PREFACE

This book is written mainly for attorneys, physicians and investigators who are concerned with accidents associated with electric current. The most identifiable audiences consist of emergency medical personnel, biomedical engineers, manufacturers of medical devices, electric power companies, expert witnesses and accident investigators. The material is presented in two ways: non-technical and technical; the former is for attorneys and physicians, the latter is for their expert witnesses and engineers. The contents of this book are based on about fifty years of personal research and teaching medical and biomedical engineering students. Material has been included from experience as an expert witness for plaintiffs and defendants in many litigations involving electrical injury. There is no typical electrical accident, and it is hoped that the selected accidents described here and the material in the chapters will allow the reader to explain the cause of any particular electrical accident.

The first chapter presents a short history of electrical accidents, along with selected accident descriptions in the home, work place and hospital. Chapter 2 deals with the fundamental processes whereby electric current stimulates excitable tissue, such as sensory receptors, nerve and muscle. The response to the passage of low-frequency alternating current through the body e.g. muscle stimulation, ventricular fibrillation and burns, are covered in Chapter 3. Lightning and lightning injuries are discussed in Chapter 4. The effect of high-frequency (electrosurgical and diathermy) currents, and the type of injury encountered, are discussed in Chapter 5. Because current preferentially seeks tissues with the lowest resistivity, a knowledge of the resistivity values for tissues, organs and body fluids permits estimation of the current path; Chapter 6 provides such information. The same chapter presents information on the resistance of body segments and of a contacting conductor, showing the nonlinear nature of such contacts where tissues are boiled, charred and burned.

Because there are so many types of electrical accidents, it is hoped that the material contained in this handbook will allow the reader to understand the cause and the nature of specific electrical injury. The accident investigator should be able to identify the cause of an accident, whether due to carelessness or an act of God. The diagnostician and therapist need to know the effect of electric current and its pathway to select the appropriate therapy. It is hoped that all who have an interest in electrical accidents will find the information that they seek in this handbook.
Many have provided valuable information that has been included in this handbook, and the author hereby recognizes such assistance. I wish to thank Timothy Malloy, a patent attorney who taught me about the legal aspects of scientific information and what is expected of an expert witness in the tense atmosphere of the courtroom. Larry Conrad of Public Service Indiana Energy and Harold E. Amstutz, DVM of Purdue University are to be thanked for providing many papers and monographs on stray voltage. Dr. Amstutz also provided a wealth of literature on the environmental aspects of high-voltage power lines. Special thanks must go to Prof. Emeritus Theodore Bernstein of the EE Department of the University of Wisconsin for sharing the treasure chest of information that he has collected and so eloquently presented in papers and lectures; many of the latter I have attended and been entertained and informed by Ted's unique presentation style.

L.A. Geddes
Jan. 1, 1994
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Chapter 1
ELECTRICAL ACCIDENTS

INTRODUCTION
Generators that convert mechanical energy to electrical energy first appeared around the middle of the 19th century; electrical energy was first used to drive motors in factories and in locomotives. The outdoor gas lamps were replaced by electric arc lamps for street lighting in the late 1800's. However, it was the development of the carbon-filament electric lamp by Swan in the UK and Edison in the US in 1879 that brought electricity into the home. Edison in the US and Siemens in Germany were quick to sell electrical energy. Edison's direct current could not be transmitted efficiently very far from the generating station because of the need for large-diameter conductors. It was Tesla and Westinghouse who solved this problem by using alternating current, thereby eliminating the distance limitation with a transformer to step up the voltage for long-distance transmission with low current, requiring only small-diameter conductors. A step-down transformer at the user site recovered the electrical energy at any desired voltage.

HISTORICAL BACKGROUND
With the increasing availability of electrical energy from the mid 1850's, there arose the opportunity for accidents. Jex-Blake (1913) was the first to collect early accident reports and wrote: "I believe that no loss of human life from industrial currents of electricity occurred before 1879, though currents strong enough to have caused death were employed in lighting the operatic stage in Paris at the first performance of Meyerbeer's Le Prophête as long ago as 1849, and in lighthouses on and off the coast of England in 1857. In 1879 a stage carpenter was killed at Lyon by the alternating current of a Siemens dynamo that was giving a voltage of about 250 volts at the time. The man became insensible at once and died in twenty minutes; artificial respiration was not applied. The first death in this country (UK) took place at a theater in Aston, outside Birmingham, in 1880, where a bandsman short-circuited a powerful electric battery, became insensible, and died in forty minutes." As will be seen, modern electrical accidents have rather similar scenarios; Table 1.1 presents a recent summary of death statistics in the US (1987–89) due to electricity.
MICROSHOCK AND MACROSHOCK

The term "microshock" refers to cardiac arrhythmias produced by low-intensity current passing through the heart, usually via an intravascular or intracardiac catheter; microshock is discussed elsewhere in this book. The term macroshock is used to describe all other shocks. Electrocution refers to the loss of life due to electric current. Although there is no standard electrical accident, it is useful to provide an overview of the types of injury that can occur. The author prefers to distinguish between cases in which there has been obvious current flow through the body (or part thereof) and cases in which there was no obvious current flow through living tissue. Examples of the former are easily recognized. Examples in which there was injury with no current flow through the body would be eye or ear damage, or a burn resulting from being present when a sudden high-current discharge occurred, accompanied by a flash and an acoustic shock wave, as with an electric arc or lightning. Arc welders can sustain such flash injuries.

Injury can occur with a very low current flowing through the body (or a segment thereof) due to a startle reaction by the surprise encounter of a voltage source which produces a mild shock. If the subject were standing on a ladder when the shock was encountered, equilibrium can be lost and injury results from the fall, not due to the current flow. Physiological and pathological responses can result from electric current, depending on: 1) the current pathway, 2) type of current, 3) its duration of flow and 4) magnitude. Moderate power-line (50–60 Hz) current passing through the arms, legs and chest muscles can produce strong muscle contractions; pain often lasts long after current flow has stopped. Current flowing through the thorax can contract the respiratory muscles and impair or prevent continued breathing. A slightly higher power-line current passing through the chest can cause ventricular fibrillation, a

Table 1.1: Deaths in the US due to electrical injury, 1987-1989*

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>1989</th>
<th>1988</th>
<th>1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic wiring and appliances</td>
<td>143</td>
<td>122</td>
<td>121</td>
</tr>
<tr>
<td>Generating plants, distribution stations, transmission lines</td>
<td>143</td>
<td>165</td>
<td>177</td>
</tr>
<tr>
<td>Industrial wiring, appliances and electrical machinery</td>
<td>61</td>
<td>75</td>
<td>64</td>
</tr>
<tr>
<td>Other and unspecified electric current</td>
<td>355</td>
<td>714</td>
<td>760</td>
</tr>
<tr>
<td>TOTAL</td>
<td>702</td>
<td>714</td>
<td>760</td>
</tr>
</tbody>
</table>

*From Accident Facts 1992
condition in which all fibers of the main pumping chambers (ventricles) of the heart contract and relax randomly and cardiac output falls to zero. Irreversible brain damage starts to occur within three minutes. Therefore prompt cardiopulmonary resuscitation (CPR), followed by defibrillation, is essential for survival. Such current flowing through the respiratory center at the base of the brain can arrest breathing; again, prompt resuscitation is necessary for survival.

Higher current will produce heating and burns. The heating is proportional to the current squared and the duration of flow, as well as the area of contact. The concept of energy density factor, namely the current density squared multiplied by the duration of current flow (amps per sq. cm. squared multiplied by time), was introduced by Pearce et al. (1983) to provide a means for quantitating the severity of electrical burns due to radio-frequency current.

A more complicated scenario is associated with lightning injury, where there may be a burn as well as respiratory arrest and the loss of consciousness due to current flow through the brain.

**JOULE HEATING, ARCS AND FLASHES**

The thermal processes associated with electric current are Joule heating and arcs and flashes. Joule heating is the familiar temperature rise due to a current flowing through a conductor, examples of which are the electric toaster and stove. The temperature rise depends on the square of the current (I), the resistance (R) of the conductor and the duration of current flow (t in sec). The number of calories produced is \(0.24I^2Rt\). One calorie is the energy required to raise one gram of water one degree Centigrade. The temperature rise \(\delta T\) in °C for a mass of m gram with a specific heat of S is \(0.24I^2Rt/mS\), assuming no heat loss. Therefore, if current is injected into the body, without an arc occurring at the contact points, the intervening tissues will be heated. However the current flow between the contact points will not be uniform because of the differing conducting properties (resistivities) of the body tissues and fluids. The current density (amps per square centimeter) will be highest in the lowest-resistivity tissues. Moreover, the current density at the contact site will not be uniform.

In electrical accidents in which current flows through the body from skin-surface contacts, there is usually a thermal injury on the skin due to arcing at these sites. An arc represents the breakdown of an insulator (dielectric). All dielectrics, including air, have a limit to the voltage/cm that they can sustain without becoming ionized, resulting in an arc, i.e. an intense flow of ions and electrons, producing radiant energy in the form of light and heat. The temperature in an arc is typically 5,000 to 6,000°C. Therefore nearby flammable objects can be ignited. When the voltage between two conducting bodies in air exceeds about 75,000 volts/inch (pk), an arc is struck.
This breakdown voltage depends on the barometric pressure, the temperature and the shape of the conductors. Arcing occurs at a lower voltage for pointed conductors. Figure 1.1 illustrates the relationship between breakdown voltage (peak) and air-gap length for 760 mmHg barometric pressure and 25°C for pointed (needle) conductors and smooth spheres. The breakdown voltage is approximately proportional to the pressure and inversely proportional to the absolute temperature in degrees Kelvin (ITT Handbook 1968).

When an arc is struck, the voltage between the conductors drops considerably. In fact it takes many times the voltage to strike an arc
compared to that which sustains it. Bernstein (1993) stated that it requires about 50 volts/inch to sustain an arc with alternating current.

When an arc is struck there is an explosive liberation of energy which includes a shock wave. Privette (1993) reported that light-weight clothing was blown off a manikin at a distance of six inches from a one-foot arc carrying 8,000 amperes for 166 msec. He reported that the heat flux at six inches from such an arc is 171 calories per square cm-seconds. For 10 cycles of current (0.166 sec), the heat flux is 28 cal/cm². The radiant thermal energy emitted by such a pulse melted polyester underwear beneath protective clothing on a manikin. Note that these events were not associated with current flow through the manikin.

**BURNS**

The reciprocal nature of temperature and exposure time for a first-degree burn (skin reddening) was reported by Moritz and Henriques (1947) who used the pig, the skin of which is a good analog of human skin. Using a copper block, heated to different temperatures, they determined the relationship between temperature and exposure time for a first-degree burn, which is reddening of the skin, much like a mild sunburn. Figure 1.2 shows that the same first-degree burn can be produced by a high temperature presented for a short time as a low temperature for a longer time. The asymptote is the lowest temperature for a first-degree burn for an infinitely long exposure time which requires about 42°C. Curves for second and third-degree (full-thickness) skin burns were not obtained, but it is obvious that they would lie above the first-degree burn curve.

![Figure 1.2: Temperature versus exposure time for burns. (Redrawn from Moritz and Henriques 1947).](image-url)
Another important aspect of a burn caused by a metal conductor that injects current to the skin is the nonuniform current density distribution thereunder; Nelson et al. (1975), Overmeyer et al. (1979), Caruso et al. (1979) and Pearce et al. (1983, 1986) all demonstrated this fact. Figure 1.3A illustrates the current density under a circular skin-surface electrode; note that the current density is highest under the perimeter of the electrode. Recall that the heating depends on the current density squared. Therefore the skin under the conductor perimeter will be hotter than under the center. Figure 1.3B is a thermogram obtained just after removing a circular electrode that delivered current into the skin. The high-temperature (white) ring identifies the perimeter of the electrode. Many accounts of electrical burns describe this characteristic pattern.

**CURRENT FLOW AND CONTACT SITES**

In all cases of electrical injury, the investigator seeks to provide a rational explanation for the event; contact sites provide useful information on the current path. The terms entry and exit sites are often used, being derived from the study of gunshot wounds where the entry wound is small and the exit wound is large; this terminology is not appropriate with electric current injury. If one contact site is small and the other is large in area, the injury will be more severe at the small-area contact site because it is the current density squared multiplied by the duration of current flow that determines the heating and hence the extent of injury.

In a particular case, the voltage is known, but the current and its duration are not. The current is equal to the source voltage divided by the impedance of the circuit, which consists of three parts: 1) that of the two contact sites, 2) that of the body segment through which the current flows and 3) the impedance of the voltage source, which in the case of power-line current, is low. Many investigations have been made of the impedance offered to power-line current applied at various sites on the body. It has been established that the circuit consisting of the contact sites and that of the body segment is nonlinear, i.e. the overall impedance decreases with increasing voltage, the reduction being the greatest for voltages up to about 200 volts. This reduction in impedance is due to breakdown of the dielectric (insulating) properties of the skin, as well as local heating. According to Lee (1977), from 200–500 volts the body-circuit resistance is relatively constant, amounting to 500–1,000 ohms. Detailed information on this relationship is found in Chapter 6.

When a high current flows for an appreciable time, the tissue is heated. Because living tissues are made up largely of electrolytes, it is useful to recognize that electrolytes have a negative coefficient of resistivity, amounting to about 2% decrease in resistivity for a 1°C increase in temperature. Therefore as the current flow is prolonged, the tissue temperature rises and its resistance decreases, resulting in a
further increase in current and a further reduction in resistance etc. When the tissue fluids boil, there is an increase in resistance.

Figure 1.3: (A) Theoretical current density distribution under an electrode delivering current. Redrawn from Overmeyer et al., (1979). (B) Thermogram illustrating skin temperature under a circular disk electrode on the thigh after immediate removal of the electrode. (From Geddes and Baker, Principles of Applied Biomedical Instrumentation, 3rd edition, New York 1989. John Wiley & Sons. By permission.)
When an arc occurs, there may be a further increase in impedance if the current flow becomes intermittent. Therefore the events at a burn site can change rapidly; Chapter 6 provides additional information on this subject.

**ELECTRICAL ACCIDENTS**

Electrical accidents can occur in the home, workplace, hospital, indoors and outdoors. The source of the electricity can be the power line, devices connected to it or lightning. The types of electrical accident are many and can be bizarre. It has been said wisely that electricity and water do not mix. The presence of water not only provides a means for improving contact with the body, but also provides a ground-return path. Water issuing from a tap or hose provides an excellent ground. With these facts in mind it is useful to examine a few common accident scenarios. Additional explanations for these accidents can be found in the chapters that follow.

**HOME ACCIDENTS**

The home can be a hazardous environment because it has both a source of electrical energy (the power line), grounded devices and water. In reviewing the following cases, recall that one side of the domestic power line is grounded (see Chap 3). The letter G identifies cases investigated by the author.

Case 1G. An adult male came out of the shower and sat on the stainless steel counter surrounding the sink. He reached up and pulled the beaded metal chain on the light fixture to turn on the light. He received a shock, became unconscious immediately and fell to the floor. When the paramedics arrived about 10 minutes later, the victim was cyanotic (blue) and pulseless. He was given CPR (cardio-pulmonary resuscitation), after which the ECG showed coarse (low-frequency) ventricular fibrillation. Defibrillation was attempted but fibrillation occurred again and he was pronounced dead on arrival at the hospital. Obviously the beaded metal chain was in contact with the hot (ungrounded) side of the power line and the current flowed in the head-to-foot direction, producing ventricular fibrillation.

The invitation to disaster presented in Figure 1.4 illustrates the hazard when a grounded subject comes into contact with the 60-Hz power line via faulty insulation of the beaded pull chain that turns the light on. A similar scenario is popular in murder mysteries in which a subject in a bathtub is using a line-operated appliance, or one is thrown into the bathtub.
Case 2G. A householder was standing on a metal stepladder in the basement starting to repair a light fixture. The switch was off and there was some water on the floor. When he touched one of the wires to the fixture, he received a strong shock and fell off the ladder, injuring his back. On investigation, it was found that the light switch was in the cold (ground) side, rather than the hot (ungrounded) side of the power circuit. His fall disconnected him from the power line and probably saved his life.

Case 3G. A householder was using a knife to dislodge a piece of toast that failed to emerge from an automatic toaster which was on a grounded metal surface. The knife touched the red-hot element and the toaster housing. A flash occurred, molten metal injured the householder’s hand, and the fuse blew. The subject escaped with minor injury.

Case 4G. An adult female was using the telephone during a thunderstorm. There was a lightning strike nearby and the woman was thrown from her chair to the floor. She felt a shock to the head and complained of ringing in the ear with temporary hearing impairment.
It is important to recognize that lightning is characterized by a series of very short-duration pulses (see Chapter 4) and that an ohmic contact is not needed between the subject and the telephone. The metal parts in the headset and the hand and the head form the “plates” of a capacitor through which very short-duration pulses pass readily. Whether the muscular response was due to the current flow or the startle reaction due to the loud auditory sensation is not known. The subject returned to work on the following day and recovered completely.

There are reports of rodents chewing on the insulation of a two-conductor 120-volt, plastic insulated cable. When the insulation is gnawed through, the exposed conductors can pass current through the tissues or can become short circuited and an arc occurs, burning the rodent; such a spark can cause a fire. Rodents are not the only subjects that chew power-line cables; there are cases of children chewing extension cables. Severe oral lesions occur when the two conductors come in contact in the mouth.

**INDUSTRIAL ACCIDENTS**

Case 5G. At the completion of work at an outdoor construction site where cement had been poured, a worker was sent to clean out an electrically operated (230-volt) cement mixer with a water hose. His co-workers noticed that he had not returned and one was sent to check up on him. The worker was found several feet from the mixer, pulseless and not breathing with his feet and head in line with the opening of the mixer. The hose was found nearby, water still issuing therefrom. When the paramedic arrived, the victim could not be resuscitated and the ECG showed coarse ventricular fibrillation. The distance of the victim from the mixer is probably due to the strong muscular contraction due to the shock that he received from the metal parts of the mixer which was later found to be ungrounded and there was a high leakage current to the mixer frame.

Case 6G. Two workers were erecting an aluminum flagpole in the vicinity of an 11,000-volt transmission line. A gust of wind blew the pole into contact with the transmission line. Both workers were thrown to the ground and received hand burns. They were dazed but recovered. Obviously, the high-voltage and short duration of contact did not produce ventricular fibrillation.

A similar accident occurred when a crane came in contact with a high-voltage power line. When this occurred, the crane was raised to the potential of the high-voltage transmission line. The operator within the cab of the crane felt nothing because his environment was equipotential. However, a worker standing on the ground and touching the metal tracks of the crane received a shock.
Lee (1961) reported the following several types of electrical accident:

Case 13. A 60-year-old laborer, wearing rubber boots, was standing in a damp trench sawing through (an armored) cable believed to be dead. In fact, the cable was energized to 11,000 volts. There was a sudden flash and he became rigid and was thrown backward into the trench; the saw was destroyed. He felt very dazed and although able to climb into the ambulance, he did not really recover consciousness until he arrived in hospital a few minutes later. He was kept only a few hours and then sent home. As a result of the accident the backs of his hands were scorched, but not badly enough to require dressing. He was off work only for one day. As he was wearing rubber boots it is considered more likely that the path of the current was from right hand to left hand (his left hand was holding the grounded armored covering of the cable) than from hands to feet. He was not wearing gloves.

Lee reported a similar incident as follows:

Case 65. A joiner was using a wooden-handled hacksaw, held in the right hand, to cut through an 11,000-volt cable believed to be dead. He supported the cable with the toe of his left boot. There was a sudden explosion and a flash which vaporized the hacksaw blade. The joiner was quite definite that he did not receive a shock. The current had passed from the core of the cable and along the blade to the grounded armored casing of the cable. He was thrown out of the pit by the explosion, temporarily blinded by the flash, and was trembling all over and feeling very cold. He was given first-aid treatment (warmth and warm drinks) by his mate and taken to the nearest hospital where he was kept for three hours and then resumed work.

The two foregoing cases are similar, except that a shock was reported in Case 13 and no shock in Case 65. The fact that a high-voltage shock was received in Case 13 probably explains the lack of ventricular fibrillation (see Chap 3).

Lee (1961) described an interesting case in which the chest muscles were contracted strongly by arm-to-arm power-line current. He reported:

Case 19. A 21-year-old linesman, working outdoors in hobnailed boots, was standing on wet dewy soil, and grasped a copper wire in contact with a live conductor at 230 volts with the right hand. He could not let go and felt his right arm tightening, and then his chest. He later stated that he was losing consciousness when rescued and reported that his colleagues said he was going blue. They applied artificial respiration to him at once and he was taken to the medical unit of a nearby industrial firm (unfortunately the firm kept no record of this incident). He felt "shaky" for half an hour and rested for the remainder of the day although he felt all right.
For a week afterwards he felt a stiffness in his neck and chest as though he had unaccustomed exercise.

Case 81. A 54-year-old female assistant cook was cleaning the top of an electric cooker. She was wearing rubber shoes, she had her left hand on the top of the cooker and a wet cloth in her right hand. She felt a shock up her right arm and the hand contracted breaking the circuit immediately. She was quite well immediately after and lost no time from work. This was presumably a brief arm-to-arm shock. (Presumably due to leakage current).

Lee (1961) described the following burn associated with an electrical arc:

Case 58. A 31-year-old fitter's mate was working in a substation when a three-phase flashover occurred on the 11,000 volt circuit. He received burns to the back of his hands and front of his face, neck, and right wrist (these necessitated a period in hospital of about three or four weeks). The man remembers little of what happened, having only "islands" of memory until about three days after the accident. Artificial respiration was administered at the time of the accident by his colleagues.

HOSPITAL ACCIDENTS

In the environment of a patient experiencing medical treatment, three types of electrical hazard can be identified. One relates to sparks produced by static electricity or environmental instruments; a second results from the indirect contact with the power line energizing diagnostic, monitoring, therapeutic and assistive devices. The third type of hazard results from radio-frequency electrosurgical current, which is used to cut and coagulate living tissue. In some treatment areas, radio-frequency current is used to produce heat; the name for this technique is diathermy. These three types of hazard are variably present and depend on the particular circumstances, that is, whether the patient is in the operating room, coronary/intensive care unit, ward or specialized diagnostic or therapeutic area. Parker (1967), van der Mosel (1970), Feldtman and Derrick (1973), and Stanley (1974) have written extensively on this subject. It should be recognized that these environments have other hazards, such as infection and radiation of a variety of types; these however, will not be discussed. All accidents occurring in a hospital are investigated and followed by the filing of an incident report.

ELECTRIC SPARK HAZARD

Static electricity, one of the many causes of electric sparks, is the electricity of friction which is produced when different insulating materials are rubbed, the most familiar occurring when the hair is combed or
when walking over a carpet on a dry day. Contact between the subject and a nearby metal object results in a spark which discharges the static charges separated by the energy of friction. Equally good static-electricity generators are clothes made of synthetic fibers. The potentials developed in such cases are in the tens of thousands of volts, and the spark discharge can be centimeters in length. A single spark can stimulate sensory receptors, nerve and muscle. In the latter case, if the discharge is applied directly to an exposed motor nerve or skeletal muscle, it can evoke a twitch. If such a discharge is applied to heart muscle it can evoke an extrasystole. It is not known if such a discharge presented during the ventricular vulnerable period can evoke ventricular fibrillation when applied directly to the heart or the body surface.

Sparks from static electricity, motor starters and thermostats used to be serious hazards in the operating room when flammable anesthetics were used. Modern inhaled anesthetics are nonflammable.

**FIRE**

For a fire to occur, three ingredients must be present: 1) a source of flammable material, 2) oxygen and 3) a source of ignition (i.e. a spark or high temperature as produced by a laser beam). In the operating room all three ingredients can be present and circumstances can conspire to cause a fire or explosion; the following are a few selected examples.

Typically during anesthesia, 80–95% oxygen is used with the anesthetic agent applied to the airway via a plastic tracheal tube. Occasionally there may be a leak in an anesthetic circuit and oxygen accumulates around the patient who is covered with sterile paper or cloth drapes.

Case 7G. A defibrillation shock was delivered to two chest electrodes, one of which was not well applied and there was an arc under this electrode; the result was a flash that ignited the drapes, even though they were treated with a flame retardant.

Electrosurgical (high-frequency) current (see Chapter 5) is used to cut and coagulate tissue by the production of a small arc at the tip of an electrode in contact with (or just above) the tissue.

Case 8G. In an anesthetized subject with a plastic tracheal tube in place, a surgeon entered the trachea with an electrosurgical probe. The combination of a spark, oxygen and an flammable material (plastic tracheal tube) resulted in an explosion, melting the anesthetic-machine tubes and burning the patient.

The return path for electrosurgical current is via a large-area dispersive electrode on the subject. Occasionally this electrode is poorly applied or becomes dislodged, resulting in a small area of contact and a high current density at the skin, causing a burn. Sometimes the disper-
sive electrode is not applied or not plugged into the electrosurgical unit (sometimes called a Bovie), and the return path for the current is by any contact with a grounded object, such as the operating table, via ECG monitoring electrodes or an electronic rectal thermometer. At these sites, burns can occur due to what is called an alternate ground path. Many such burns have occurred (see Chapter 5).

**BOWEL-GAS EXPLOSION**

Explosion of gas in the gastrointestinal tract, ignited by an electrosurgical cutting electrode or by a laser scalpel, is not unknown. Levy (1954) reviewed much of the literature to that time and pointed out that digestive processes, bacterial fermentation, diffusion of gas (presumably inhaled flammable anesthetic gas) from the bloodstream, and swallowed gas are responsible for such accumulation. The composition of bowel gas is influenced by the amount of milk and legumes ingested (Table 1.2).

From these sources, hydrogen and methane are produced; both are flammable. On the average diet, the bowel content for hydrogen is about 21%; for methane it is about 7%; and the carbon dioxide content is between 9–69%. On a milk diet, gut hydrogen increases to about 44%, and on a legume diet, methane also increases to about 44%.

<table>
<thead>
<tr>
<th>Table 1.2: Bowel Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diet</strong></td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Milk</td>
</tr>
<tr>
<td>Legume</td>
</tr>
</tbody>
</table>

Hussey and Pois (1970) reviewed the literature on bowel-gas explosions from the time of Levy’s report (1954) to 1970, and described a case of bowel-gas explosion which occurred when the large bowel was opened with an electrosurgical cutting electrode. The bowel was ripped by the explosion and required resection. Septicemia developed and the patient died.

Prevention of bowel-gas explosion merely requires attention to the hazard. For example, opening the bowel can be achieved with a scalpel to let the gas escape; thereafter the electrosurgical unit can be used. Some advocate purging the bowel with an inert gas such as nitrogen. Obviously dietary management of a patient is important prior to bowel surgery.

It would be difficult to find a better example of the disastrous combination of a combustible substance, oxygen and a source of ignition than that reported by Wegrzynowicz et al. (1992) who stated “A 35-year-
old man presented for laser ablation of recurrent laryngeal papillomata. History and physical examination were unremarkable other than a 20-pack/yr smoking history, a bushy mustache, and a weight of 129 kg. Anesthesia was induced with thiopental and Fentanyl. Ventilation via mask with oxygen, nitrous oxide, and isoflurane was without difficulty. Vecuronium was given to provide relaxation. The surgeon inserted an adult Dedo laryngoscope, and jet ventilation was instituted with oxygen via a 13-G cannula inserted in the left light-carrier channel of the Dedo laryngoscope. A thumb-controlled valve and 50-psi oxygen powered the jet (were used).

"The patient's face and the perioral area were covered with soaking wet towels such that only the barrel of the Dedo laryngoscope was visible. Anesthesia was maintained with thiopental and Fentanyl during jet ventilation. There were no intraoperative problems except for brief periods of decreased hemoglobin oxygen saturation measured by pulse oximetry (S) during some episodes of apnea that were requested by the surgeon to eliminate movement of the vocal cords.

"Near the end of the surgical procedure, the surgeon suddenly yelled "fire," and bright blue and orange flames accompanied by a muffled roar were observed coming up through and around the laryngoscope. Jet ventilation was stopped; the towels were removed and the patient's blazing mustache was extinguished with the wet towels. The surgeon, who was in a great deal of pain, noted that the latex glove had been burned away from two of the fingertips of his right hand. The Dedo laryngoscope was removed, and bag-and-mask ventilation was commenced. Subsequent rigid bronchoscopy revealed no carbonaceous material in the trachea, and except for evidence of lasering, the glottis was normal. Muscle relaxation was reversed and the patient was awakened. Recovery from anesthesia was otherwise unremarkable.

"The patient suffered second-degree burns to his right upper lip and nasal rim. These were treated with 1% silver sulfadiazine (Silvadine) and healed over the next 2 weeks without further incident. The only other evidence of airway fire was burned nasal hair. The surgeon suffered second-degree burns to the right index and middle fingers that were severe enough to prevent him from operating for a week.

"This patient experienced an unusual complication. An errant laser strike on the surgeon's latex glove ignited the glove, producing hot volatile fuel that was entrained by the jet ventilator. Combustion of the vaporized latex accelerated dramatically in the oxygen-enriched atmosphere of the airway. The gaseous products of combustion escaped through either the patient's nose or mouth and in turn ignited his mustache, despite the "protective" wet drapes. It would be impossible to determine to what degree the patient's mustache contributed to his facial burns, or whether combustion alone under the drapes would have been adequate to cause the degree of injury sustained."