). Argon energies penetrated red but not white clots. Since spectrophotometric studies demonstrate that the former (containing haemoglobin) but not the latter absorb light from the argon wavelength band, the argon laser provides the therapeutic modality for lysis of human red clot, while a different laser source is required for white clot dissolution. Furthermore, water attenuates argon energies, hence a fresh (wet and soft) clot, in
contrast to organised thrombus, may be better dissolved with a thrombolytic agent such as streptokinase, urokinase, or tissue plasminogen activator.

Potential adverse effects

To simulate clinical laser angioplasty, a flexible optical fibre used to transmit laser irradiation was inserted into a guiding catheter positioned by fluoroscopy in the coronary orifice in animals\(^1\). Argon energies approaching those used to dissolve atherosclerotic plaque and thrombotic obstructions were applied. Coronary perforation was a frequent complication, producing pericardial tamponade and haemodynamic and electrical instability\(^2\). Studies in atherosclerotic animals fed an atherogenic diet demonstrate the consequences of the laser beam transmitted by quartz fibre upon the vascular wall\(^2\). Muscular wall damage with aneurysm formation developed in half of the animals followed for several days\(^2\). These complications are common when catheter laser angioplasty is randomly applied without visualisation of the specific plaque target and/or using safe dose increments of power intensity and duration of exposure.

Furthermore, the transmission of argon energies into blood exposes human red blood cells to intense heat. Consequently, there was lysis of erythrocytes as reflected by a fall in haematocrit in cells subjected to direct laser exposure and thermal damage to the erythrocyte membrane of red blood cells in the surrounding medium, as shown by a rise in plasma haemoglobin\(^2\). Prolonged laser firing using the flexible quartz fibre immersed in a blood-filled vessel caused blood clotting at the fibre tip as detected by two-dimensional echocardiography\(^2\).

The laser cautery cap and its effects on vascular obstructions

Since laser radiation delivered by available flexible quartz fibres for vaporising atherosclerotic plaque obstructions presents risks to the operating personnel (i.e., retinal damage), as well as subjecting patients to complications such as vascular damage, aneurysm, and perforation, we have attempted to minimise these untoward problems of the beam straying and/or scattering from its target by mounting a metal cap at the distal fibre-optic tip\(^2\). The original idea was based upon our work in the late 1970s using an electrically heated metal cap device which was successful in dissolving atherosclerotic fatty fibrous plaques.

The metallic tip at its distal end was heated by laser energies from an argon--ion laser source and directed into the diseased human cadaver plaques\(^2\). The plaques were instantly vaporised on contact with the metal cap (Figure 3). The depth of penetration was largely dependent on the contact time and the physical characteristics of the plaque obstruction. Following the laser-heated metal cap treatment, there was no entrapped debris in the treated regions\(^2\). This differs from the situation following the shattering effect of vaporisation caused by direct laser free-beam radiation.

**Figure 3** Photograph depicting postmortem atherosclerotic coronary artery before (left) and after (right) vaporisation of atherosclerotic plaque using laser-heated metal cap.
Vaporisation of atherosclerotic obstruction with the fibre-optic laser catheter

Due to the importance of targeting plaques for laser vapourisation, a fibre-optic laser catheter was conceived by us in the late 1970s incorporating features of the balloon angioplasty catheter\[29\] and fibre-optic laser systems used in medicine at that time\[11\]. Designed for use in peripheral vessels, one version of the catheter was tested in arteries of living animals\[30\] and in animals implanted with human atherosclerotic vascular segments to determine its feasibility of simultaneous in vivo visualisation and laser vapourisation of atherosclerotic disease\[31\]. Another catheter assembly (3 mm outer diameter and 100 cm long) is connected to a viewing handpiece, which could be attached to a television monitor. This device has three hollow passageways extending from the handpiece to the catheter tip. These are channels for viewing, laser delivery and suction/flushing.

Early experimental work using this instrument demonstrated its ability to visualise and vapourise atherosclerotic plaques implanted in living animals\[32\]. By viewing the obstruction, the operator can direct the laser beam to the diseased target for controlled thermal therapy, avoiding the normal vascular wall and thereby minimising the risks of perforation and aneurysm formation. Moreover, the visualisation of the obstruction can help distinguish plaque from thrombus, which is important, since different energies may be required for laser absorption.

The use of this new laser technology may someday revolutionise the treatment of atherosclerosis. Vascular surgeons have begun early intraoperative work using lasers on diseased peripheral arteries. Gradual progress to smaller vessels, including the coronary arteries, is planned. Although the potential for dissolving coronary obstruction by phototherapeutic techniques is great, a further understanding of laser vascular consequences and improvements in laser delivery systems are needed before it is applied in man.

We thank Mr James Metcalfe and Mr Harry Miller for their support and Ms Leslie Silvernail and Mrs Irene Wong for their secretarial assistance. We also thank the San Francisco Laser Center for its generous support.

References


