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Endovascular Electrocoagulation: Concept, Technique, and Experimental Results

Cheng Ji, Guido Guglielmi, and Hank Chen

PURPOSE: To evaluate the safety and efficacy of an embolotherapeutic technique that uses electrolytically detachable platinum coils and radio frequency (RF) energy to achieve rapid and distal occlusion of targeted vessels. **METHODS:** In swine, branches of the ascending cervical artery and the hepatic artery measuring 1.5 mm or less were subjected to endovascular electrocoagulation. RF energy was delivered through modified Guglielmi detachable platinum coils that were placed in the targeted arteries. Ohmic heating generated by RF caused vessel occlusion. After the vessel occlusions were confirmed angiographically, the platinum microcoils were electrolytically detached from the delivery wire and left in the vessels as implants. **RESULTS:** All vessels were rapidly and superselectively occluded by endovascular electrocoagulation. Following use of the appropriate methods derived from this research, we did not observe rupture of the artery, dissection of the artery, unintended occlusion, or migration of the platinum microcoil. Histologic examination of treated vessels at 6 and 12 weeks revealed obliteration of the vessel lumen by the platinum microcoil surrounded by granulation tissue. **CONCLUSION:** Endovascular electrocoagulation is a rapid method of achieving vessel occlusion. It may be a useful and controllable embolotherapeutic technique when expeditious occlusion of small vessels and distal superselectivity are desired.

Index terms: Animal studies; Arteries, therapeutic blockade; Interventional instruments, coils

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In the past few decades, embolotherapy has become an indispensable tool of interventional neuroradiology. Many different materials are used to occlude vascular lesions via the endovascular route, including polyvinyl alcohol, steel and platinum coils, cyanoacrylate, and detachable balloons. However, reflux or migration of these embolic materials cannot always be avoided, and none of these embolic agents has proved to be ideal when distal, controlled, superselective, or rapid occlusion of small vessels is desired.

In search of a rapid and effective method of embolization, a few investigators turned to the

phenomenon of electrocoagulation (1–6). Electrocoagulation was discovered at the turn of the century by researchers who observed that when sufficient electricity was passed through biological tissue, heat was produced (7). When this heat reached a critical temperature, proteins denatured and formed a material called *coagulum*. The phenomenon of coagulum formation caused by electrical energy was termed *electrocoagulation*. It was also observed that alternating current of greater than 10 000 cycles per second (10 kHz) at moderate levels did not produce significant pain or generalized muscle contraction in the human body (1, 7). Current above this cycling rate was known as radio frequency (RF). By applying RF energy to an area just proximal to the aperture of a bleeding vessel, surgeons have long been using electrocoagulation to achieve hemostasis and vessel occlusion quickly, safely, and effectively. Heat energy generated from RF causes vessel occlusion by the following mechanisms: desiccation of the vessel wall leading to shrinkage and retraction of the vessel; coagulation of blood pro-

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teins resulting in the formation of an occlusive coagulum; and induction of thrombosis following vessel wall injuries (8).

It was the rapidity and the efficacy of surgical electrocoagulation that prompted the investigators to explore its use for achieving vessel occlusion via the endovascular route (1–6). Via catheters, a guidewire serving as an electrode was positioned in the targeted vessel and RF energy was delivered through the guidewire. The results were disappointing; many investigators reported vessel rupture and/or unsatisfactory occlusion rates (1, 2, 5). It is believed that these failures were due to either application of excess energy or removal of the adherent guidewire after electrocoagulation. During electrocoagulation, thermal energy causes vessel walls and blood proteins to become adherent to the guidewire. At this point, the blood vessel is occluded by the shrinkage of the vessel wall, the coagulum, and the physical presence of the guidewire. Continued application of RF energy to the targeted vessel beyond this point will overheat the vessel wall and cause it to rupture. Even if application of excess energy is avoided, the subsequent withdrawal of the adherent guidewire removes the occlusive coagulum, which leads to recanalization or to tearing of the vessel wall, which leads to rupture. Unlike with surgical electrocoagulation, in which the surgeon can see the vessel, these investigators could not know when the vessel was occluded and when to turn off the power.

In the early 1990s, the platinum Guglielmi detachable coil (GDC) system became available for clinical use. The GDC can be detached at will from the delivery wire, by electrolysis, and left in place as an implant. GDCs, which are formed by many centimeters of looped platinum coil, are used primarily for brain aneurysms (9). A shorter (0.4 to 1 cm), crescent-shaped version of the GDC can be used for the endovascular occlusion of small feeders of arteriovenous malformations, fistulas, and hypervascular tumors (G. Guglielmi, "Controlled Distal Occlusion of Anterior Choroidal and Anterior Spinal Artery Feeders of AVMs Using Detachable Coils," presented at the annual meeting of the American Society of Neuroradiology, Washington, DC, June 1991). This coil is controllable beyond the tip of the microcatheter and can be steered and then detached into the targeted vessel. Complete occlusion of each vessel, however, requires dense mechanical filling of the

vascular lumen, often with multiple parallel coils, and can be time-consuming to such an extent as to become impractical. As a result, chances of incomplete occlusion or recanalization may become significant.

To enhance the efficacy and rapidity of the technique of distal, selective, and controllable occlusion of small vessels, it was decided to combine the technique of electrocoagulation with GDC technology. The aim was to achieve from the inside of the vessel what in surgery is done from the outside of the vessel: instantaneous occlusion of blood vessels by electrocoagulation.

This study was undertaken to evaluate this concept, which was conceived in our laboratory to overcome the problems of the adherent electrode and the delivery of excess energy encountered by earlier investigators. It was also our objective to demonstrate that this technique of endovascular electrocoagulation is capable of providing distal vessel occlusion in a safe, rapid, controllable, and superselective manner.

Materials and Methods

To develop the technique of endovascular electrocoagulation, an experimental study was performed in swine with the material and methods described below.

RF

Two different systems of RF generation were tested, constant voltage and constant power. A constant voltage system maintains the same voltage throughout its activation. Changes in the resistance of the circuit are countered by opposite changes in the current according to Ohm's law (voltage = current $\times$ resistance); voltage is not affected by changes in resistance. On the other hand, a constant power system maintains the same power throughout its activation. Since power = voltage $\times$ current = voltage²/resistance, any change in the resistance of the circuit is met by a corresponding change in voltage.

Figure 1 is a diagrammatic representation of the components used in a constant voltage system. A signal generator (CFG 280, Tektronix, Wilsonville, Ore) is set at a frequency of 500 kHz with a continuous sine wave output. The signal is sent to an RF amplifier (75A220, Amplifier Research, Souderton, Pa), where it is amplified. A power meter capable of measuring both forward power and reflected power (ThruLine Wattmeter, Bird Electronics, Cleveland, Ohio) is connected to the amplifier. The power meter has two output alligator grabbers for delivering RF alternating current. One grabber is connected to the dispersive electrode or ground pad (E7506, Valleylab, Boulder, Colo) placed on the abdomen of the animal. The other grabber is connected to the proximal end of the detachable

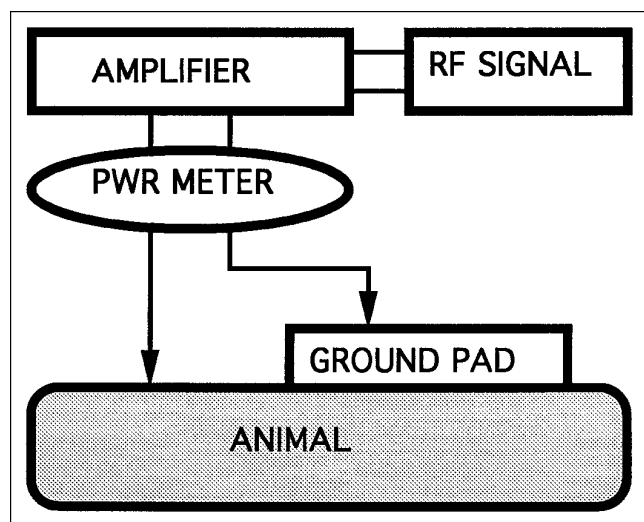


Fig 1. The components used in a constant voltage system for endovascular electrocoagulation.

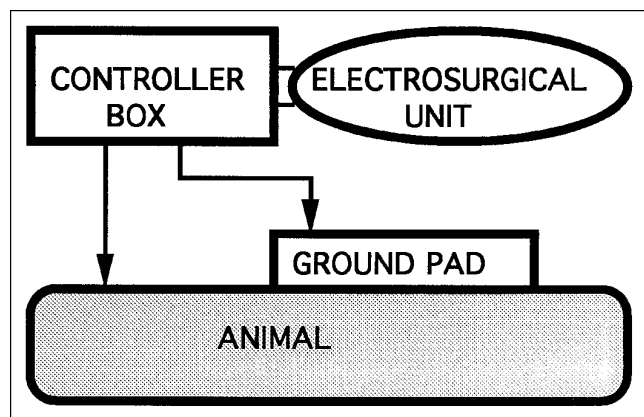


Fig 2. The components used in a constant power system for endovascular electrocoagulation.

endovascular electrocoagulation device, which is described below.

Figure 2 illustrates the components assembled in a constant power system. A constant power RF generator commonly used in electrosurgery (Surgistat, Valleylab) serves as the source of energy. Its 1-MHz modulated sine wave (coagulation mode) output is sent to a controller box designed and built by one of the investigators (G.G.). The controller box has two alligator grabbers that are connected to the ground pad (E7506, Valleylab) and to the proximal end of the detachable endovascular electrocoagulation device. The function of the controller box is to activate the generator in order to initiate the electrocoagulation process and to shut down the generator once electrocoagulation is complete. As discussed in the introduction, vessel occlusion during endovascular RF electrocoagulation is caused by desiccation and shrinkage of the vessel wall as well as by coagulation of blood proteins around the platinum coil. These events lead to insulation of the platinum coil, with consequent dramatic increase in

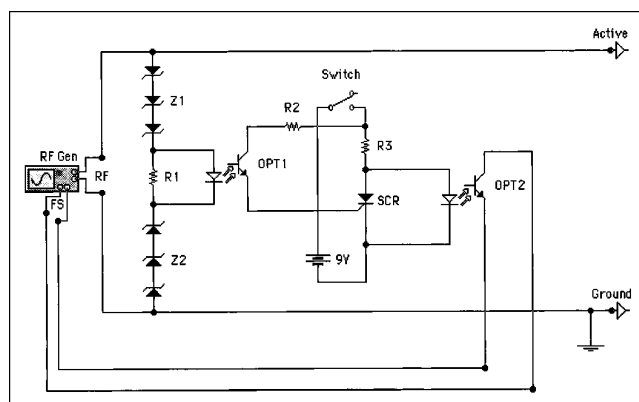


Fig 3. Electronic circuitry of the controller box used in the constant power system. *RF Gen* indicates Surgistat electrosurgical unit; *RF*, radio frequency output; *FS*, footswitch input of *RF Gen*; *Z1* and *Z2*, chain of Zener diodes (total value = 250 V); *R1*, 10 ohms; *R2*, 2200 ohms; *R3*, 820 ohms; *Switch* momentary switch; *OPT1* and *OPT2*, infrared light-emitting diode optically coupled with infrared phototransistor; *SCR*, silicon controlled rectifier; *9V*, 9-volt battery.

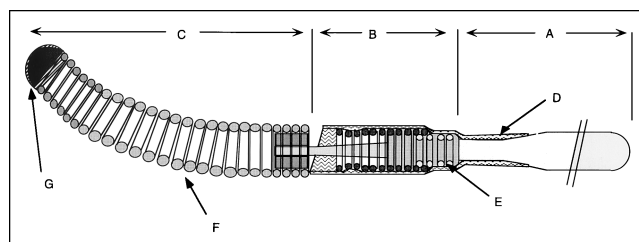


Fig 4. The detachable endovascular electrocoagulation device. *A* and *B* indicate stainless steel delivery wire; *A*, proximal component; *B*, intermediate component; *C*, distal component; *D*, insulation layer; *E*, soft stainless steel coil; *F*, platinum microcoil; *G*, insulated tip of the platinum microcoil (see also text).

the electrical resistance of the system. The increase in electrical resistance is met by a rise in voltage as the generator attempts to maintain constant power. The controller box senses the rise in voltage and through a feedback loop shuts off the generator automatically in a fraction of a second, preventing overheating of the coil. The electronic circuitry of the controller box is illustrated in Figure 3.

Detachable Endovascular Electrocoagulation Device

The electrode used to deliver RF energy to the vessel is a detachable endovascular electrocoagulation device. Its overall design is similar to that of the GDC (Target Therapeutics, Fremont, Calif), an embolization device for the treatment of cerebral aneurysms (9). It is reliant on the same electrolytic detachment principle as the GDC. The device consists of three components: proximal, intermediate, and distal (Figure 4). The proximal component (0.25 mm in diameter, 170 cm in length) consists of a

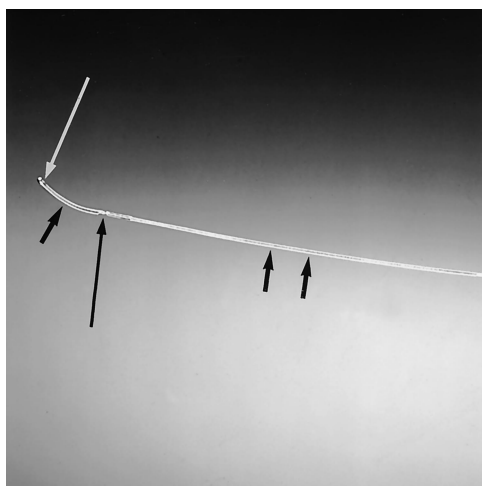


Fig 5. The distal end of the detachable endovascular electrocoagulation device shows stainless steel delivery wire (double arrows); uninsulated steel junction (long black arrow); crescent-shaped 6-mm long platinum coil (short arrow). The distal, 1-mm, portion of the platinum coil is insulated (white arrow) to avoid possible convergence of the RF energy in a too-small area of the vessel.

stainless steel core wire, which is laminated with an insulation layer except at its most proximal portion. This uninsulated portion is connected to the RF energy source. The intermediate component (0.25 mm in diameter, 3 cm in length) is made of a very soft, electrically insulated tapering stainless steel wire. At the distal portion of the intermediate component, the tapering stainless steel wire is uninsulated; this is the site of electrolytic detachment. Together, the proximal and the intermediate components are known as the delivery wire. The distal component is made of a crescent-shaped platinum microcoil (it is shaped with a curve to allow for vessel selectivity). The platinum microcoil comes in two diameter sizes: 0.010 inches (0.25 mm) and 0.015 inches (0.375 mm), known as #10 and #15, respectively. Both versions are 6 mm in length. Except at its most distal 1 mm, the platinum microcoil is uninsulated. This is where RF energy exits the device and where electrocoagulation occurs. The platinum microcoil is also the component that is left in the vessel as an implant following electrolytic detachment. Figure 5 is a photograph of the detachable endovascular electrocoagulation device.

Direct Current Generator

After the vessel is occluded, a direct current generator (GDC Power Supply, Target Therapeutics) with a 1.0-mA output is used to electrolytically detach the platinum microcoil, which is left in the vessel as an implant.

Endovascular Electrocoagulation Protocol

Since June 1993, 112 arteries (branches of the ascending cervical artery and the hepatic artery) of Red Duroc

swine have been subjected to the endovascular electrocoagulation protocol approved by the Animal Research Committee of our institution. Branches of the ascending cervical artery were chosen because they are superficial and easy to expose and retrieve. Branches of the hepatic artery were used because they allow the assessment of possible periarterial parenchymal damage. Also, occlusion of these arteries does not impair the survival of the swine. All arteries were 1.5 mm or less in inner diameter as assessed angiographically. Arteries 1.0 mm or less in diameter were treated with both the #10 and the #15 devices and those between 1.0 and 1.5 mm diameter were treated with the #15 device only. Sixty-four of the arteries were treated with the constant voltage system and 48 were treated with the constant power system. With the swine under general anesthesia a ground pad was placed on the animal's abdomen (RF return electrode). Then, under systemic heparinization, a 6F nontapered transfemoral angiographic catheter (Fasguide, Target Therapeutics) was positioned in either the hepatic or ascending cervical artery. Preocclusion angiography delineated the location and the size of the arteries to be occluded. A 2.0F or 2.7F microcatheter (Tracker 10 or Tracker 18, respectively, Target Therapeutics) was introduced through the guiding catheter. Both the guiding catheter and the microcatheter were continuously flushed with pressurized saline by means of side-arm adapters. The detachable endovascular electrocoagulation device was then passed through the microcatheter and the platinum microcoil positioned beyond the microcatheter tip in the targeted arterial segment under digital roadmapping. In many instances, the targeted arteries were too small in diameter and/or too tortuous to be reached by the microcatheters. Placement of the platinum coil simply involved pushing and steering it into the desired vessel by maneuvering the delivery wire, as one would do with a microguidewire. This was possible because the coil was pushable, torquable, steerable, and radiopaque.

Figure 6 is a diagrammatic representation of the endovascular electrocoagulation technique. The platinum distal portion of the device was positioned in the targeted arterial segment through a microcatheter under fluoroscopy and roadmapping. Note that the platinum microcoil can be extended far beyond the tip of the microcatheter and it can be repositioned again and again until the location is satisfactory. Application of RF energy induces desiccation and retraction of the vessel wall, formation of the protein coagulum and thrombus, and adhesion of the platinum microcoil to the arterial segment.

In the constant voltage system, RF energy is slowly increased from zero at the start of the procedure until the above events occur, which dramatically increases the electrical resistance of the circuit. This great increase in resistance reduces the actual power delivered to the vessel to close to zero, since $\text{power} = \text{voltage}^2 / \text{resistance}$. Most of the power is reflected back to the generator, and this is seen as a surge in reflected power in the power meter. This surge is taken as the end point of the electrocoagulation process and it typically occurs within seconds of RF en-

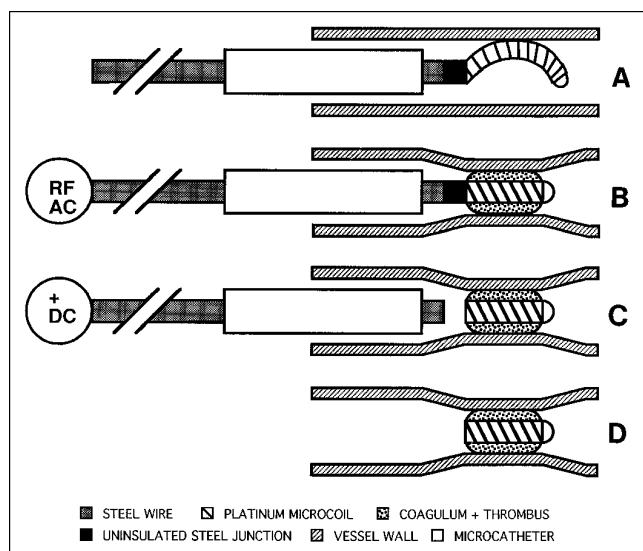


Fig 6. The endovascular electrocoagulation technique.

A, Platinum microcoil is positioned in the targeted vessel segment through a microcatheter. Note that there is still control of the microcoil beyond the microcatheter tip.

B, Application of RF energy induces retraction and desiccation of the targeted vessel segment, local formation of coagulum and thrombus, and adhesion-straightening of the platinum microcoil to the vessel wall.

C, Application of positive direct current causes the uninsulated steel junction to undergo electrolysis. The platinum microcoil is separated from the steel delivery wire.

D, The delivery wire and the microcatheter are removed. The platinum microcoil remains as an implant.

ergy application. Once this surge in reflected power is seen on the meter, the energy is turned off manually. This procedure is done three times to ensure complete electrocoagulation of the artery. An angiogram at this time can confirm that the artery is occluded. After occlusion has been confirmed, the RF generator is disconnected and the delivery wire is connected to the DC generator. Application of the positive, 1-mA direct electric current induces electrolysis of the uninsulated steel junction and separates the adherent platinum coil from the delivery wire. Detachment typically occurs within 2 minutes of direct current application. Following detachment, the delivery wire is withdrawn and a repeat angiogram confirms occlusion of the artery and the position of the platinum microcoil that has been left behind as an implant.

In the constant power system, the Surgistat electrosurgical unit is set at level 5 (12 watts) in the coagulation mode. Pushing a switch on the controller box (Fig 3) activates the electrocoagulation process. As in the constant voltage system, an increase in electrical resistance of the circuit signals occlusion of the vessel. Because it is a constant power generator, the Surgistat will raise its output voltage when the resistance of the system increases in an effort to maintain constant power ($\text{power} = \text{voltage}^2 / \text{resistance}$). This rise in voltage is detected by the controller box, which in turn automatically shuts off the Surgistat in a matter of fractions of a second, thus preventing deliv-

ery of excess energy. As it is in the constant voltage system, the application of RF alternating current is done three times to ensure complete electrocoagulation of the vessel. The coil is then detached electrolytically.

Results

All arteries were occluded within 15 seconds, typically, within 3 to 6 seconds, by endovascular RF electrocoagulation, whether via the constant voltage system or the constant power system. In all cases, an immediate postelectrocoagulation angiogram showed the occlusion of the targeted artery, the preservation of the parent artery, and the position of the platinum microcoil (Fig 7). Following use of the appropriate methods described above, we did not observe rupture of the artery, dissection of the artery, unintended occlusion, or migration of the platinum microcoil; nor did the platinum microcoil ever fail to electrolytically detach from the rest of the device. Follow-up angiograms obtained 1 week to 12 weeks after the procedure confirmed in all cases persistent and complete occlusion of the targeted arteries and patency of the parent vessels. Migration of the platinum microcoil, pseudoaneurysm formation, and dilatation of the vessel segment proximal to the platinum microcoil were never observed throughout the experimental period (Fig 7).

Histologic examination of vessels treated via the constant voltage system showed that at 1 week the vessel lumen was occluded by the platinum coil, denatured fibrin, and red blood cells (eg, occlusive coagulum). Loss of the endothelium and some minor damage to the internal elastic lamina were also observed, together with mild periadventitial acute infiltrate. At 6 weeks, the vessel lumen was obliterated by granulation tissue within and surrounding the platinum coil. The endothelium was not present and a thickened fibrous adventitia surrounded a thinner muscularis. The periadventitial soft tissue showed a thin ring of fibroblastic proliferation (Fig 8). Histologic findings at 12 weeks were similar to those seen at 6 weeks, except for a thinner muscularis and adventitia.

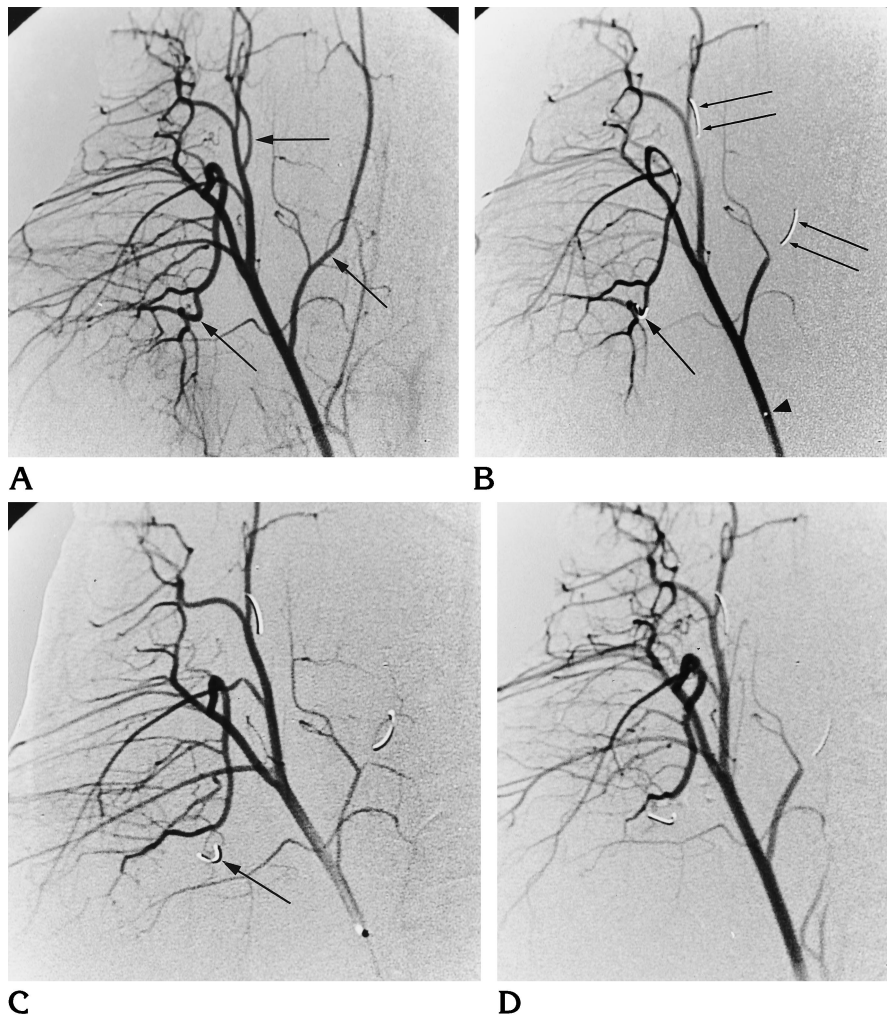
No adverse reactions were observed in the experimental animals either during or after endovascular electrocoagulation. All animals were examined daily by the veterinary staff, and all animals were determined to be healthy during the experimental period.

Fig 7. A, Arteriogram of the right ascending cervical artery of a swine, anteroposterior view. Arrows point at the three target locations to be occluded.

B, A Tracker catheter was placed in the proximal portion of the ascending cervical artery (arrowhead). From that location, two platinum coils (double arrows) were delivered through the Tracker to two of the targeted locations, and vessel occlusion was achieved by RF and electrolytic detachment. Through the Tracker, still positioned in the original location, a third coil was steered into a distal and tortuous location (single arrow): before RF application there was still flow of blood around the coil.

C, Angiogram shows that after RF application and electrolytic detachment, the third distal vessel was also completely occluded (arrow).

D, Control angiogram at 4 weeks shows persistent occlusion with patency of the surrounding vascular tree.



Discussion

Biophysics of Electrocoagulation

Over the past century, the biophysics of electrocoagulation has become well understood. A typical electrosurgical system consists of an active electrode in the form of a needle or a blade, a dispersive electrode (also known as a ground electrode) in the form of a conductive pad with a large surface area, and an RF current generator to which the two electrodes are connected. An electrical circuit is completed when the dispersive electrode is applied to the skin and the active electrode touches the body. During its application, RF energy travels through the intervening biological tissue between the two electrodes and generates electromagnetic heating called resistive or ohmic heating (10). It is through this heating effect that hemostasis is achieved. The heat generated is proportional to

the square of the current intensity, which is inversely proportional to the surface area of the electrode (11, 12). Thus, heat is greatest at the active electrode, owing to its small surface area and high current intensity. Because resistive heating decreases with distance from the active electrode to the fourth power ($1/r^4$), significant resistive heating only occurs within a narrow (<1 mm) rim of tissue in direct contact with the active electrode (10, 11). Although heat is also produced underneath the dispersive electrode, it does not reach a high enough level to cause tissue damage. This is because heat is diffused over the large area of the dispersive electrode and is dissipated rapidly (7, 12).

Heat energy generated from RF alternating current causes surgical hemostasis by the following mechanisms: desiccation of the vessel wall leading to shrinkage and retraction of the vessel, coagulation of blood proteins and con-

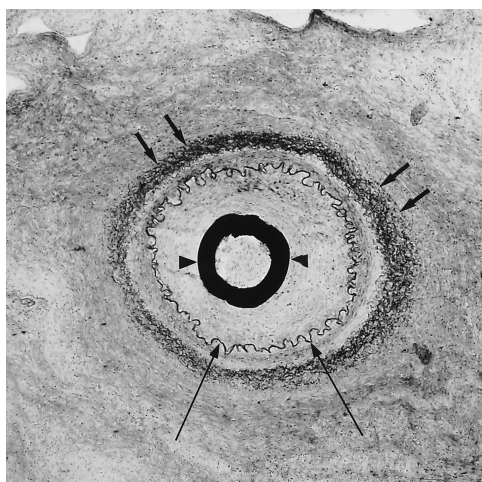


Fig 8. Low-power photomicrograph of an axial section of a hepatic artery of a swine, obtained 6 weeks after coil positioning, RF application, and electrolytic coil detachment. The 0.25-mm platinum coil (between *arrowheads*) is near the center of the artery. Granulation tissue is within and surrounding the coil. No endothelium is discernible. The internal elastic lamina is visible (*long arrows*). A thickened fibrous adventitia (*double arrows*) surrounds a thinned muscularis. A periadventitial thin ring of mild fibroblastic proliferation is observable (hematoxylin-eosin, original magnification $\times 2.5$).

nective tissues resulting in the formation of an occlusive coagulum, and induction of thrombosis consequent to vessel wall injuries (8). Bleeding is usually stopped with a few seconds of energy application. If, however, more energy is applied beyond this point, denatured protein along with glucose deriving from the pyrolysis of the collagen will appear, causing the electrode to stick to the vessel (10, 13). Experienced surgeons can usually prevent the adherence of the electrode by shutting off the energy when they see the vessel shrink.

With any electrical medical device, possible interference with the cardiac conduction pathways is a concern. However, as was known in the late 1890s, high-frequency current above 10 000 cycles per second (10 kHz) at moderate levels does not produce muscle contraction (7). Today, most electrosurgical units operate between 300 kHz and 3 MHz, which is high enough to prevent rapid myocardial depolarization and, therefore, the induction of ventricular fibrillation (10). In fact, high-frequency alternating current is applied directly to the myocardium for ablation of arrhythmogenic pathways without inducing ventricular fibrillation (14, 15). Over the past century, surgical hemostasis by electrocoagulation has proved to be a safe and effective technique.

Development of Endovascular Electrocoagulation

The success of surgical hemostasis by electrocoagulation prompted investigators to study its potential for achieving vascular occlusion via the endovascular route. Electrocoagulation, when applied successfully from within the blood vessel, certainly appeared to be advantageous relative to existing embolotherapeutic techniques; it could be precise, effective, easy to use, and unaffected by reflux, migration, coagulopathy, or blood flow velocity. In 1970, Taren and Gabrielsen (4) reported on endovascular RF thrombosis of the feeding arteries of arteriovenous malformations of the jaw in two patients, with good clinical outcome. These researchers used a 0.5-mm wire and a 100-mA alternating current for 5 to 15 seconds to occlude branches of the external carotid artery. Both patients were awake during the treatment, under local anesthesia supplemented by intravenous ketamine hydrochloride. In 1973, Phillips (5) evaluated endovascular occlusion by RF energy. In that study, a regular guidewire protruding 2 to 3 mm beyond the catheter tip was placed in canine abdominal vessels. Current was passed through the guidewire (serving as an active electrode) from a constant power electrosurgical unit set on coagulation mode. Phillips found that a few seconds of RF energy would cause either vessel occlusion or vessel rupture; the amount of energy necessary to cause occlusion differed only slightly from the amount that would cause rupture. Moreover, he lacked a mechanism that could detect vessel occlusion and thus signal when to stop the RF energy. Delivering more energy to an already occluded and desiccated vessel led to the destruction of the vessel wall and its eventual rupture. Phillips also observed that the guidewire tip became adherent to the vessel wall during electrocoagulation and that tearing of the vessel wall sometimes occurred with removal of the guidewire.

In 1975, Gold et al (3) described a clinical case in which a vessel was occluded via high-frequency alternating current. These investigators successfully occluded several arterial branches to a pseudoaneurysm in the head of the pancreas by using a regular guidewire and a constant power electrocoagulation unit. The applied electric current was increased in a stepwise fashion until vessel occlusion was observed an-

geographically. This method presumably avoided overheating and consequent rupture. Adhesion of the guidewire tip to the vessel wall was not reported.

To prevent the guidewire/electrode tip from adhering to the vessel wall during electrocoagulation, Cragg et al (1) in 1982 withdrew the guidewire while applying RF energy to the cephalic and lateral saphenous veins of dogs. Nevertheless, failure to withdraw the guidewire quickly led to one case of guidewire tip adhesion. Subsequent extraction of this guidewire resulted in a vascular tear. Using this withdrawal method, these investigators observed only one immediate and 13 permanent occlusions (assessed at 4 weeks after treatment) in a sample of 20 vessels in dogs. The poor occlusion rate could be attributed to the fact that the coagulum formed during electrocoagulation was removed with the withdrawal of the guidewire. Vessel occlusion was caused solely by thrombus formation resulting from heat injury of the vessel wall. However, thrombus induction did not always occur, as it was affected by a variety of factors: speed of blood flow within the vessel, status of the subject's blood clotting system, and extent of vessel wall injury.

In 1983, Brunelle et al (2) improved the safety of endovascular electrocoagulation by using a constant voltage power supply and monitoring the current level during the procedure. By progressively increasing the voltage every 30 seconds until a current drop was observed, rupture of the canine anterior tibial arteries during electrocoagulation was prevented. A decrease in current was used as the end point of the electrocoagulation process, and was explained by Brunelle et al as the local desiccation of tissues surrounding the guidewire as a consequence of heat, resulting in an opening of the electrical circuit. The main factor is that high temperature causes the adhesion of proteins and connective tissues to the guidewire, leading to a dramatic increase in electrical resistance (16). In a constant voltage system, an increase in resistance is balanced by a decrease in current (Ohm's law: voltage = current $\times$ resistance), which translates into a proportional decrease in power (power = voltage $\times$ current = voltage²/resistance). In such a system, heating is a self-limited phenomenon; the decrease in power (and thus decrease in heating) makes it unlikely for vessel rupture to occur by overheating. This is in contradistinction to constant

power systems used by previous investigators, in which a rise in resistance was compensated by a rise in voltage, thus maintaining the same power output. Despite the improvement in safety, Brunelle et al were not able to achieve a satisfactory occlusion rate, as vessel closure was still dependent on thrombus formation after removal of the guidewire. Only six of 11 anterior tibial arteries in dogs were permanently occluded. Tanigawa et al (6) reported on the clinical use of endovascular RF electrocoagulation in a case of a fibrous histiocytoma of the right thigh. They did not use a definite safety method to automatically control the RF energy delivery.

Such unsatisfactory occlusion rates and/or the danger of extracting an adherent guidewire tip eventually led investigators to abandon the endovascular electrocoagulation technique.

Development of Electrolytic Detachment

Electrolysis is defined as the nonspontaneous chemical reaction driven by direct electric current (17). It is seen when two electrodes connected to a source of direct electric current are dipped into a solution. Under these conditions, the immersed end of the positive electrode dissolves while the negative electrode recruits the migrating ions from the anode to the cathode. Certain metals such as iron and silver are susceptible to electrolysis while noble metals such as platinum are not (18). In 1991, Guglielmi et al described the phenomenon of electrolysis to detach embolic coils into cerebral aneurysms (9, 19) and feeders to arteriovenous malformations (Guglielmi, "Controlled...").

Using a device that consisted of a platinum coil joined to an insulated steel delivery wire by an uninsulated steel junction, these researchers were able to position and reposition the platinum coil inside the cerebral aneurysm until the location of the platinum coil was satisfactory. This repeated positioning was possible because the platinum coil remained attached to the delivery wire. Once the coil was properly placed inside the aneurysm, a direct current passed along the device electrolytically dissolved the uninsulated steel junction, thus separating the platinum coil from the delivery wire. This device, the GDC described earlier, is used in the treatment of high-risk intracranial aneurysms and has been approved for clinical use by the Food and Drug Administration. The GDC represented a significant improvement over exist-

ing embolic coil technology, such as pushable coils, because it gave users a great degree of control over the placement of the coil. A modified version of the GDC was used in the present study.

Development of the Present Endovascular Electrocoagulation Technique

It is clear that the failure of endovascular electrocoagulation reported by previous investigators stemmed from two problems: the extraction of the adherent electrode (typically a guidewire) after endovascular electrocoagulation, with consequent tearing or recanalization of the vessel, and the inability to know when vessel occlusion has occurred, which resulted in vessel rupture due to the application of excess energy.

The first problem was solved in our laboratory by employing the concept of electrolysis to detach the adherent electrode. To solve the second problem, a method was needed to detect precisely when a vessel has been occluded by endovascular electrocoagulation during energy application. In our early experience, using a standard constant power electrosurgical unit (Surgistat, Valleylab) without a controller shut-off mechanism, we successfully occluded many vessels by combining electrocoagulation with detachment of the adherent portion of the electrode. RF energy was applied through the electrode in intervals of a few seconds, and angiograms were obtained between the intervals. When an angiogram revealed occlusion of the targeted vessel, the adherent portion of the electrode was electrolytically separated from the rest of the electrode by applying a small positive direct current to it. However, in these early experiences, there were instances in which the vessel ruptured after the RF energy was applied. Because it was not known when the vessel was occluded, the continued and excessive application of energy to the vessel sometimes caused it to rupture. As described above, previous work has shown that when a vessel has been occluded by electrocoagulation, the electrical resistance of the circuit increases dramatically. By monitoring the electrical resistance of the circuit during RF application, it became possible to determine when the vessel was occluded and to shut off the energy in fractions of a second. Therefore, a controller unit was built (Figs 2 and 3) that could monitor the electrical resistance and shut off the electrosurgical unit

once the electrical resistance had risen. The time of response of the controller unit can be varied. To avoid tissue damage beyond the adventitia, a very short response time was needed. Also, in a constant voltage system, vessel rupture due to excess energy application is unlikely, because resistive heating is a self-limited phenomenon (see "Development of Endovascular Electrocoagulation" section). Although resistance monitoring in a constant voltage system was not needed to prevent excess power delivery, it did signal when the vessel was occluded. Therefore, on the basis of this experience, we determined that both the constant voltage and the constant power generators are efficacious in achieving rapid vessel occlusion. However, the constant voltage generator seems to have intrinsic safety properties. With the constant power generator, safety is achieved by adding the controller shut-off unit.

Although this report describes our experience with the occlusion of vessels 1.5 mm or smaller, larger vessels may be occluded using platinum coils with larger diameters (thereby matching the increased size of the vessel), or by using multiple parallel coils. In fact, we believe that both electrocoagulation and mechanical occlusion are necessary for the long-term efficacy of the technique.

Acute, 6-week, and 12-week histologic studies of the occluded arteries showed persistent occlusion and only a thin ring of mild fibroblastic periadventitial proliferation. However, longer term histologic and angiographic studies, as well as a more accurate analysis of the extent of possible tissue damage beyond the arterial wall, are needed. These will allow a more thorough assessment of the long-term efficacy and of the safety of the technique.

Conclusions

Endovascular electrocoagulation has been attempted in the past by many investigators to achieve vessel occlusion, without much success. Some of these failures were due to the application of excess RF energy that resulted in vessel rupture. By monitoring the rise in electrical resistance, we were able to determine when a vessel has been occluded and to prevent overheating. We think that other failures resulted from the extraction of the adherent electrode/guidewire after electrocoagulation; that is, withdrawal of the adherent electrode/guidewire re-

moved the occlusive coagulum and/or tore the vessel wall. By using the GDC crescent-shaped platinum coil, we were able to electrocoagulate the vessel and then leave the electrode/coil in the vessel as an implant/embolic material. This was accomplished by applying the RF energy first, followed by electrolytic direct current detachment of the coil. Using this approach, we were able to occlude small arteries of swine permanently in a rapid, controlled, and super-selective manner. No substantial differences were noticed between the constant power (with automatic shut-off mechanism) and the constant voltage generators. The former are easier to find in commerce; the latter, being self-limiting, have intrinsic safety properties. Unlike with embolic materials, such as pushable coils, polyvinyl alcohol, and cyanoacrylate, placement of the detachable endovascular electrocoagulation device in the targeted vessel is not dependent on the position of the microcatheter; the device can enter those small and tortuous vessels distal to and unreachable by the microcatheter in much the same manner as that of a microguidewire. The preliminary experimental data observed in this work make this technique suitable for the preoperative or definitive embolization of a variety of vascular disorders, including arteriovenous malformations, arteriovenous fistulas, and hypervascular tumors.

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