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Vaporization of Atherosclerotic Plaques by Spark Erosion

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An alternative to the laser irradiation of atherosclerotic lesions has been developed. A pulsed electrocardiogram R wave-triggered electrical spark erosion technique is described. Controlled vaporization of fibrous and lipid plaques with minimal thermal side effects was achieved and documented histologically in vitro from 30 atherosclerotic segments of six human aortic autopsy specimens. Craters with a constant area and a depth that varied according to the duration of application were produced. The method was confirmed to be electrically safe during preliminary in vivo trials in the coronary arteries of seven anesthetized pigs. The main advantages of this technique are that it is simpler to execute than laser irradiation and potentially more controllable.

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In recent years, the use of lasers has been proposed for the improvement of perfusion through obstructed arteries (1–3). At present, several approaches can be distinguished depending on the type of obstruction. For example, argon laser-emitted wavelengths in the green part of the spectrum can be selectively absorbed by hemoglobin in fresh thrombi. This can be used to advantage as the vessel wall will be less affected by these wavelengths. When atherosclerotic material has to be removed, the selection of a particular type of laser is not so straightforward. Selective absorption at a particular wavelength by degenerated tissue has not been demonstrated. When atherosclerotic lesions can be stained selectively, a more refined application of the laser is feasible. Until now, the specific characteristics of the laser radiation, namely, its coherency and monochromaticity, have not been of decisive importance for the vaporization of atherosclerotic tissue. The only relevant variable for a successful application of the proposed laser types (4) is the energy density that can be obtained at the target area combined with maximal local absorption. Because carbon dioxide laser-emitted radiation (wavelength 10.6 μm) is strongly absorbed by water and biological tissue, this type of laser will produce the best results for tissue vaporization. Recently, appropriate optical fibers were developed for transluminal intravascular application (5). However, an intense and localized delivery of energy can also be reached with other (less expensive) techniques.

In this report, we describe the application of a spark erosion technique to vaporize atherosclerotic plaques in specimens of human aortas obtained at autopsy. Spark erosion is commonly used in the electrical discharge machining technique and is specially suitable for the fabrication of small metal parts. The removal of material is performed by local melting and vaporization of the metal caused by controlled electrical sparks between a stamp electrode and the material to be processed. In medicine the well known radiofrequency electrosurgical cutting technique partly uses the same fundamental erosion process but also incorporates desired side effects such as dehydration and coagulation of the treated tissue to achieve hemostasis.

For the application of the spark erosion technique the electrosurgical cutting technique was modified to minimize dehydration and coagulation and to accentuate tissue vaporization. In addition, pulsed, rather than continuous application is used to enable triggered delivery restricted to the refractory period of the ventricular cycle. In this way potential influence on the heart's electrical activity can be avoided.

Methods

Autopsy material. Segments of atherosclerotic human aortas measuring approximately 4 × 7 cm were obtained at autopsy from six patients (age range 61 to 83 years). These segments were treated within 2 days of autopsy. Until then, they were covered by a gauze, wetted with saline solution and kept at a temperature of 4°C.

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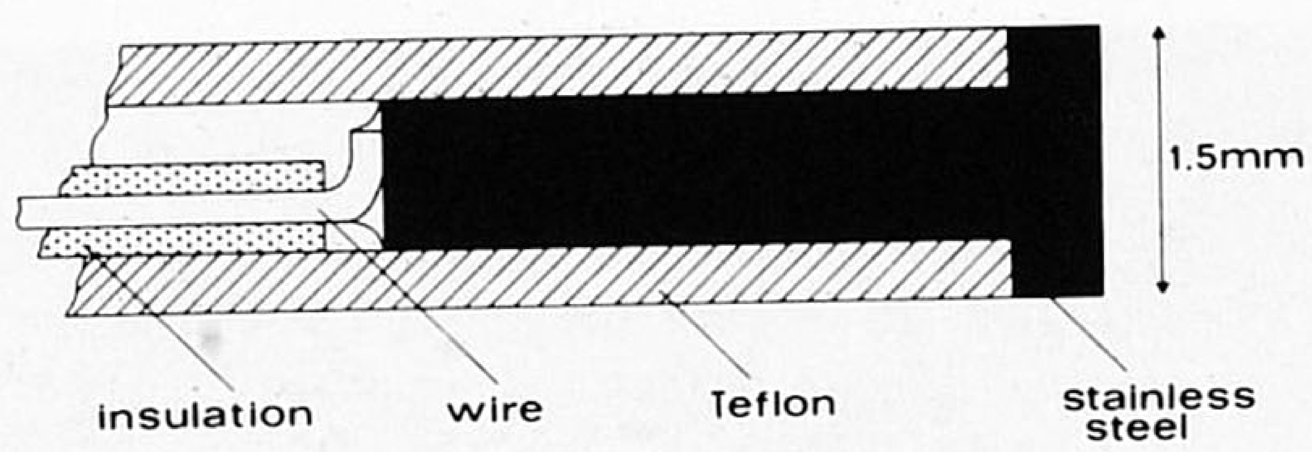

Figure 1. Schematic drawing of the spark erosion electrode used for the in vitro experiments.

Animal preparation. In a series of seven anesthetized closed chest pigs, tests were performed to study the effects of the spark erosion technique on the electrical aspects of the heart's activity. For this purpose, selective coronary catheterization was performed using a balloon angioplasty guiding catheter (8F). A flexible catheter (4F) with a wire electrode tip was passed through the lumen of this catheter and positioned 2 to 5 cm distal from the ostium in either the right, left circumflex or left anterior descending coronary artery. During the experiment, the electrocardiogram and aortic pressure (tipmanometry) were recorded continuously at a paper speed of 10 mm/s^{-1}.

Spark erosion. The electrical spark generator was designed and constructed in our workshop. For safety reasons, it is electrically isolated from the main voltage line. It has a balanced symmetric output stage coupled to the load by two series capacitors to prevent the primary delivery of any direct current. The output impedance equals 180 Ω. The generated square-wave voltage has a peak to peak value of 1200 V at a frequency of 250 KHz.

Trigger unit. For in vitro use, a manual command immediately activates the generator during a period of 10 ms. For different atherosclerotic lesions, the applied number of successive exposures was varied from 1 to 10, with intervals of 2 to 4 seconds.

For in vivo application, an external synchronizing signal is used in addition to the manual command. This signal is derived from the electrocardiogram by an R wave peak-detecting circuit. An adjustable time delay can also be added to the synchronization procedure such that the generator pulse occurs with a delay of 100 to 1,000 ms after the signal of the peak detector, sensing the R wave of the electrocardiogram.

Electrodes. For the in vitro tests of the spark erosion technique, the aortic segment and a return electrode (area 4 cm^2) were immersed in saline solution (0.9%). The spark electrode (diameter 1.5 mm) has an active 4 mm^2 area exposed to the tissue (Fig. 1). The distance between both electrodes varied from 2 to 10 cm. For the in vivo testing of electrical safety with respect to the heart's electrical activity, a subcutaneous needle (10 cm) functioned as the return electrode. Part of a flexible guidewire (diameter 0.4 mm) was used as the active electrode. To prevent perforation of the vessel wall, three small spherical epoxy resin droplets centered the electrode inside the lumen (Fig. 2). The resting length of the guidewire exposed to the blood is 2 mm.

Histologic study. After the in vitro tests with the spark erosion technique, the aortic segments were fixed in 10% buffered formalin. Samples of the treated lesions were dehydrated and embedded in paraffin. Sections perpendicular to the aortic wall were made at 5 μm and stained with hematoxylin-eosin.

Results

Aortic Segments

With the spark erosion technique, vaporized craters having a diameter slightly greater (1.6 to 1.7 mm) than that of the applied electrode could be easily created in human fibromuscular, collageneous and lipid-containing plaques. The depth of the craters varied with the total pulse time and was equal to 0.18 ± 0.1 mm times the number of applied 10 ms pulses. No difference in depth of the craters could be observed among the various types of lesions. During vaporization, small gas bubbles were produced in the target area.

Histology. Histologic examination of the treated fibromuscular or collageneous areas showed sharp edges of the vaporized craters and no necrotic debris within them. A small rim of coagulated tissue with a median thickness of 40 μm surrounded the craters (Fig. 3A).

In the plaques containing a significant amount of lipids, the edges of the craters were frayed and some residual coagulative material could be observed within. The coagulative zone was extended over a median distance of 200 μm. Vaporization of superficial atheromatous layers was associated with more thermal damage (Fig. 3B) than vaporization of buried atheromatous layers (Fig. 3C).

In the plaques consisting of lipid and small scattered calcifications, the lipid was destroyed and the calcareous particles were found as debris in the crater lumen. No effect could be observed in mainly calcified areas and these areas have not been analyzed.

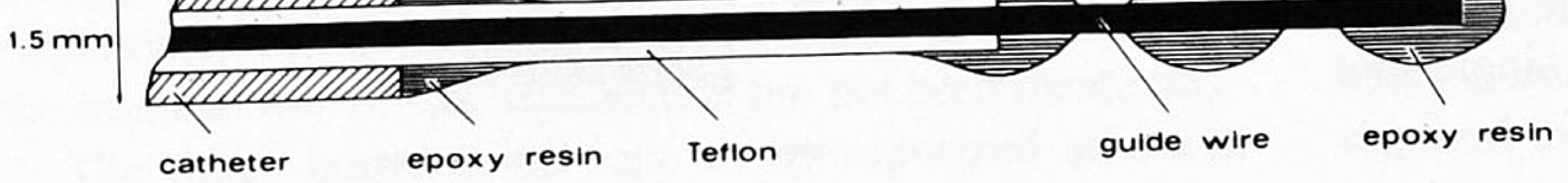

Figure 2. Flexible guidewire spark erosion electrode for the in vivo generation of sparks in the coronary arteries of pigs to test electrical safety of the technique. Epoxy resin droplets centered the electrode in the lumen to prevent vessel wall perforation.

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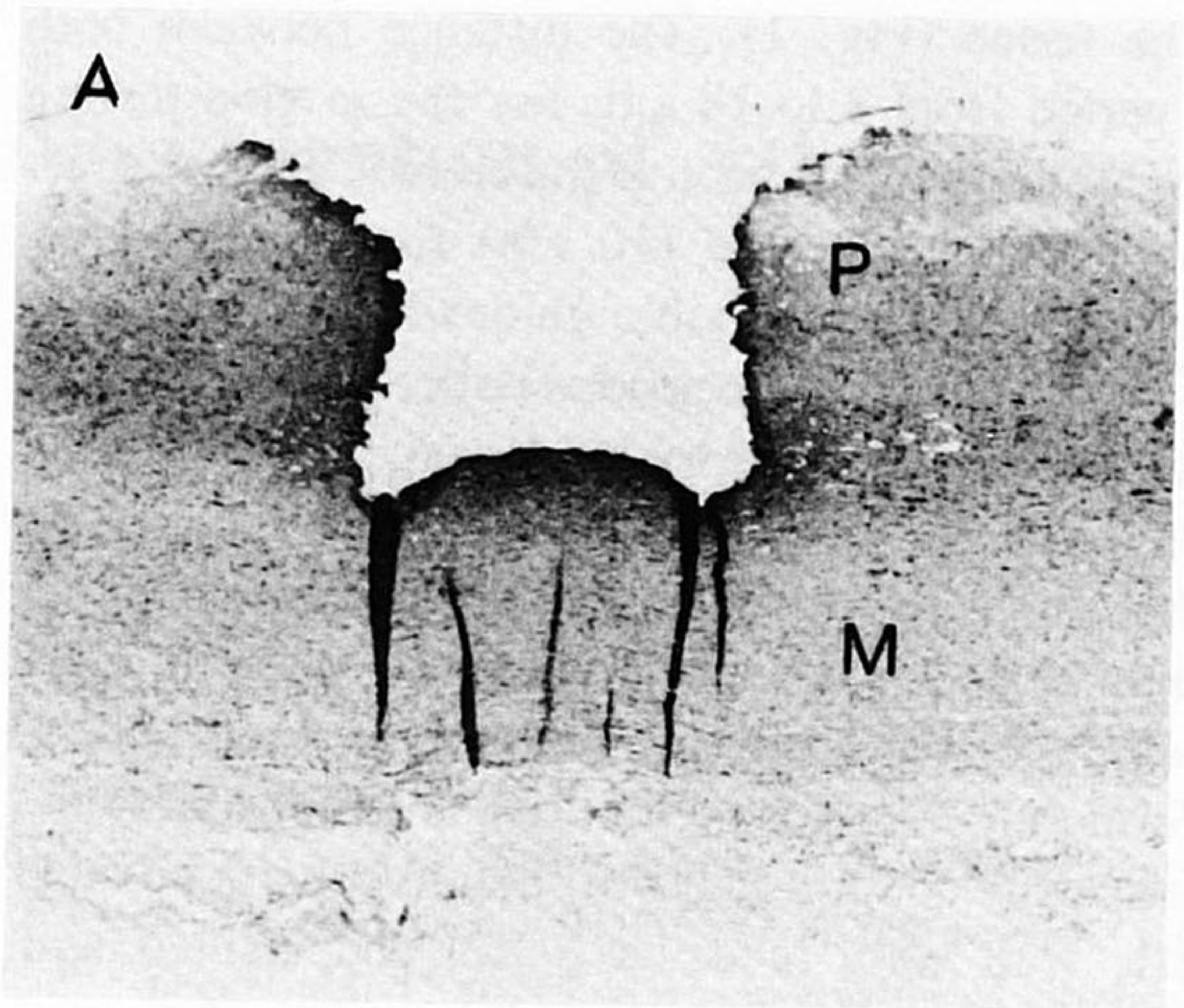
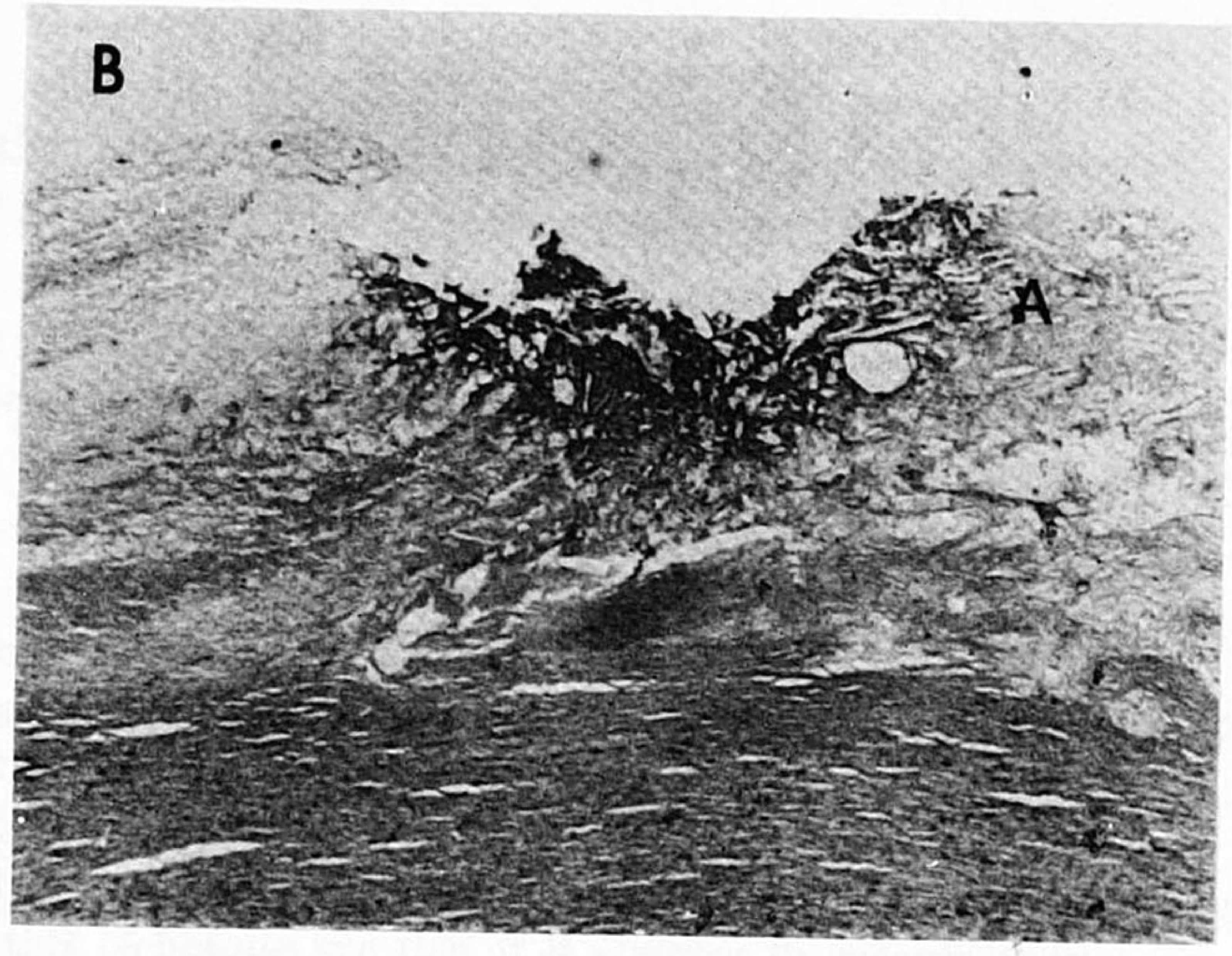




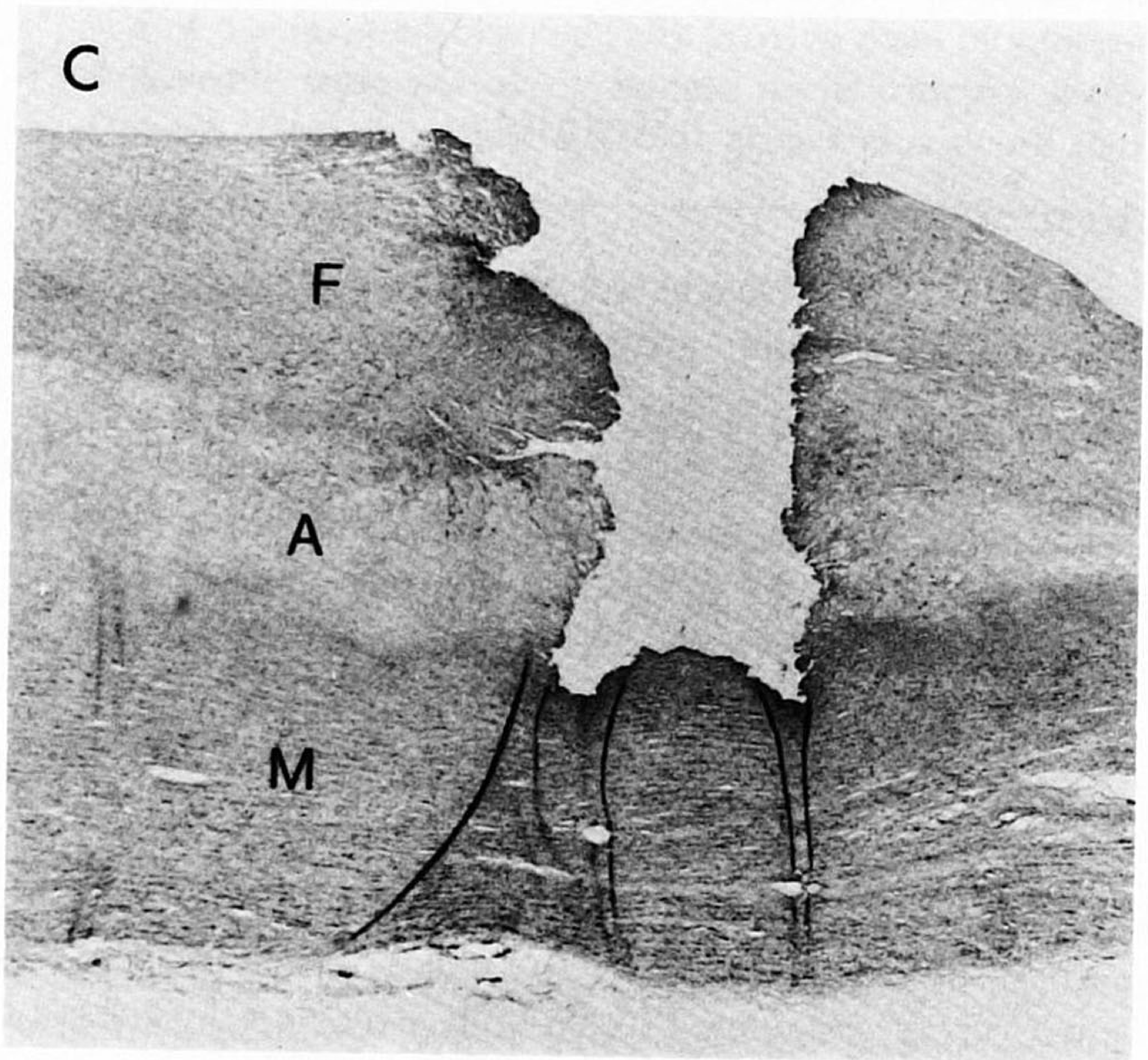


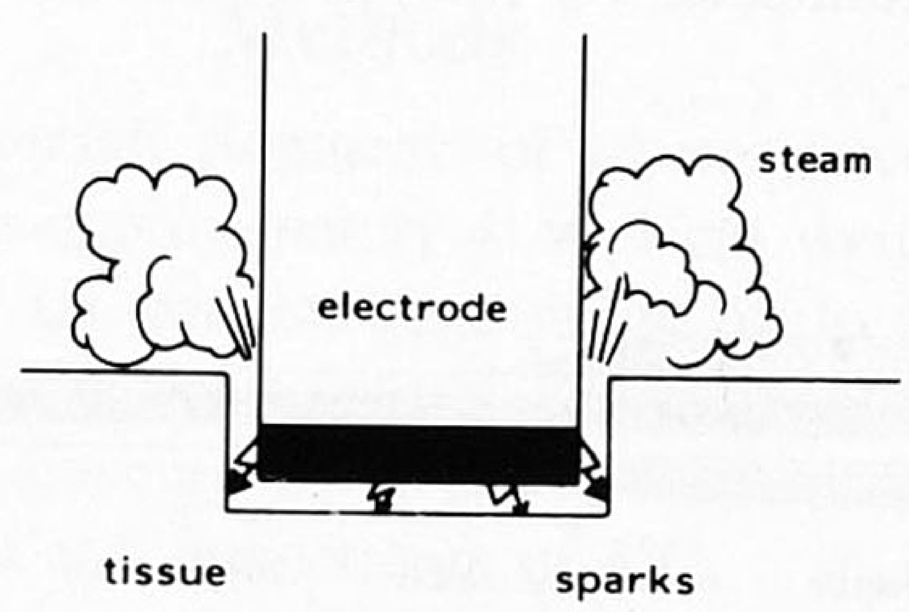
Figure 3. Histologic sections. **A**, Section through the aortic wall with a mainly fibrous plaque (P). Application of the spark erosion method in a direction perpendicular to the area of the plaque produced a punched-out crater extending to the superficial layers of the media (M). Two 10 ms pulses, each delivering approximately 1.7 J, produced this result. Note the very small dark rim that represents the coagulation zone. **B**, Section through the aortic wall with an atheromatous plaque with extensive lipid deposits (A). The crater created by the spark erosion technique was achieved with three 10 ms pulses, each delivering approximately 1.7 J. Note the frayed aspect of the border of the lesion and the broad dark coagulation zone. **C**, Section through the aortic wall with an atheromatous plaque (A) covered by a fibrous cap (F). The crater which extends to the superficial layers of the media (M) was achieved with four 10 ms pulses. Along the border of the crater, only a very small dark coagulation zone can be observed. (Hematoxylin-eosin stain; magnification 28× in **A**, 23× in **B** and 27× in **C**.)

Delivered energy. During spark erosion, the delivered peak to peak voltage to the load was measured on an oscilloscope. Because the output impedance of the generator and its open output voltage are 180 Ω and 1,200 V peak to peak, respectively, the load impedance can be derived from these data. In this way, it was shown that during the first 1 or 2 ms while the pulse was applied, the load resistance increased from an initial value of 200 to 800 Ω to a final value of 2 to 3 kΩ. Only at the higher final resistance values did sparking occur because the electrode became isolated from the tissue by the self-produced steam layer at that stage (Fig. 4). From these data, the power ratings delivered to the tissue can be derived. In the primary heating phase, the delivered power starts at a level of 300 to 500 watts and decreases to a level of 100 to 150 watts in the sparking phase. Therefore, the total energy delivered in a single shot pulse of 10 ms is in the range of 1.2 to 2.2 J.

Animal Studies

In seven pigs, intracoronary sparking was carried out in eight instances: five times in the proximal part of the left anterior descending coronary artery, two times in the left

Figure 4. Schematic drawing of the spark erosion process. The self-produced steam layer isolates the electrode from the tissue. Sparks jumping between the electrode and the tissue produce very high local energy densities that lead to tissue vaporization.



circumflex coronary artery and one time in the right coronary artery. At every location, ten 10 ms pulses, each immediately after the peak of the R wave on the electrocardiogram, were generated. In all eight cases, no effects on cardiac rhythm or aortic blood pressure could be observed.

In a following test, 10 pulses were given subsequently, each at a different time delay after the R wave, ranging from 100 to 1,000 ms by 100 ms increments. Pulses given at a delay of 300 ms or more after the R wave generally induced ectopic beats. Ventricular fibrillation did not occur.

Discussion

Laser techniques. In recent years, different types of lasers have been suggested and tried for potential curative application in the vascular field (1–3,5). The vaporization of vascular obstructions by radiation with intense laser light is tested on a considerable scale. This radiation is guided transluminally through flexible fiber optics to the end of the catheter. However, specific laser beam characteristics, such as coherency and monochromaticity, are not essential requirements to vaporize obstructions with the proposed types of lasers (4). In fact, the only property essential for successful application has been the controlled effective production of heat of a sufficiently high level at the target area. New types of lasers with nonthermic cutting capabilities (for example, those operating in the ultraviolet region [6] and those generating short high intensity pulses [7]) were announced recently. Experimental application of these laser techniques on diseased vascular tissue is probably under investigation now. In this study, we demonstrated the potential use of electrical spark erosion, which is a less complicated, less expensive and more easily controllable technique.

Electrical spark erosion. This technique is commonly used in industry for the accurate production of intricate holes in metals, but it is also used on a wide scale in the medical field for the cutting of biological tissue. The powerful erosion effects associated with the electrical sparks are a result of the extremely high current density that can be reached at the target point. At this point, the very small and well conducting ionization channel (the spark) makes contact with the tissue. In addition, the heat accumulated during the generation of the ionization channel also contributes to the eroding effect of the spark. We suppose that in biological tissue, both heating factors lead to such a rapid conversion of water into steam that cells "explode" and nonwater-containing tissue parts are fractioned into many small particles (Fig. 4). A similar explanation has been construed for cutting mechanisms of the carbon dioxide laser (8) and for electrosurgery (9). However, in the latter, more theoretical explanation of the mechanism of cutting by electrosurgery, the essential role of spark generation has not been mentioned.

The tissue border zone next to the vaporized area will be exposed only to a relatively small amount of heat. The current density in the tissue decreases with the second power of the distance to the center of the ionization channel, and the power density (expressed in watts per cm^3) even decreases with the fourth power of this distance (9). The explosion effect further reduces the secondary transport of heat from the target area to the border zone as contact between both areas occurs only for a very short time. The heat accumulated in the steam will be easily absorbed by the vast tissue area over which it is distributed. These factors explain the minor importance of secondary heat-induced tissue damage.

Electrocautery with, for example, an electrically heated wire can also be used for tissue cutting. However, this technique must be clearly distinguished from electrosurgical cutting, in which sparking from a cold electrode and the subsequent electrothermal conversion process in tissue play a decisive role. Electrocautery relies on the heating of tissue from an external source through thermal conduction. It has not proved equally effective for vaporizing tissue while minimizing unwanted side effects such as dehydration, coagulation and carbonization. A recently proposed cautery technique (10,11), also based on the transport of heat from an external source, uses a copper shield mounted at the end of a fiber optics catheter which is heated by a laser beam.

Histologic findings. It is evident that when applied to electrically conducting tissue, the spark erosion process will produce results equivalent to those described after thermic laser utilization. Indeed, histologic examination of the zone around the craters produced by vaporization of fibromuscular and collageneous plaques shows a remarkably sharp edge with only a very small rim of coagulated tissue. The amount of material that could be removed per joule of delivered energy compares well with that described after the application of the carbon dioxide laser (12).

The diameter of the craters is mainly determined by the dimensions of the spark erosion electrode and only to a small extent by the spark erosion procedure itself. Sparks only jump over a short distance which is not influenced by the total duration of application. The characteristic of the process that allows for precise control of transversal destruction depth may become valuable for constructing devices for transluminal in vivo application with a reduced risk of vessel wall perforation.

The variability observed in the coagulative effect is caused by different local electrical and thermal conducting properties and by the varying water content of the treated tissue. In this respect, the influence of the distance between the reference electrode and the active electrode can be neglected as can be derived from the calculated power density function near the active tip (9).

Methodologic problems. The construction of special spark erosion catheters is rather easy because the flexibility required for intracoronary application can be acquired with

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conventional techniques. Also, the use of thin flexible guidewires as currently applied for the guidance of the balloon angioplasty catheters will be possible. However, these measures in themselves will not prevent wall perforation in all circumstances. New guiding principles for local transversal position control of spark erosion as well as for the laser procedure will have to be invented, especially for the treatment of asymmetric lesions.

Concerning the potential in vivo application of the pulsed spark erosion technique, the preliminary tests in pigs have shown that from the electrical point of view, the method can be safely applied. Further investigations must elucidate whether electrical safety is preserved in the presence of myocardial ischemia.

One of the areas deserving further attention is the local production of gas bubbles. Because of the relatively powerful short pulses used, more gas is produced at once, thus creating larger bubbles with a relatively long lifetime. Modification of the pulsing method and the electrode configuration combined, when necessary, with a suction technique may be used to treat this problem.

Clinical implications. The healing response after carbon dioxide laser application in diseased blood vessels has been reported to be quite good (12). Although further investigations will be necessary, we do not expect problems with respect to the vascular healing response after the application of spark erosion because the vaporization and coagulative effects of this technique are comparable with those produced by the carbon dioxide laser. It has also been demonstrated that adequate and rapid healing responses can be obtained after the application of other optimized electrical radiofrequency cutting techniques in dental surgery (13,14). Apparently the passage of electrical current has no additional significant effect on the tissue healing response.

In conclusion, a low cost and controllable electrical spark erosion technique with great potential for the transluminal vaporization of atherosclerotic lesions has been developed. Before successful in vivo application, further studies have to be carried out regarding arterial healing response, controlled production or removal, or both, of gas bubbles and debris and improvement of catheter guidance to prevent vessel wall perforation.

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