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The Distribution of Radiofrequency Current and Burns

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During electrosurgery, nine patients were burned at the sites of electrocardioscope electrodes. Causes were: 1) broken patient-plate ground wires detectable only by conductivity measurements; 2) defective silicon-controlled rectifiers in the sentry modules; 3) a design fault apparent only when the foot switch of one company was used with the electrosurgery machine of another; 4) improper use of the active (knife) electrode; 5) capacitive coupling of radiofrequency current in electrocardioscope cables; and 6) radiofrequency current division. The average maximum radiofrequency current in the ground electrode of an electrocardioscope system was 175 milliamperes (range 20–290). Approximately 100 milliamperes/cm² for approximately 10 sec can cause skin damage. Current through an ECG ground electrode during a median sternotomy was ten times greater when this electrode was placed on the upper arm rather than the calf—in each case the ground plate was under the buttock. Radiofrequency inductors (chokes) may prevent these burns. (Key words: Inductors; Capacitors; Current division; Resistances; Electrode paste; Silicon-controlled rectifier.)

ELECTRICAL AND ELECTRONIC DEVICES are used in conjunction with electrosurgical machines. Many accidental burns have resulted.[1–11] Almost invariably, these burns are not reported in the official reports or in scientific writing.[10] This study was prompted by second- or third-degree burns to nine patients at this hospital within ten months—in eight of the patients at the site of one of the ECG electrodes. Major burns during electrosurgery tend to occur, as in our patients, at ECG ground electrodes or other low-impedance points, excluding the patient ground plate. Our purpose was to reexamine the inherent hazards of electrosurgical machines.[3,5,9,10,12] We hope to suggest possible modifications which will ensure greater safety under modern conditions.

Methods

These electrosurgery burns were investigated in the following ways: 1) examination of the nine patients; 2) examination of electrocardioscopes and cables in use when the patients were burned; 3) examination of alarm systems of electrosurgery units in use when patients were burned; 4) examination of electrosurgery patient ground plates and cables in use when patients were burned; 5) examination of radiofrequency (RF) currents flowing during electrosurgery; 6) evaluation of different electrosurgery units; 7) evaluation of electrocardioscope cables and paste; 8) determination of radiofrequency current capable of producing symptoms and burns.

The methods used for these eight phases of the study follow.

1) The burn of each patient was examined and the patient asked whether any burn or mark had been present before operation.

2) Each electrocardioscope in use when a patient sustained a burn was checked for excessive 60-Hz ac leakage. The 60-Hz ac leakage measurements were made with a Simpson model 460 digital volt–ohm–milliammeter (DVOM). One lead of this meter was attached to ground and the other was attached in turn to each of the ECG electrodes, first with each electrocardioscope grounded and then with them ungrounded. The electrocardioscope cables were checked for breaks and the power cords were checked with a Simpson 460 DVOM for broken ground wires.[13]

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3) *Alarm systems of electrosurgery units* in use when patients were burned were examined.

Valley Lab SSE-2 electrosurgery units have no alarm systems. For all CSV Bovie electrosurgery units, the following steps were taken:

a) Examination of the function of both original and modified (fig. 1) § sentry alarm modules with and without the patient ground plate and cable attached to the electrosurgery unit.

It was verified that there are two wires from the electrosurgery unit to the patient plate. One of these wires is connected to ground at the electrosurgical machine, while the other is connected to the gate of a silicon-controlled rectifier (SCR) through a 1,000-ohm resistor.¶ The performance of a sentry alarm module was tested by attaching to the electrosurgery unit the patient ground plate and cable. This plate was placed on a wooden table and the electrosurgery unit main power switch was turned "on." At this moment the operation light should come "on" and the alarm should not sound. The patient ground plate was then disconnected from the electrosurgery unit and the procedure repeated. If the alarm failed to sound, defective systems were replaced.

To evaluate the function of the CSV Bovie sentry module further and to simulate a patient lying on a ground plate with a broken ground wire in the patient ground-plate cable, we determined the maximum resistance or impedance to the partially rectified ac current in the sentry module that can be present between the silicon-controlled rectifier gate and ground without triggering the alarm of the sentry module. The wire coming from the SCR gate was soldered to terminal 1 of a Bourns model 3509-S ten-turn 20,000-ohm linear potentiometer (fig. 2). A capacitor (Elmenco precision dipped Mylar tubular capacitor type 1MD-3-154) in series with a 5.11-ohm 1 per cent resistor was soldered across the fixed ends (terminals 1 and 3) of the variable ten-turn potentiometer. One of the fixed ends (terminal 3 of the potentiometer) was soldered to terminal 2, the slider arm. A calibrated ten-turn Duodial model RB-2M was attached to the shaft of the potentiometer (fig. 2). The Duodial was set to 0 resistance and the electrosurgery unit main power switch was turned on. The Duodial was then advanced until the alarm on the electrosurgery unit sounded. The resistance was recorded and the measurements repeated several times. During these evaluations of the sentry alarm module function, the partially rectified ac currents and voltages were measured across the ten-turn potentiometer. Peak currents were measured with a Hewlett-Packard model 1110A ac current probe. The probe was clamped to the wire coming from the SCR gate only. The current probe was attached to a Hewlett-Packard model 1111A ac current amplifier. The peak voltage was measured on channel 1 and the output of the ac current amplifier was measured on channel 2 of a Tektronix model 564 dual-beam storage oscilloscope, with a model 2B67 time-base, model 3A74 dc-2-mHz amplifier, and model C27 Polaroid camera.

4) *The electrosurgery patient ground plates and cables* were examined and x-rayed and measurements of conductivity were made with the Simpson model 460 DVOM.

5) *Examination of RF currents flowing during electrosurgery:*

a) Experiments on anesthetized dogs. Two 12-cm² silver electrodes were applied with MPI Mon-it No. 130 creme conductor paste, one electrode to the shaved neck, the other to

§ The silicon-controlled rectifier (SCR) is part of the sentry module. It connects to and controls the relay, which makes or breaks the ac current to the power transformer of the electrosurgery unit. The gate of the SCR controls the currents flowing between the anode and cathode of the SCR. As long as the partially rectified ac current flows in the gate circuit, the relay remains closed and the electrosurgery unit operates. In the event that the circuit is broken or the resistance to flow of the partially rectified ac current is increased above a critical value, for instance by a broken ground cable, the current keeping the relay closed is diminished. The relay then opens, sounds the alarm, and stops the electrosurgery unit.[11]

¶ Patients 1, 2, and 3 were burned when the original type of CSV Bovie sentry module was in use. Ritter Corp. modified all our CSV Bovie sentry modules to prevent damage when the patient ground-plate cable is broken and RF current surges into the gate of the SCR (fig. 1). Their modification protects against this problem only. The performances of modified and unmodified sentry modules were otherwise identical. Patients 4, 5 and 8 (table 1) were burned when the modified sentry modules were in use.

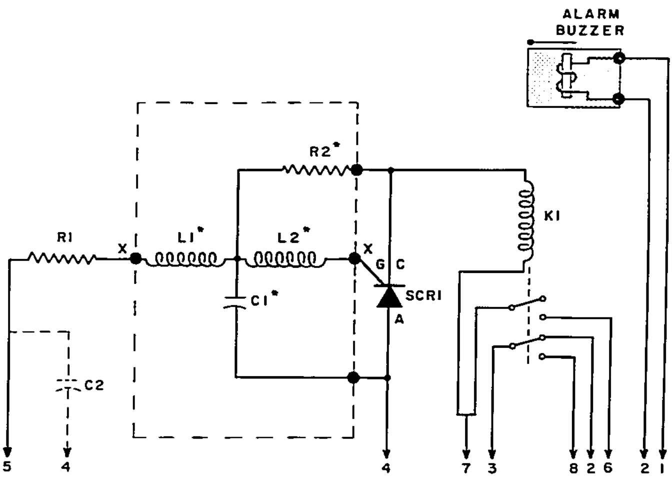

FIG. 1. Schematic of CSV Bovie sentry module. The area enclosed by the dashed line is the modification by the manufacturer's engineers, made to prevent surges of radiofrequency current from destroying the silicon-controlled rectifier (SCR). C = capacitor; K = relay; L = radiofrequency inductor (choke); R = resistor. Components marked by asterisks were added during the manufacturer's modification. They do not affect the normal function of the sentry module (see text). We have since added an extra capacitor (C2 of 0.1 microfarads at 3,000 volts) in order to provide a path to ground for any radiofrequency current entering the sentry module. The "X's" mark the point of insertion in the gate wire of the modification. Numbers designate male pin terminals on the sentry module which plug into the CSV Bovie. The functions of the pins are: 1, to ac line (117 volts); 2, to malfunction-indicator lamp; 3, to ac line (117 volts); 4, to ground at chassis of CSV Bovie; 5, gate wire to patient ground plate; 6, sentry module ac supply line (9.86 ac volts RMS); 7, off–on switch; 8, to primary winding of high-voltage power transformer.

the shaved lower abdomen of each of three 15-kg dogs that had been given 450 mg pentobarbital iv. Two 20 × 36-cm disposable patient ground plates (MPI, DGP1) were placed under the shaved backs of the dogs; one plate was placed under the thorax, and the other under the sacral area (fig. 3). Contact over at least 75 per cent of the plate was produced by the MPI Mon-it No. 130 creme conductor paste. To the shaved medial surfaces of both upper forelimbs and to the shaved area over the lower portion of the sternum were applied 3.8-cm² disposable silver ECG electrodes (Electronics for Medicine Inc.). The active cutting electrode of the electrosurgery unit used was connected to a Simpson model 137 (0–1,500-RF milliampere) ammeter (M1) by the standard 12-foot active electrode cable used in routine operations. The ammeter was connected in series to one of the 12-cm² silver electrodes by 18 inches of no. 18 insulated hook-up wire.

Both wires of the two-wire ground-plate cables (MPI type) were cut two inches from the patient end, soldered together, and attached in series with a Simpson model 137 (0–1,500 RF milliampere) ammeter (M2). The 18-inch wires of the Electronics for Medicine disposable silver ECG electrodes were attached to a bakelite junction box (Allied Radio Shack No. 270-232) via banana jacks and plugs to a three-pole rotary switch (Centralab type 1461). The rotor end of this switch was attached to one terminal of a Simpson model

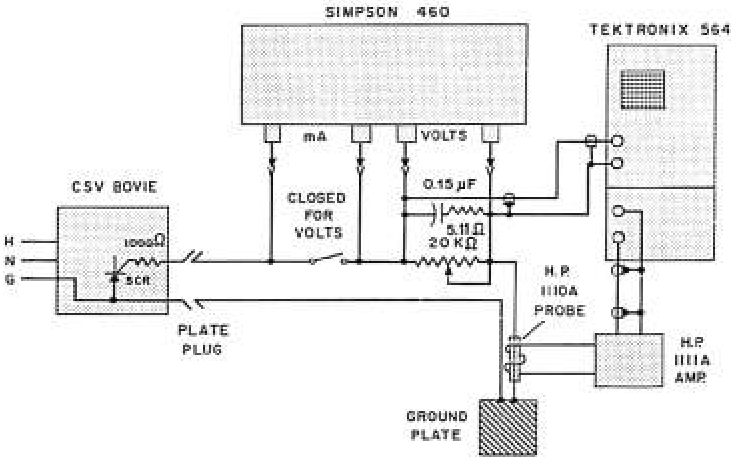

FIG. 2. Diagram of model used to simulate the electrical circuits present when the ground wire of the patient ground plate breaks. The 0.15-microfarad capacitor and ten-turn potentiometer, set to 1,000 ohms, simulate typical mammalian tissue impedance and capacitance. The switch (marked "closed for volts") across the milliampere input terminals of the Simpson 460 (DVOM) is closed in order to measure voltage and opened for measurements of current. G = ground, H = hot wire (ac line), H-P = Hewlett-Packard, mA = milliamperes, μF = microfarad, N = neutral wire (ac line), SCR = silicon-controlled rectifier, Ω = resistance in ohms, KΩ = 1,000 ohms.

137 (0–500-RF milliampere) ammeter (M3). The other terminal of the meter was attached to the rotor end of another three-pole rotary switch (fig. 3). The first pole of this switch was attached directly to ground; the second pole was connected to ground through a National R40-33, 3.3-millihenry ferrite-core inductor. The third pole was connected to a banana plug which was connected in turn to the ECG electrodes attached to the cable of Lexington D-303 and Electrodyne PMS-5 electrocardioscopes. The cables were connected to their electrocardioscopes with either the Electrodyne 108 cable with molded electrodes or standard Lexington C-301 cable, each with its standard extension. The total length of each of these cables with its standard extension was approximately 24 feet. The ground plate under the thorax was not grounded and the 12-cm^2 electrode on the abdomen was disconnected, while the patient plate under the sacral area was grounded through the ammeter to the electrosurgery machine ground. The RF current was then applied to the 12-cm^2 silver electrode on the neck and recordings were made from each ammeter. The RF current was next applied to the 12-cm^2 electrode on the abdomen, with the neck electrode disconnected, and the same recordings made. The ground plate under the sacral area was now disconnected and the ammeter and ground wire attached instead to the ground plate under the thorax (fig. 3). Measurements were again made with the RF current similarly applied in turn to the neck and then to the abdominal electrodes. The measurements were next repeated with both ground plates disconnected. All dogs were then sacrificed.

b) Surgical measurements. During routine operations on the chests or abdomens of six patients, a 20 × 36-cm disposable patient ground plate (MPI, DCP1) was placed under

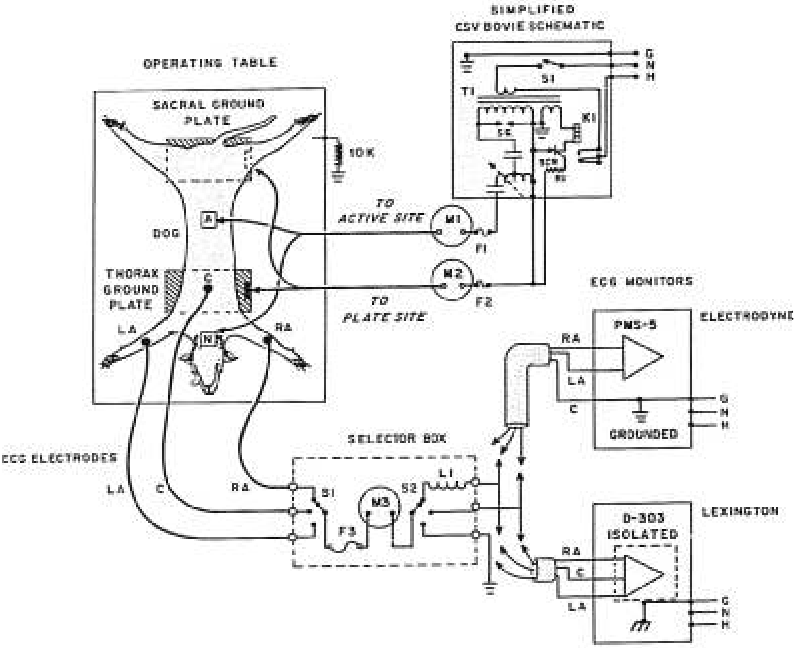

FIG. 3. Diagram of circuits used to test for radiofrequency current division in anesthetized dogs undergoing electrosurgery. The dogs were placed on a sheet-covered semiconductive operating table mattress with a 10,000-ohm (10K) resistance to ground. Electrocardioscope leads were placed on the left foreleg (LA), the right foreleg (RA), and the ground electrode over the sternum (C). The knife electrode was applied in turn to electrodes on the neck (N) and abdomen (A). Disposable ground plates had been placed under the sacrum and thorax. Measurements were made of currents flowing with first one ground plate in use and then the other. F = fuse; G = ground; H = hot wire (ac line); K = relay; L1 = 3.3-millihenry inductor; M = meter; N = neutral wire (ac line); R = resistor; S = switch; SCR = silicon-controlled rectifier; T = transformer. Details of meters are given in the text.

the buttock. CSV Bovie electrosurgery units were used. RF currents were monitored in type 108 cables (with molded electrodes) of the Electrodyne PMS-5 electrocardioscope system after the three electrodes had been placed across the front of the chest. One ammeter (Simpson model 137 0–500-RF milliampere) was attached in series, within one foot of the patient end, to each of the three electrode wires in a modified 108 electrocardioscope cable. In order to make this modification 12 inches from the patient end of the 108 cable, the rubber jacket and cable shielding were carefully removed for approximately one inch and the inner conductor was cut in two, soldered to the RF ammeters, and placed in a bakelite junction box (Allied Radio Shack no. 270-232). The inner conductor was not grounded and still functioned normally, as verified by an unaltered ECG signal on the electrocardioscope.

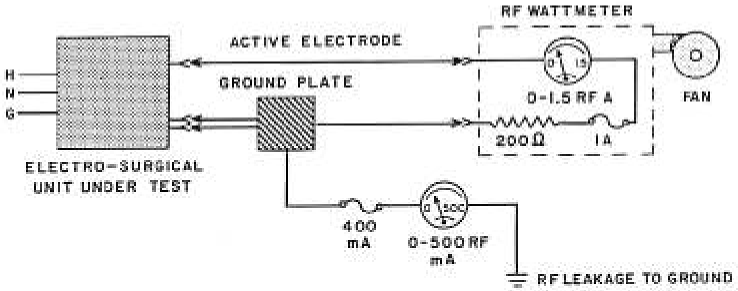

FIG. 4. System used to measure radiofrequency (RF) power and leakage to ground from electrosurgery units at each control setting. Results of these tests are shown in figures 7 and 8 and table 4. A = ampere; F = fuse; G = ground (ac line); H = hot wire (ac line); MA = milliamperes; N = neutral wire (ac line); RF = radiofrequency.

6) *Experimental testing of electrosurgical units.* The following units were classified as RF-grounded units from their schematics: Bovie models AG, CSV, PS/automatic and solid-state. The EMS ES-101[14] and Valley Lab SSE-2 (with optically coupled foot switch) electrosurgical units were classified as RF-isolated units; that is, their schematics showed that their RF current generator outputs were not directly connected to ground.[15] In order to test the RF isolation of the EMS ES-101 and Valley Lab SSE-2 electrosurgical units, the patient plates and cables were attached to the units and the patient plate was isolated from ground by placing it on a wooden stool. The active electrode was attached in series to a Simpson model 137 0–500-RF milliampere ammeter and thence to ground. The units were then activated in all cutting and coagulation modes, the controls turned up in steps, and the currents monitored on the ammeter. The controls were then returned to zero and the patient plate grounded. The controls of the units were then turned up again. Degree of isolation was determined by ratio of ungrounded to grounded current. These experimental procedures were then repeated with the "RF-grounded" units.

Electrosurgery machines were also tested against known impedance loads to simulate their operational performance. The patient plate cable and the active cutting electrode were attached to an RF wattmeter, which consisted of two Ohmite 2405, 100-ohm, 175-watt noninductive resistors, a Buss FO2A 1-ampere 250-volt fuse, and a Simpson model 137, 0–1,500-RF milliampere ammeter.[16] The patient-plate end of the wattmeter was attached in series to ground by a Buss 400-milliampere fuse and a Simpson model 137 0–500-RF milliampere ammeter (fig. 4). This ammeter recorded the RF leakage from the plate during the test of the electrosurgery units. The air circulation necessary to dissipate the heat generated during the tests was provided by an Oster model 202 portable blower (fig. 4). The controls of the electrosurgery units were increased in steps from zero and the current readings recorded.[17] Thus, the power (P) in watts of each electrosurgery unit could be calculated from:

$$P = I^2 \times R$$

where I is the current in amperes, read from the ammeter, and R is the resistance (200 ohms). Radiofrequency current waveforms were measured by clamping the ac current probe onto the active (knife) electrode wire and recording with a Tektronix 564 oscilloscope system.

7) *Evaluation of electrocardioscope cables and paste.* A Simpson model 137 0–1,500-RF milliampere ammeter was placed in series between a Bovie AG electrosurgery unit and its active, or "knife," electrode. This unit was

TABLE 1. Electrosurgical Burns*

	Operation	Site of Burn	Degree of Burn	Probable Cause
Patient 1	Cholecystectomy	Anterior chest under ground electrode	Third	Broken patient-plate ground wire; sentry circuit completed through patient
Patient 2	Excision of neuroma of foot	Anterior chest under ground electrode	Third	Broken patient-plate ground wire; sentry circuit completed through patient
Patient 3	Nephropexy	Anterior chest under ground electrode	Third	Broken patient-plate ground wire; defective silicon-controlled rectifier in sentry
Patient 4	Ethmoidectomy	Anterior chest under ground electrode	Third	ECG ground electrode near surgical field; current division
Patient 5	Cholecystectomy	Anterior chest under ground electrode	Third	ECG electrodes near surgical field; current division
Patient 6	Inguinal herniorrhaphy	Mid-abdomen under towel clip	Third	Automatic knife electrode against towel clip
Patient 7	Tracheostomy	Mid-scapular under ground electrode	Third	Patient ground plate emitted radiofrequency current while knife electrode in air and foot switch depressed on Valley Lab SSE-2
		Right chest under signal electrode	Second	
		Left chest under signal electrode	Second	
Patient 8	Radical right mastectomy	Right scapular signal electrode	Third	ECG signal electrode near surgical field; current division
Patient 9	Transurethral resection of the prostate	Anterior chest ground electrode	Second	Patient ground plate emitted radiofrequency current while knife electrode in air and foot switch depressed on Valley Lab SSE-2

* All patient ground plates were located under the buttocks.

used without its patient plate attached (in which mode it can be used clinically). The knife electrode was grounded and the power control of the electrosurgery unit advanced until 1,000 RF milliamperes was recorded on the ammeter. The knife electrode was then transferred in turn to each of the two molded electrodes of the PMS-5 Electrodyne electrocardioscope system. The molded electrodes lay on a wooden table and the 12-foot cable and 12-foot extension lay on the floor between the operating table and the electrocardioscope. The current was recorded from the ammeter. This procedure was then repeated for a Lexington D-303 electrocardioscope attached to a standard 12-foot cable and extension with disposable Lexington ECG electrodes, again on a wooden surface. These measurements on the Electrodyne and Lexington electrocardioscope systems were repeated after National R40-33 3.3-millihenry RF inductors had been inserted between the ECG electrode and the patient electrocardioscope cable.

Evaluation of electrosurgical conductive pastes. Five types of paste were evaluated:

1) Ritter Bovie Liquid Conductor (Chuckit)
2) MPI Mon-it No. 130 creme conductor paste
3) Valley Lab Lectrogel
4) Electrodyne Trucon Electrode Paste
5) EKG sol, Burton, Parsons and Co.

The test was accomplished by spreading approximately 2 inches of the paste to a depth of 0.125 inches on a wooden board and measuring conductivity across 1 inch of the material. In addition, we observed the effects of time on the pastes.

TABLE 2. Performance Variations of Sentry Modules in CSV Bovie Unit*

	Resistance When Alarm Sounded (ohms)	(1,000-ohm Resistance)				Voltage Supply to Silicon-controlled Rectifier in the Sentry Module AC (RMS)
		Voltage across Potentiometer		Current through Potentiometer		
		AC (RMS)	DC	AC (RMS)	DC	
Machine 1	3,600	1.87 v	1.10 v	1.94 ma	1.10 ma	10.1 v
Machine 2	2,300	1.75 v	0.90 v	1.81 ma	0.91 ma	9.1 v
Machine 3	9,800	1.86 v	1.14 v	1.73 ma	1.10 ma	10.6 v
Machine 4	11,300	1.70 v	1.01 v	1.57 ma	1.00 ma	9.8 v
Machine 5	13,800	1.16 v	0.78 v	1.20 ma	0.75 ma	8.5 v
Machine 6	8,400	1.76 v	1.03 v	1.63 ma	1.00 ma	10.0 v
Mean	8,200	1.68 v	0.99 v	1.64 ma	0.98 ma	9.68 v
SE	±1,822	±0.11	±0.05	±0.10	±0.11	±0.31

* RMS = root mean square; v = Volts; ma = milliamperes.

8) *Determination of RF current capable of producing symptoms.* Each of four volunteers had either a 3.8-cm² disposable silver ECG electrode or a Ferris Red Dot (1-cm²) (Hinsdale, Ill.) disposable electrode attached to the back of the hand. RF current was applied from a Bovie AG electrosurgery unit to the volunteers through the disposable electrode via a Simpson model 137 0–500-RF milliampere ammeter. The power controls were increased approximately every 10 seconds and the RF current monitored on a Simpson model 137 (0–500-RF milliampere) ammeter until heat, and finally severe pain, were perceived. These stepwise increases were continued on one subject (CMB) for 20 seconds until a second-degree burn of the hand was sustained.

Results

1) *Examination of patients.* Five of the nine patients sustained third-degree burns on their chests under the molded 7-cm² ground electrode of the 108 cable of an Electrodyne PMS-5 electrocardioscope system. One patient sustained a third-degree burn under a towel clip; another patient, undergoing tracheostomy, sustained a third-degree burn under the molded 7-cm² ground electrode and a second-degree burn under each of the other two molded 7-cm² signal electrodes of an Electrodyne PMS-5 electrocardioscope system. A further patient, undergoing a mastectomy, sustained a second-degree burn under a molded 7-cm² signal electrode placed on the scapular region of the back. The ninth patient, undergoing a transurethral resection, sustained a second-degree burn under a grounded 3.8-cm² disposable silver ECG electrode (Electronics for Medicine, Inc.) attached to an Electronics for Medicine electrocardioscope EAI-5.

Seven of the nine patients were burned while a CSV Bovie electrosurgery unit was in use. The burn under the towel clip was sustained while a PS/automatic cutting control Bovie attachment for the CSV Bovie electrosurgery unit was being used. During the transurethral resection and the tracheostomy, a Valley Lab SSE-2 electrosurgery unit with CSV Bovie switch and adaptor cable (E0008) was in use (table 1).

2) *Examination of electrocardioscopes and cables.* In all electrocardioscope systems the 60-Hz ac leakage current was less than 30 microamperes. One Electrodyne PMS-5 108 cable was found to have a 3-cm tear in its outer rubber coating. All power cords were found to have ground wires intact.

3) *Examination of alarm systems of electrosurgery units in use when patients were burned:*

a) One sentry alarm module was totally defective: the silicon-controlled rectifier was internally shorted. This module was replaced by the manufacturer (Ritter) with its sentry alarm circuit modification (fig. 4). The other five model CSV electrosurgery units in this hospital were similarly modified.

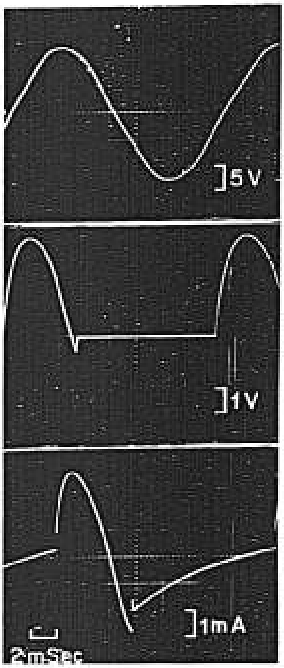

FIG. 5. Recordings from Tektronix 564 oscilloscope and camera system of the voltage and current waveforms, other than radiofrequency, observed in the sentry modules of CSV Bovie electrosurgery units. The upper panel shows the peak ac voltage supplying the sentry module; the middle panel shows the partially rectified ac voltage measured across the resistor–capacitor network. The lower panel shows the peak ac current through the network, measured by clamping the Hewlett-Packard 1110A ac current probe over the wire coming from the silicon-controlled rectifier in the sentry module. These ac and dc currents, necessary for the operation of alarm modules, have been implicated in patient burns.[7] We found no evidence that these currents caused the burns of any of the nine patients, but such ac currents could, with a broken patient ground-plate wire, cause ventricular fibrillation via a grounded indwelling intracardiac line containing electrolyte or via an intracardiac wire.

b) Further evaluation of the sentry modules' function revealed that the resistance necessary to trigger the sentry alarm system of the model CSV electrosurgery unit varied between 2,300 and 13,800 ohms (mean 8,200 ± 1,822 SE) (table 2). The voltages supplying the sentry module averaged 9.68 volts ac (root mean square, RMS) (table 2). The partially rectified ac voltage from the silicon-controlled rectifier gate of the sentry module, when the CSV Bovie electrosurgery unit is "on" but not producing radiofrequency current, measured across 1,000 ohms to ground, averaged 1.68 volts ac (RMS) and 0.99 volts dc: the peak ac voltage was 3.5 (table 2 and fig. 5). The corresponding currents through the 1,000-ohm resistor to ground averaged 1.64 ac millamperes (RMS) and 0.98 dc: the peak current was 3 ac milliamperes (table 2 and fig. 5).

4) *Examination of electrosurgery patient ground plates and cables.* Neither of the two wire cables was defective by external visual examination, but by conductivity measurements, three of 20 patient ground-plate cables (Medical Plastics Inc.) in use were found to have completely broken ground wires. A broken cable is shown in figure 6; these breaks are difficult to see on x-ray. Another cable had broken strands. The completely broken cables had dc resistances of infinity on the ground wires, while the other wires within the broken cables had dc resistances less than 1 ohm.

5) *Examination of RF currents flowing during electrosurgery.* The placement of the ground plate affected the RF currents flowing through the ECG electrodes (table 3). The nearer the ECG electrodes were to the cutting knife electrode and the farther away the ground plate, the larger the percentage of current flowing to ground through the ECG electrodes (table 3). When the ECG electrodes were attached to Electrodyne PMS-5 electrocardioscopes, twice as much current flowed into the ground reference ECG electrode as into the other high-impedance signal electrodes. With the Lexington model L-303, isolated electrocardioscope capacitive coupling to the grounded floor by the 12-foot ECG C-301 cable and 12-foot extension led to 200-RF ma

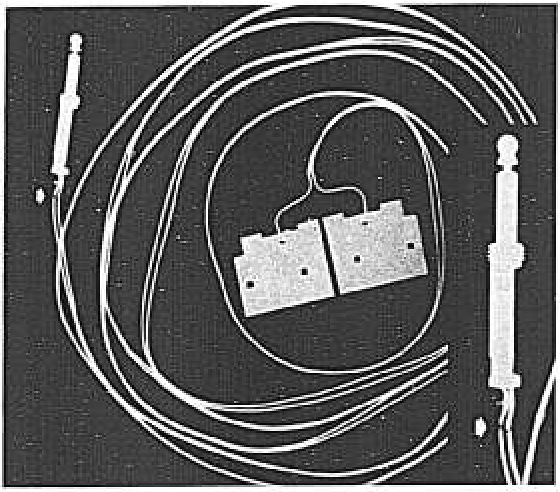

FIG. 6. Roentgenogram of a typical break (shown by arrow) in a patient ground-plate wire. These breaks are often difficult to see by radiologic examination; they cannot be detected by inspection or palpation and are probably best discovered by conductivity testing of each wire. However, with conductivity measurements, intermittent breaks are sometimes missed while the frayed wires show on roentgenograms.

flowing through signal electrodes when the ground plate was disconnected. The 3.3-millihenry ferrite-core inductors placed in series with each ECG wire prevented measurable RF current from flowing to ground through the ECG wires.

Surgical measurements. The average maximum RF current in the ground electrode of the Electrodyne PMS-5 electrocardioscope system was 175 ma (range 20–290). The current that flowed through this ground electrode during a median sternotomy was ten times greater when this electrode was placed on the upper arm (250 ma) rather than the calf (25 ma)—in each case the ground plate (MPI, DGP1) was under the buttock. The nearer the knife electrode to the ground electrode of the electrocardioscope system, the higher the RF current in the ground wire of its cable. The maximum time of peak recording did not exceed 10 seconds.

6) *Experimental testing of electrosurgical units: test of RF isolation of EMS ES-101 and Valley Lab SSE-2 electrosurgical units.* The knife electrode of the EMS ES-101 unit carried as much as 1,200 RF milliamperes even though the patient ground plate was not grounded; at each setting the current produced was only 25 per cent less than when the plate was grounded (table 4). By contrast, the maximum RF current carried through the Valley Lab SSE-2 active electrode when the patient ground plate was not grounded was 160 RF milliamperes (table 4). The higher RF current leakage in the EMS ES-101 results from excessive capacitive coupling between the primary and secondary windings of the toroidal RF output transformer. Some leakage results from the design of the foot switch and plate alarm circuit. With the RF-grounded units, as expected, performance was the same whether or not the patient ground plate was grounded.

The leakage of RF current from the patient ground plate during simulated operational use of the various electrosurgery units is shown in figure 7; for each control setting, the leakage current varied from machine to machine (fig. 7). The performance of Valley Lab SSE-2 electrosurgery machines depends on the foot switch used (fig. 8). We ascribe two of the burns to accidental grounding of one of the

TABLE 3. Radiofrequency Currents When CVS Bovie Electrosurgery Unit was Set at 40 in Cut Mode Number 2: Mean Values (all SE ± 15 per cent)*

ECG Electrode Location	Radiofrequency Current (ma) to Ground through			
	1 1.5-foot ECG Wire to Ground	2 Plate	3 24-foot ECG Cable and Electrodyne PMS-5	4 Plate
Cutting electrode on neck, ground plate under sacral area				
Left forelimb	310 (0)	450 (725)	150 (0)	650 (850)
Right forelimb	320 (0)	400 (725)	150 (0)	650 (850)
Sternum	200 (0)	480 (725)	430 (0)	450 (850)
Three electrodes†	500 (0)	550 (1050)		
Cutting electrode on abdomen, ground plate under sacral area				
Left forelimb	200 (0)	700 (900)	210 (0)	680 (890)
Right forelimb	185 (0)	700 (900)	210 (0)	680 (890)
Sternum	166 (0)	725 (890)	400 (0)	550 (950)
Three electrodes†	300 (0)	650 (990)		
Cutting electrode on neck, ground plate under thorax				
Left forelimb	160 (0)	725 (885)		
Right forelimb	180 (0)	725 (905)		
Sternum	150 (0)	700 (850)		
Three electrodes†	300 (0)	650 (900)		
Cutting electrode on abdomen, ground plate under thorax				
Left forelimb	125 (0)	825 (950)		
Right forelimb	125 (0)	800 (950)		
Sternum	125 (0)	800 (950)		
Cutting electrode on neck, no ground plate			24-foot ECG C-301 cable and Lexington D-303	
Left forelimb	725 (0)		200 (0)	
Right forelimb	725 (0)		200 (0)	
Sternum	725 (0)		233 (0)	
Cutting electrode on abdomen, no ground plate				
Left forelimb	680 (0)			
Right forelimb	680 (0)			
Sternum	680 (0)			

* Values in parentheses were made after a 3.3-millihenry inductor was inserted between ECG electrode or electrodes and ground.

† All three 1.5-foot wires combined through ammeter to ground. When current was measured through either forelimb or sternal electrode, that electrode was grounded and the other two were not.

foot switches used (fig. 8). The solid-state Bovie unit was monitored to setting 7 only, since its circuit breaker had to be reset repeatedly. We concluded that its surgical performance might be inadequate when high currents are needed for cutting under water, as in a transurethral resection of the prostate.

When the RF wattmeter was disconnected from a patient ground plate lying on a wooden stool and the active electrode of the Valley Lab SSE-2 was placed on another wooden stool, RF leakage to ground from the patient plate was 300 RF milliamperes after the machine controls had been set to maximum; of course, the active electrode was inactive at this time (RF current measuring less than 160 milliamperes to ground).

The output power of each machine except the solid-state Bovie unit during cutting was 300 watts. During coagulation the maximum power was 150 watts. The power generated by the solid-state Bovie unit was generally less than 200 watts when the circuit breakers blew.

All RF current and voltage waveforms are similar to those previously described.[5, 10]

7) *Evaluation of electrocardioscope cables.* When the knife electrode was activated on the grounded electrocardioscope electrode, the entire 1,000-RF milliampere current flowed in the ground wire. When the knife electrode, with the unit at the same setting, was applied to one of the signal electrodes, 450–700 RF milliamperes flowed in the signal wire of the electrocardioscope cable (table 5). Capacitive coupling was greatest with the longest cables; the cables we examined ranged from 30 to 100 picofarads per foot, according to their manufacturers. After insertion of the 3.3-millihenry inductors (chokes), no RF current flowed in the cables.

Evaluation of electrosurgical conductive pastes. The dc resistances of 1-inch amounts of the 0.125-inch layers of paste ranged from 10,000 to 20,000 ohms. The conductivities of the pastes were not statistically different. The Ritter (Chuckit) paste was not sufficiently viscous to remain within the circle. The Valley Lab Lectrogel and Electrodyne Trucon Electrode pastes were significantly dried out at six hours. At radiofrequency (0.5–3 mHz), the impedance of 1 inch of a 0.125-inch layer of each paste was less than 50 ohms.

TABLE 4. Tests of Isolation of "Radiofrequency-isolated" units with Plates Grounded and Ungrounded

Electrosurgery Unit Control Setting (Cutting)	Mean Radiofrequency Current (ma) through Active Electrode to Ground	
	Plate Grounded	Plate Not Grounded
EMS ES-101		
1	300	300
2	450	400
3	700	550
4	900	650
5	1,000	750
6	1,150	850
7	1,200	950
8	1,300	1,050
9	1,350	1,100
10	1,400	1,200
Valley Lab SSE-2		
1	300	40
2	450	75
3	550	90
4	650	105
5	750	115
6	800	130
7	950	145
8	1,050	150
9	1,200	155
10	1,300	160

8) *Determination of RF current capable of producing symptoms.* Two hundred RF milliamperes for 30 seconds produced reddening of the skin of an arm or hand of each subject. Three hundred RF milliamperes for 20 seconds produced pain and blistering; 400 RF milliamperes through 3.8-cm^2 disposable electrodes for 10 seconds produced unbearable pain. One exposure to 400 RF milliamperes through a 1-cm^2 electrode (Ferris Red Dot) for 20 seconds produced a second-degree burn on the back of a volunteer's hand.

Discussion

Nine patients were burned owing to the use of radiofrequency current in surgery. The equipment failures and operational faults that caused the burns of eight of these patients were not recognized by the operating team—nor would they have been recognized by most teams. Three of the burns could possibly have been prevented by conductivity measure-

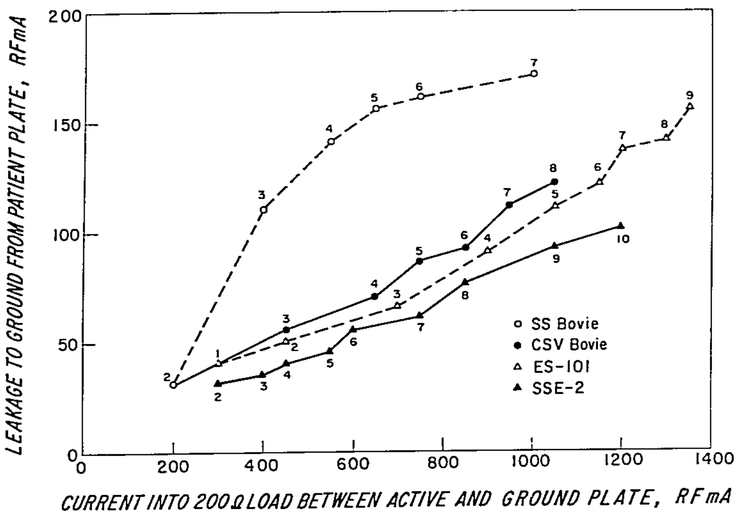

FIG. 7. Leakage of radiofrequency (RF) current from the patient ground plate during simulated operational use of the various electrosurgery units. The method of testing is shown in figure 4. The numbers on the lines represent control settings of the various electrosurgery units. O——O represents the performance of the solid-state Bovie unit set on cut mode number 2. We regard this leakage of RF current as potentially dangerous. ●——● represents the CSV Bovie electrosurgery unit set on cut mode number 2; △——△ represents ES-101 cut mode number 2," and ▲——▲ represents SSE-2 in the blend mode. Note that while the output currents of the knife electrode differ for any control setting number, the radiofrequency leakage currents from the patient ground plate are nearly the same at each output level—except that the solid-state Bovie unit has excessive leakage from the patient ground plate. Ω = ohms, ma = milliamperes.

ments on the ground wire of the two-wire ground-plate cable. X-rays of the cables are not satisfactory for detecting breaks in these wires, and even with conductivity measurements intermittent breaks can be missed. Moreover, wires can break during operation. Nonetheless, we do now recommend routine preoperative conductivity testing; for example, with ohmmeters or with electrosurgery unit alarm systems. A simple procedure is to attach the ground plate and cable to the electrosurgery unit and activate the unit with the plate on an insulated surface. Next, the plate should be removed from the cable: the alarm should then sound. If it does not, the cable must be removed from the machine. If the alarm still does not sound, the electrosurgery machine is defective and should be removed for repair, and the cable tested with another machine or ohmmeter. Resistances in the patient ground-plate cable should measure less than 1 ohm. Dobbie[5] and Wald *et al.*[11] have each recently reported a patient burn due to a broken ground wire in the patient ground-plate cable.

Another cause of RF burns is defective alarm systems. No alarm system currently available warns against inadequate contact between the patient and the ground plate, but they should protect against broken ground wires. We found internal shorting of the silicon-controlled rectifier in the sentry module

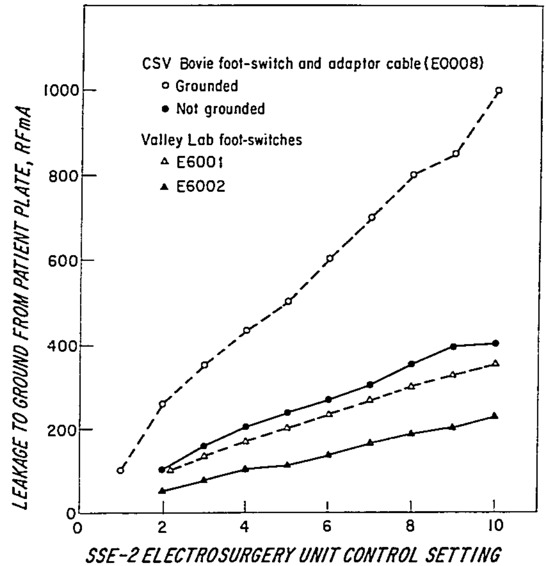

FIG. 8. When a Valley Lab SSE-2 electrosurgery unit is used with different foot switches, significant radiofrequency (RF) current can leak from the patient ground plate. This leakage occurs when the foot switch is activated but the cutting knife is not in contact with the patient. This current, largest with CSV Bovie foot switch and Valley Lab adaptor cable (E0008), burned two patients when the foot switch was accidentally grounded. One burn occurred when the foot switch became grounded by a metal footstool; the other when water and blood accumulated on the operating room floor. This adaptor cable is no longer on sale. Foot switches E6001 and E6002 operate similarly when grounded. The E6002 foot switch, when attached to the back of the SSE-2 electrosurgery unit and optically coupled, is preferable because it does not carry RF current. Valley Lab SSE-2 S/N electrosurgery units with serial numbers ending in J have this optical coupling feature. ma = milliamperes.

of our electrosurgery units. A sixfold difference in resistances necessary to trigger the alarms that were functional was due to variation in the General Electric type C20 silicon-controlled rectifier. This variation, although within the specifications of the rectifier, is a design fault of the sentry module, since the sentry alarm system is completely unable to detect when an alternate ground path is present. For instance, different broken patient ground-plate wires used for Patients 1 and 2 were not detected because the partially rectified ac current flowed through the patient impedance (approximately 1,000 ohms) to ground via the ECG ground electrode. The only value of the sentry system of the CVS Bovie electrosurgery unit is when the patient ground plate is on a totally isolated surface. This sentry alarm system does not function when in contact with a patient or any other impedance to ground, for instance, a conductive operating table mattress. The assumption that this type of alarm will sound when the ground wire of the patient ground plate breaks during operation is totally false—rather, the patient is burned and the electrosurgery unit continues to function.

In three patients the burns under the ECG ground or signal electrode were caused by RF current division within the body. Although Dobbie[5] has suggested that it is unlikely that burns are caused by current and voltage division when the patient ground plate is placed under the buttocks, we found dangerous current division in our patients and dogs. The smaller size of the United States disposable ECG electrodes as opposed to the 15-cm^2 electrodes from the British Department of Health and Social Security reported by Dobbie is the probable explanation for Dobbie's view.[5] Certainly he agrees that anesthetists frequently get detectable "RF shocks" by touching patients in whom electrosurgery is being used; the nearer the electrosurgical site,

TABLE 5. Capacitive Coupling in ECG Cables*

Electrodyne PMS-5 (grounded)			
Cable type	Electrodyne 108		Electrodyne Snap model
Cable length (feet)	12	24	24
Current to signal electrode	450	600	500
Current to ground electrode (radiofrequency ma)	1,000	1,000	1,000
Lexington D-303 (isolated)			
Cable type	Electronics for Medicine		Lexington C-301	
Cable length (feet)	12	24	12	24
Current to signal or ground electrode (radiofrequency ma)	300	550	400	700

* Current flowing after setting knife electrode to 1,000 radiofrequency milliamperes. The knife was applied to individual ECG electrode wires in turn without resetting power controls.

the more potential danger for the anesthetist. During the ten-month period of the present study, two of our anesthesiologist colleagues received second-degree burns of their fingers from this cause. Body impedances at low frequencies range from 500 to 10,000 ohms.[18] When electrosurgery units are used the impedance of the body is much lower because of the capacitive components in body tissues—hence, significant current division is not surprising. RF currents do not follow the shortest distance to ground, but go by the path of least impedance.[19, 20] Therefore, ECG electrodes must be placed as far away from the operative field as possible and the patient ground plate as near; moreover, the ECG electrodes should be as large as practical. The reason for large ECG electrodes is that a burn is produced by high current densities per unit area. We found that approximately 100 RF milliamperes per sq cm skin for 10 seconds produced a burn; Dobbie says this current gets unpleasantly hot in only 10 seconds.[5] Such a current through the ECG ground electrode can easily be produced during routine operations on the neck with the ECG ground electrodes on the chest and the patient ground plate under the buttocks. In the early 1960's, needles were commonly used as ECG electrodes during surgery—following reports of needle burns, this practice was abandoned in many centers.[8] This hospital stopped using needle electrodes for electrocardiogram monitors in 1967. Telethermometer probes, however, have produced rectal burns even with the patient ground plates properly positioned and with cables intact.

Voltage or current potential differences between different sources of ground may present problems in the use of electrosurgery units.[21] Repeated tests of our grounding systems failed to reveal abnormal grounds within our operating rooms. Ground sources for biomedical equipment should be checked periodically.[22] Sixty-Hertz ac isolation transformers provide no isolation at electrosurgery frequencies—consequently, they are of no use in preventing burns from radiofrequency current. However, RF inductors (chokes) do prevent passage of RF current into ac power lines as well as into electrocardioscope cables. The RF inductors must be attached at the patient end of the ECG cables, since capacitive coupling occurs in these cables. In Patients 7 and 8, burns occurred under the high-impedance signal electrodes. These burns can only be explained by capacitive coupling of RF current to ground through the cable insulation to the grounded operating room floor. The cables used for Patients 7 and 8 were carefully inspected and were faultless. The input impedance into the electrocardioscopes used on these patients was greater than 10,000 ohms; thus, these patients' burns were produced by capacitive coupling to the grounded shield of each cable. We have shown in this study that such capacitive coupling occurs. Isolated electrocardioscopes,[21] although they provide protection for the patient from 60-Hz current shocks, are not the entire answer during electrosurgery; capacitive coupling in the cables of these isolated electrocardioscopes provides pathways for RF current to ground. The longer the cable and the more it touches the grounded floor or becomes wet, the more likely RF current is to flow to ground. Moreover, to prevent capacitive and inductive coupling, wires carrying RF current should not be bundled together or placed next to other wires, nor should they be towel-clipped to the patient or hidden under surgical drapes. We suggest the combination of isolated electrocardioscopes and RF inductors on the patient end of the electrocardioscope cables. These RF inductors do not suppress ECG signals, and they do not remove all interference when the knife electrode is activated. Series resistors may also be used. To prevent other interference and artifacts from appearing in the ECG signal and to prevent electrocardioscope-input impedance changes, we used the RF inductors.

These problems of broken cables, defective alarm systems, and current division are complex and difficult for the average person to understand. Training in these matters is limited, and the problem is compounded by the commercial interests of biomedical equipment manufacturers. For instance, compatibility between systems is desirable, yet for safety often insufficiently tested. Patients 7 and 9 were burned because a CSV Bovie foot switch and adaptor cable (E0008) were used with a Valley Lab model SSE-2. This cable was advertized to allow this combination. When this CSV Bovie foot switch is depressed and the knife electrode is not in contact with the surgical incision, RF current leaks to ground from the patient plate (fig. 8). The amount of this leakage increases 250 per cent when the foot switch itself becomes inadvertently grounded. This happened twice in 32 surgical operations, and the relatively large RF currents (to 1,000 RF milliamperes) found their way to ground through the ECG ground and signal electrodes; the areas of skin under the ECG electrodes were burned, because 3.8-cm^2 electrodes cannot carry more than 500 RF milliamperes without causing burns. Extreme care must always be taken to prevent grounding of an isolated RF electrosurgery unit system such as the Valley Lab SSE-2.

Other authors have pointed out the risk of the use of electrosurgery units.[2,3] However, despite preventive maintenance programs, electrosurgery unit burns continue to occur. They are caused by many mechanisms, including RF current division. This current division is not satisfactorily prevented by standard equipment. Hence, we suggest the following steps to prevent burns: 1) Insert 3.3-millihenry RF ferrite-core inductors (chokes) in series at the patient end of each ECG wire (3- to 10-millihenry ferrite-core inductors are satisfactory). 2) Always test the alarm system of the electrosurgery unit before each surgical operation. 3) Place the ECG electrodes on the patient as far away from the site of the surgeon's incision as practical and the patient ground plate as near the surgical site as is compatible with excellent contact. 4) Never coil or clip electrocardioscope cables. 5) If the electrosurgery unit alarm circuit contains either a silicon-controlled rectifier or a transistor, check that it cannot be damaged by an RF current surge; if it can, get the manufacturer to modify the alarm circuit. 6) Have a preventive maintenance and educational program on electrosurgery and electrocardioscope units and cables; there are many models, each with design advantages and disadvantages. 7) Never use needle ECG electrodes. In the six months since we instituted all these steps we have not had another electrosurgery burn. If, despite these safeguards, a burn does occur, we suggest that as a start to investigation you follow sections 1–4 of our "methods" protocol.

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Obstetrics

FETAL OXYGENATION AND HEART RATE An experimental model in the subhuman primate where the cardiovascular and acid–base state of the near-term fetus can be directly monitored during labor has been developed. The relationship between late deceleration of the fetal heart rate, acid–base state, and level of oxygenation was studied in a series of 30 experiments. Fetal acidosis, hypoxia, and hypotension during labor were associated with an increase in baseline heart rate and late deceleration of the fetal heart rate following each uterine contraction. The late deceleration appeared as a marked transient bradycardia and was accompanied by a further decrease in fetal oxygen levels. In well-oxygenated fetuses, heart rate or the level of oxygenation during uterine contractions did not change. Late deceleration of heart rate was abolished or suppressed when the level of fetal oxygenation was increased by administration of a high concentration of oxygen to the mother. However, since fetal acidosis and hypotension persisted despite improved oxygenation, it is concluded that fetal hypoxia is the essential component leading to late deceleration of the heart rate. (*James, L. S., and others: Mechanism of Late Deceleration of the Fetal Heart Rate, Am. J. Obstet. Gynecol. 113: 578–582, 1972.*)