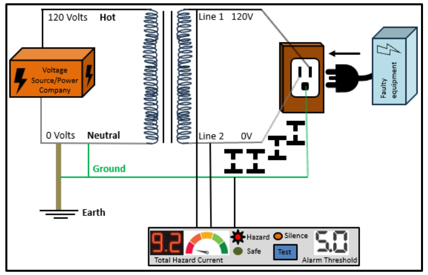
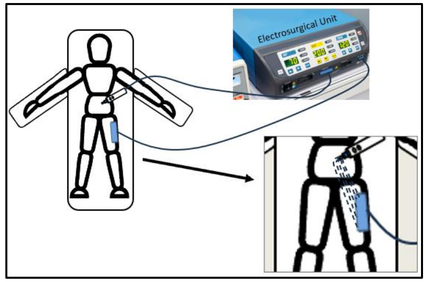
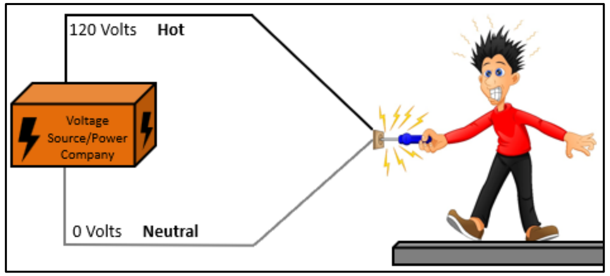


Room for notes

Electrical Safety in Anesthesiology:

Alexander Arriaga, MD, MPH, ScD





Goal and Objectives

Room for notes

Overall Goal:

- To provide an opportunity to work through common concepts in physics and electrical safety, with correlation to anesthesia principles.

Objectives:

By the end of this session, participants should be able to:

- State anesthesia implications regarding selected topics at the intersection of electrical safety and anesthesiology, to guide further learning.
- Apply topics in electrical safety towards lifelong learning in anesthesia.

This talk represents of the presenter and not necessarily the supporting agencies (views=mine). Dr. Arriaga is an Editor on the Patient Safety Editorial Board for the American Society of Anesthesiologists, and a Question Editor/Board Examiner for the American Board of Anesthesiology, both of which provide a stipend for work that is otherwise done in a volunteer capacity. The presenter does not believe that any of these represent a conflict of interest. All reasonable precautions have been taken to verify the information contained in this lecture. The responsibility for the interpretation and use of the information lies with the reader.

Question

Room for notes

A 62-year-old man in the ICU with a pulmonary artery catheter in place has the following vitals/parameters:

Parameter	Value
Mean arterial Pressure (MAP)	85 mmHg
Systemic vascular resistance (SVR)	1,200 dyne-cm-sec^{-5}
Central venous pressure (CVP)	5 mmHg

What is his cardiac output (CO)?

High-Yield Formulas: M5 Board Review URL

Room for notes

Public URL for M5 Board Review Equations (via Google search):

https://m5boardreview.com/wp-content/uploads/M5_equations.pdf

Exceptionally High Yield:

1. Allowable blood loss; Estimated blood volume
2. Volume/Pressure Oxygen-availability from E-cylinder gas tank.
3. Poiseuille’s law for IV flow rate.
4. Systemic vascular resistance formula.
5. Arterial content of oxygen including understanding of contribution from hemoglobin saturation and PaO2; Oxygen delivery
6. Alveolar gas equation.

Room for notes

Formula, Algebra, and Next Question

- $SVR = \frac{(MAP - CVP)}{CO} \times 80$
- This rearranges to: $CO = \frac{(MAP - CVP)(80)}{SVR}$
- CO = ([85-5][80])/1200 = 5.3 L/min
- What is Ohm's law, and how does this formula relate to this?

Ohm's Law

- Voltage (in Volts) = Current (in Amperes) x Resistance (in Ohms)
- **Commonly abbreviated as V = IR**, where V= voltage, I=Current, R=Resistance
- Blood pressure can be thought of as voltage, Cardiac Output can be thought of as current (or flow), and Systemic Vascular Resistance can be thought of as Resistance. Hence, our formula becomes

$$CO = \frac{(MAP - CVP)(80)}{SVR}$$ → I = V/R → **V = IR**

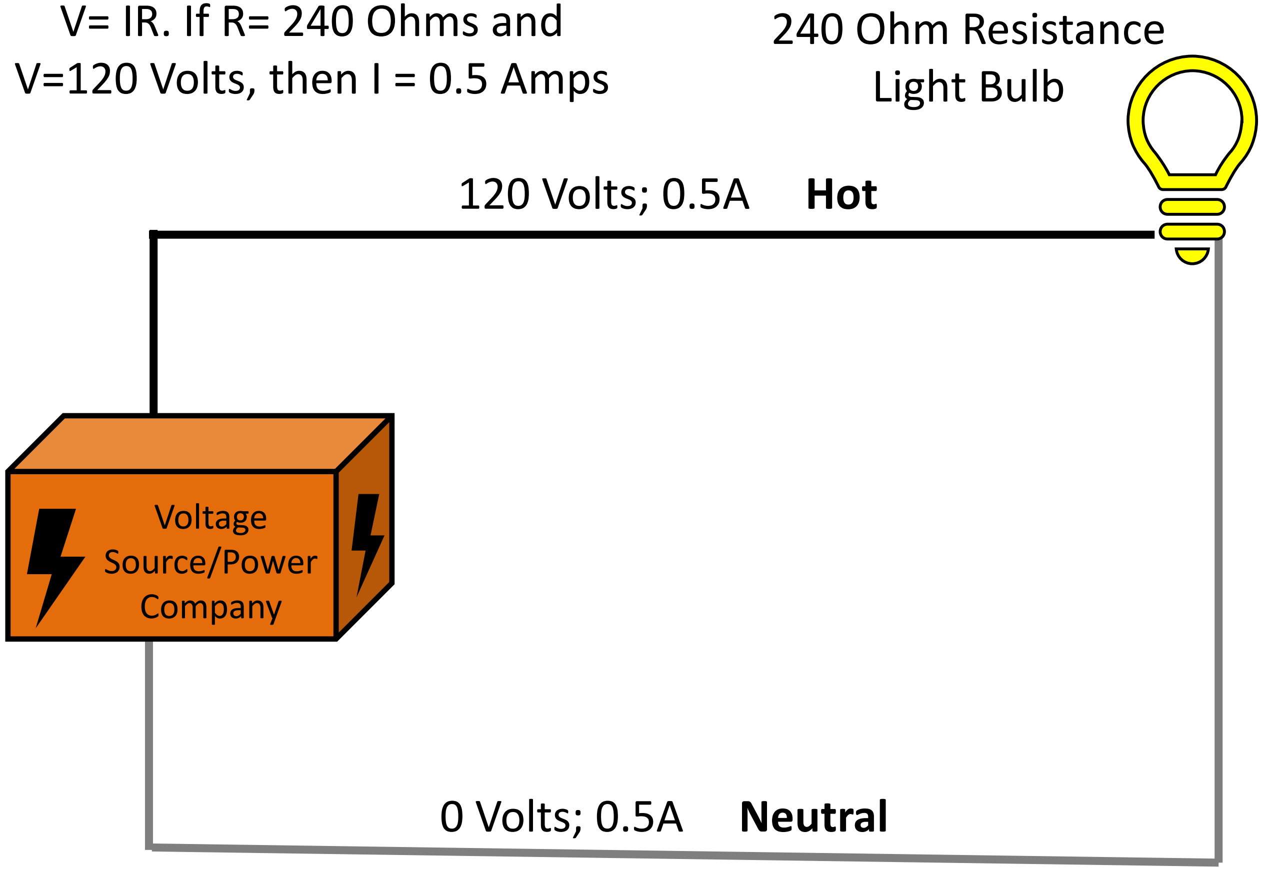
- From Ehrenwerth, 3rd Ed, Ch 24: "For a completed circuit to exist, there must be a closed loop with a driving pressure to force a current through a resistance, just as in the cardiovascular system there must be a BP to drive the CO through the peripheral resistance."

- If we assume the electrical power company supplies 120 Volts via the outlet on the wall, and you have a light bulb with a resistance of 240 Ohms, what is the current running through this circuit?

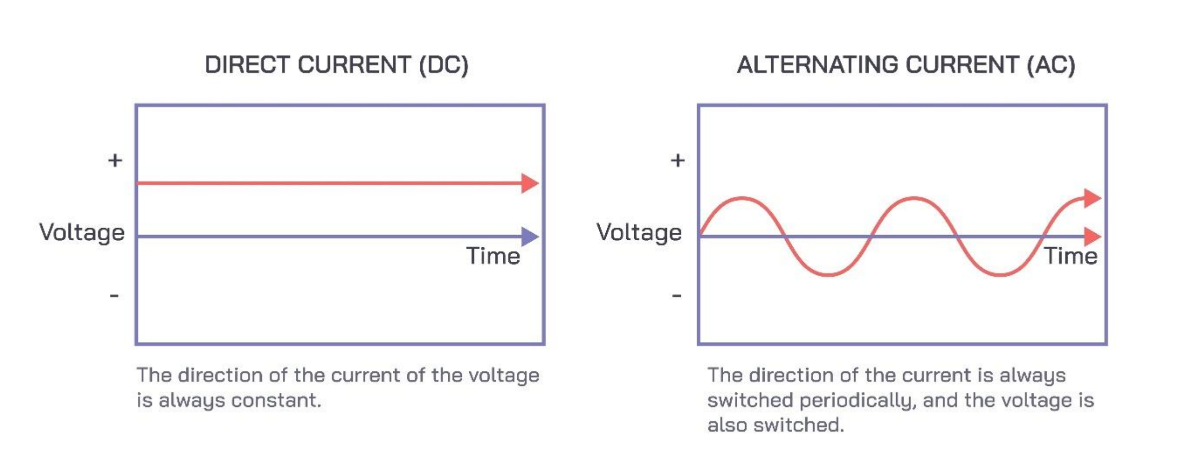
Simple Electrical Circuit for a Light Bulb

Room for notes

V= IR. If R= 240 Ohms and
V=120 Volts, then I = 0.5 Amps



A Brief Note on AC vs DC Circuits



"If the electron flow is always in the same direction, it is referred to as direct current (DC). However, if the electron flow reverses direction at a regular interval, it is termed alternating current (AC)."[1]

Terminology:

- Impedance (Z): *"the sum of the forces that oppose electron movement in an AC circuit. Impedance consists of resistance (Ohms) but also takes capacitance and inductance into account. In actuality, when referring to AC circuits, Ohm's law is defined as: V = I x Z."*

→ **For simplicity of discussion and the scope of this talk, we will use the basic physics principle of V=IR for the majority of this review.**

Additional Reference Terminology (for those pursuing a deeper dive):

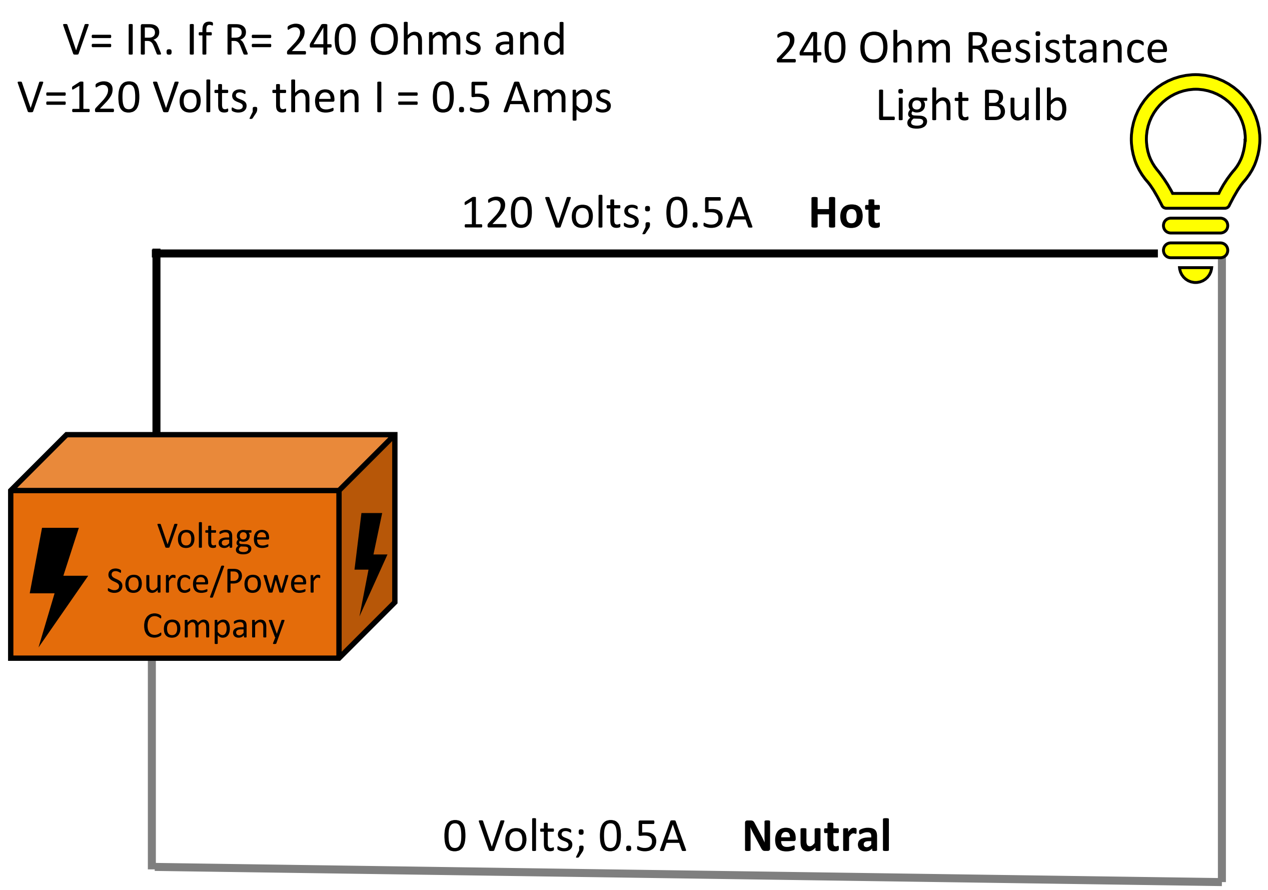
- Inductance: *"a property of AC circuits in which an opposing electromagnetic force can be electromagnetically generated in the circuit."*[1]
- Capacitor: "any two parallel conductors that are separated by an insulator, which has the capacity to store a charge (Q)."[1]
- Capacitance (C, in Farads): the measure of a capacitor's ability to store a charge (Q).[1,2]
- Relationship between capacitance (C), charge (Q), and voltage (V):[2]
  - C = Q/V

→ ***"There is […] a phenomenon known as stray capacitance – capacitance that was not designed into the system but is incidental to the construction of the equipment. All AC-powered equipment produces stray capacitance."***[1]

Ref: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed.// 2. Singh et al. Basics of electricity for anaesthetists. https://doi.org/10.1093/bjaceaccp/mkr035 // Image via shutterstock.

Room for notes

Back to the Simple Electrical Circuit for a Light Bulb



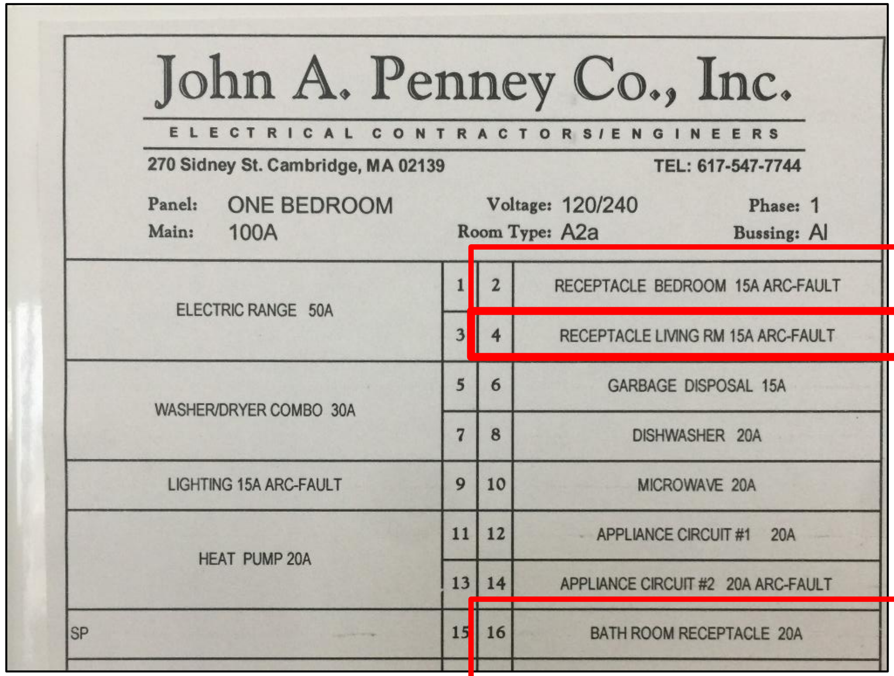
From Barash, 9th Ed, Ch5:

- Power (P): the rate at which the circuit transfers electrical energy in watts (W). P = V x I.
  - Based on the information above, this would be a P = V x I ➔ P = 120V x 0.5A ➔ 60 Watt light bulb.
- Electrical Work: power multiplied by time. Common terms for electrical work:
  - Watt-seconds (aka, Joules)
  - Kilowatt-hours

- What if we were plugging in a 1,875W hair dryer instead of a lightbulb? What would the current be for this 120 Volt system?

Room for notes

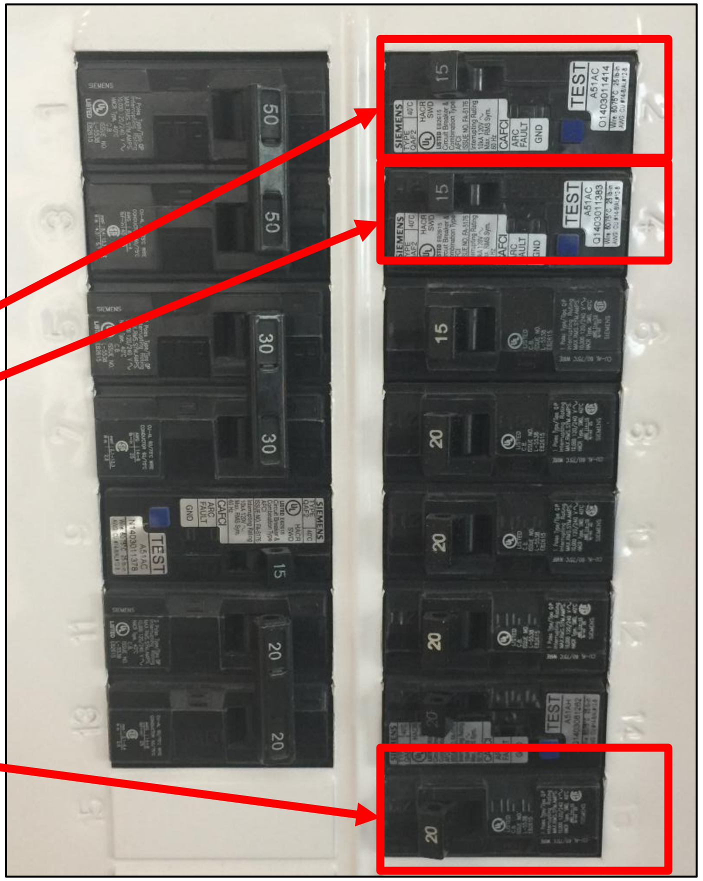
Hair Dryer



John A. Penney Co., Inc.
ELECTRICAL CONTRACTORS/ENGINEERS
270 Sidney St. Cambridge, MA 02139 — TEL: 617-547-7744

Panel: ONE BEDROOM — Voltage: 120/240 — Phase: 1
Main: 100A — Room Type: A2a — Bussing: Al

ELECTRIC RANGE 50A	1	2	RECEPTACLE BEDROOM 15A ARC-FAULT
	3	4	RECEPTACLE LIVING RM 15A ARC-FAULT
WASHER/DRYER COMBO 30A	5	6	GARBAGE DISPOSAL 15A
	7	8	DISHWASHER 20A
LIGHTING 15A ARC-FAULT	9	10	MICROWAVE 20A
HEAT PUMP 20A	11	12	APPLIANCE CIRCUIT #1 20A
	13	14	APPLIANCE CIRCUIT #2 20A ARC-FAULT
SP	15	16	BATH ROOM RECEPTACLE 20A



- $P = V \times I \rightarrow 1{,}875 = 120 \times I \rightarrow I = 1{,}875/120 =$ 15.625 Amps.
- Will the hair dryer blow the circuit in the Bedroom? Living Room? Bathroom?
- What is the point of a circuit breaker?

Room for notes

Room for notes

Overloaded Circuit

From Barash, 9th Ed, Ch 5:

- "Most outlets in a home will be 120 V and 15 or 20 A of maximum current (clothes dryers, HVAC systems, water heaters, and other large appliances may have outlets up to 240 V/50 A)."
- "If a device (or more often multiple devices) attempts to draw more than 15 A of current on a 15 A circuit, the fuse will melt and need to be replaced or the [circuit] breaker will trip and need to be manually reset."
- "It is worth noting that 120 V/15 A is enough electrical power to cause serious harm to a person. […] 100 mA of current can cause ventricular fibrillation. The circuit breaker is intended to protect wiring from melting and/or catching fire or shut off appliances with dangerous short circuits. Such systems are not intended to protect a person who contacts both the hot and neutral lines simultaneously…"

Macroshock and Microshock: "1, 10, 100"

Type of Shock	Current*	Notes
Macroshock	1 milliampere (mA)	Threshold to perceive current
	10 milliamperes	"Let go" current (above this threshold, it becomes hard to physically let go of the current due to sustained muscle contraction)
	100 milliamperes	Ventricular fibrillation may occur at or above this threshold
Microshock	10 microamperes	Recommended maximum leakage for a 60 Hz circuit
	100 microamperes	Ventricular fibrillation may occur at or above this threshold

5 mA is generally accepted as a threshold for relatively harmless current intensity.[2]

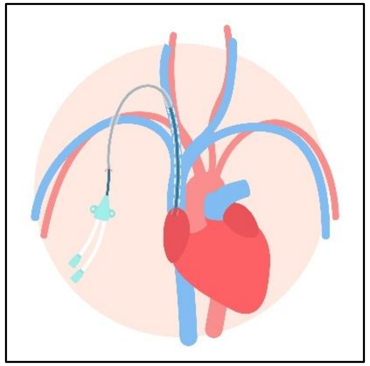
50 mA of macroshock is generally considered painful

Regarding twitch monitor for monitoring of neuromuscular blockade: Exercise caution with current greater than 50mA if patient is fully awake! (Can be painful to patient)

* Note: This table assumes an average adult human makes 1 second of contact with alternating current that is cycling at a frequency of 60-Hz. Refs: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // 2. Barash 9th Ed, Ch 5 // Twitch device image: Cropped/adapted from Renew JR et al. J Intensive Care 2020. PMID: 32483489. Creative Commons BY-4.0.

Room for notes

A Brief Note on Microshock



- The electrically susceptible patient: "*one who has direct, external connection to the heart.*"[1]
  - Examples may include a patient with a: transvenous pacing wire, saline-filled central venous catheter, or cardiac catheter with incorporated electrodes.[1-3]
    - "*The catheter orifice or electrical wire with a very small surface area in contact with the heart produces a relatively large current density at the heart.*"[1]
- Microshock: very small currents (often in microamps) that can produce injury to an electrically susceptible patient.[1-3]

How to reduce the risk of microshock?

1. **"[T]he equipment ground wire constitutes the major source of protection against microshock for the electrically susceptible patient."[1]**

- Other potential methods to reduce the risk of microshock:
  2. Wear protective gloves when touching an electrically susceptible patient, particularly when handling their catheters/wires that have direct connection to the heart.
  3. Avoid simultaneously touching an electrical device and an electrically susceptible patient's catheters/wires that have direct connection to the heart.
     - Similarly, avoid allowing an external current source (such as a twitch monitor) to come into contact with an electrically susceptible patient's catheters/wires that have direct connection to the heart.
       - "*The stray capacitance that is part of any AC-powered electrical instrument may result in significant amounts of charge buildup on the case of the instrument. If an individual simultaneously touches the case of an instrument where this has occurred and the electrically susceptible patient, [they] may unknowingly cause a discharge to the patient that results in ventricular fibrillation*"[1]

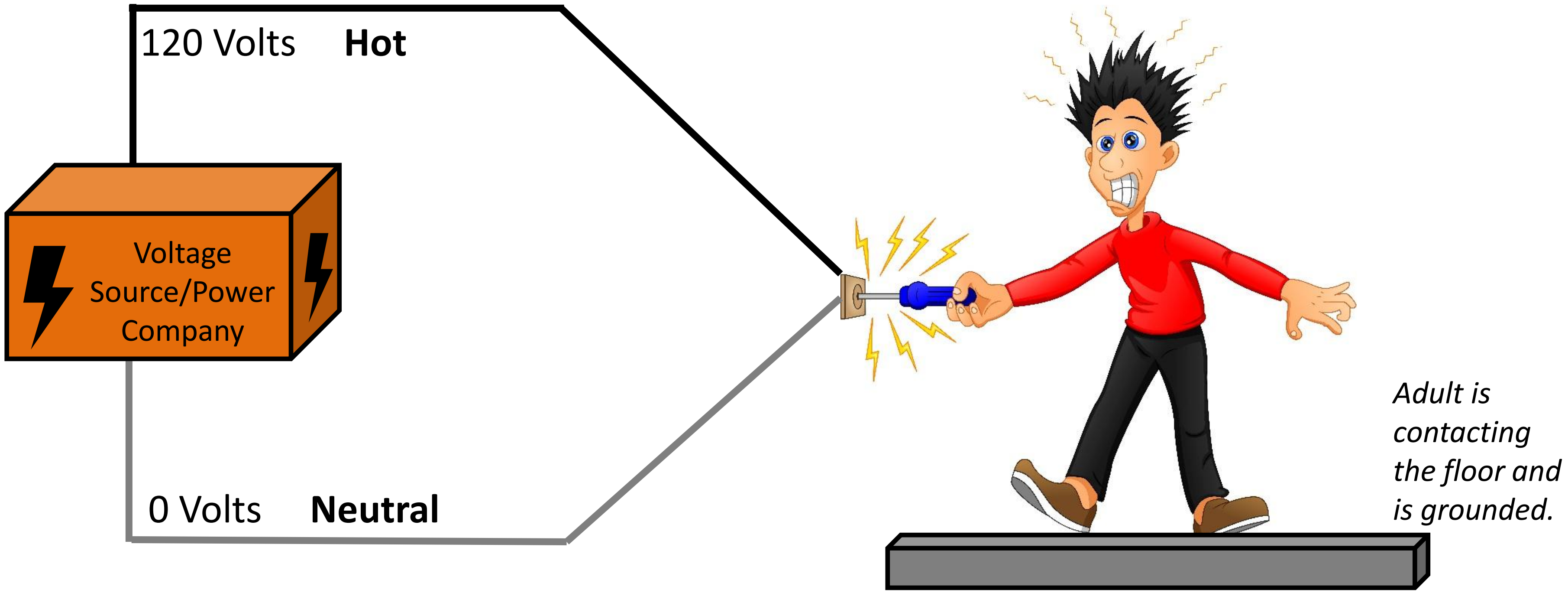
Refs: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // 2. Barash 9th Ed, Ch 5 // 3. Tooley MA. Electrical safety, defibrillation and diathermy. BJA Education 2023; 23: 84-91

Room for notes

Macroshock from Completing a Basic Circuit

Room for notes

Let's say an adult with a skin resistance of 1,000 ohms makes contact with a 120 Volt circuit and completes the circuit. Would this generate enough current to cause ventricular fibrillation?



- **V=IR** → 120 = I (1,000) → I = 120/1,000 → I = 0.12 Amps, or 120 milliamps (mA)
- From Ehrenwerth, 3rd Ed, Ch 24: "If a person with a skin resistance of 1,000 ohms contacts a 120-V circuit, [that person] would receive 120mA of current, which would probably by lethal."
- What is the purpose of Grounding an electrical system?

Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. Right side of image obtained from Shutterstock.

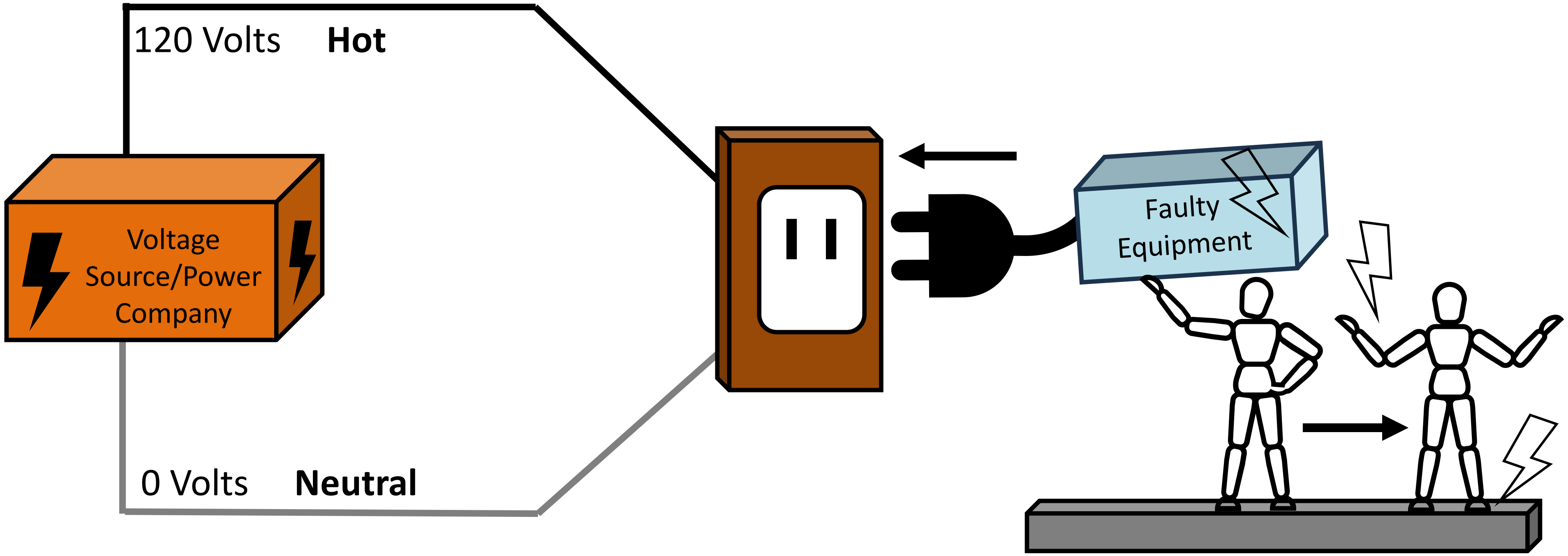
The Birds and the Squirrels

Room for notes

- Animals like birds and squirrels are able to physically contact electrical wires because they are not grounded (they have no physical connection to earth to complete a circuit).
- How can we make humans in the operating room and other procedural areas enjoy this protection while also coming into physical contact with the floor?

Image obtained from Shutterstock

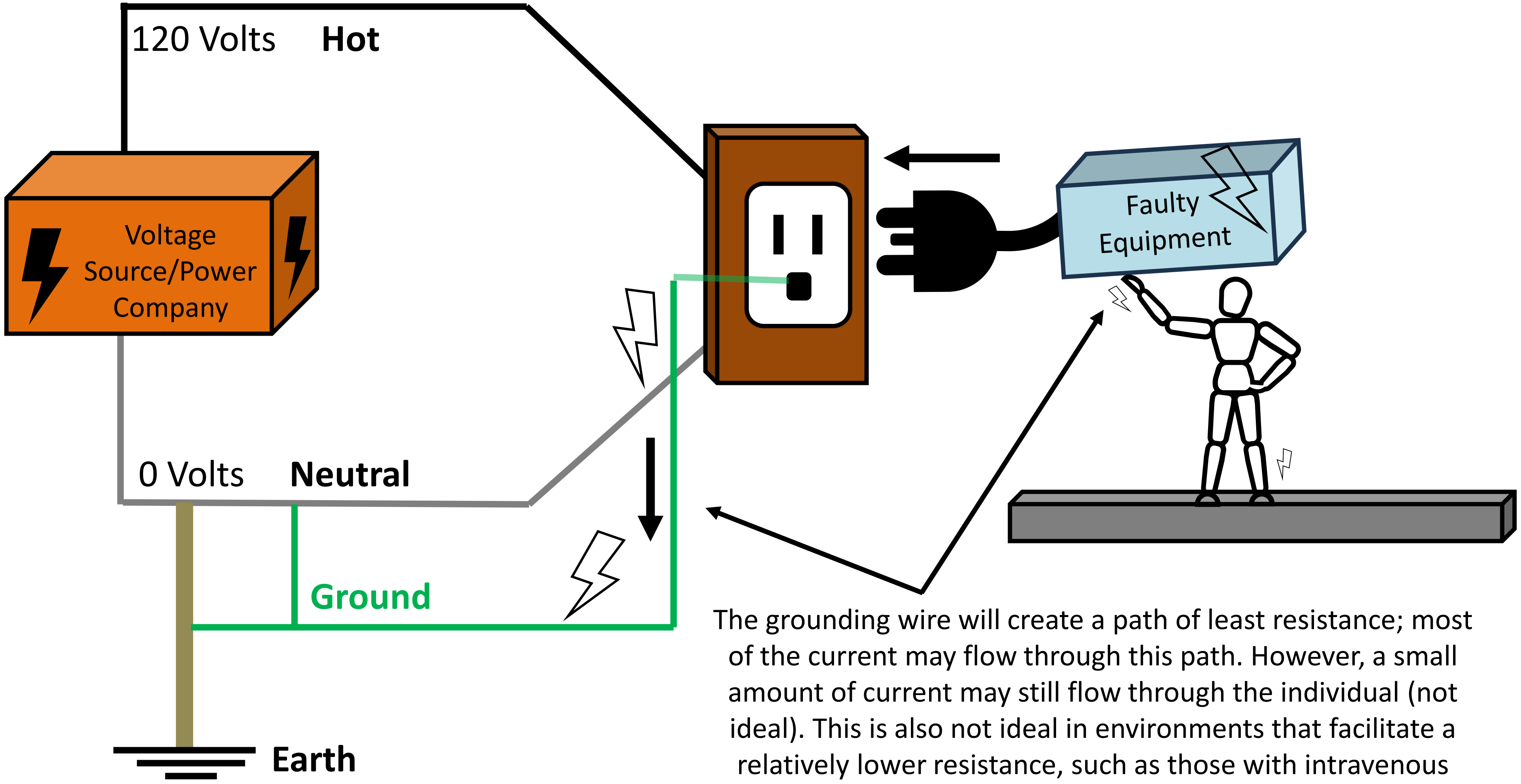
Faulty Equipment, No Ground Wire



Refs: Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed.; Barash 9th Ed, Ch 5.

Room for notes

Faulty Equipment, Ground Wire Present

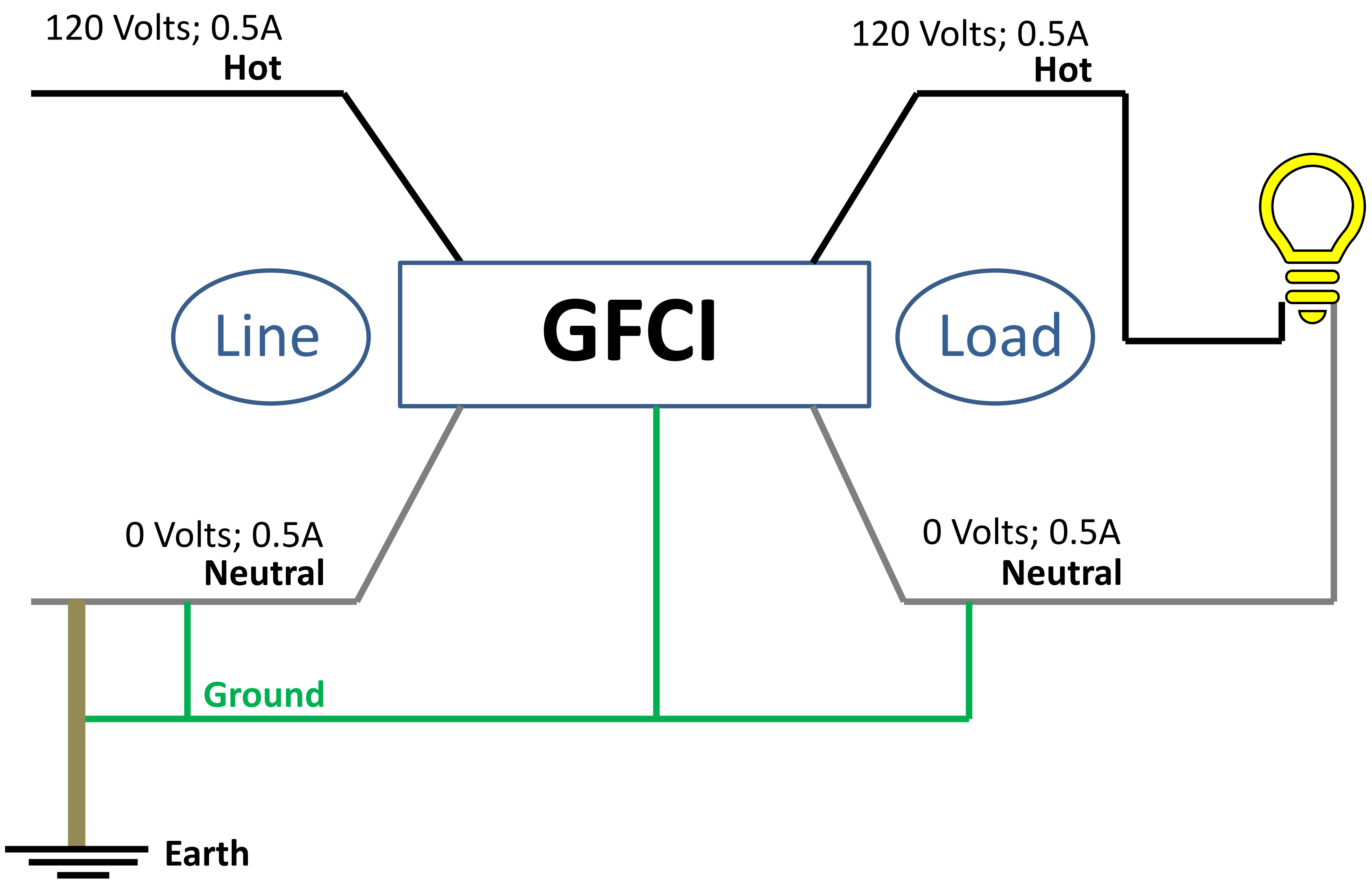


The grounding wire will create a path of least resistance; most of the current may flow through this path. However, a small amount of current may still flow through the individual (not ideal). This is also not ideal in environments that facilitate a relatively lower resistance, such as those with intravenous fluids, bodily fluids, blood, perfusion machines, etc.

Refs: Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed.; Barash 9th Ed, Ch 5.

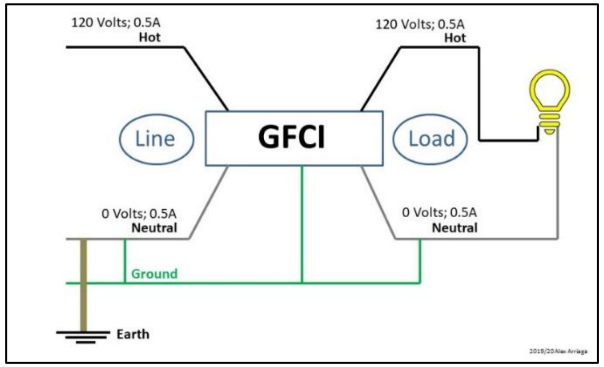
Ground Fault Circuit Interrupter

What is a Ground Fault Circuit Interrupter (GFCI)? What is its purpose? What is the main disadvantage of a GFCI in an operating room or other anesthetizing location?



Room for notes

Ground Fault Circuit Interrupter



<ins>From Barash, 9th Ed, Ch 5</ins>:

- "It should be noted that although the voltage decreases from 120v to 0v from the hot to the neutral side, the current remains the same in both limbs of the circuit."
- *<ins>Ground Fault (definition)</ins>*: "Any unintended connection between the hot line and earth ground is generally called a ground fault."

Potential ways a Ground Fault can be generated:

- *Home bathrooms/kitchens (or a clinical location with IV fluids): "*A wet person has lower skin resistance and thus conducts electricity more easily with hot line contact. If that person is in contact with earth ground via a water drain, they will readily conduct electricity between the hot line and the earth ground."
- *Faulty Equipment*: "If an individual should contact a faulty piece of equipment such that current flowed through the individual, an imbalance between the two sides of the circuit would be created, which would be detected by the GFCI."

What does a GFCI do?:

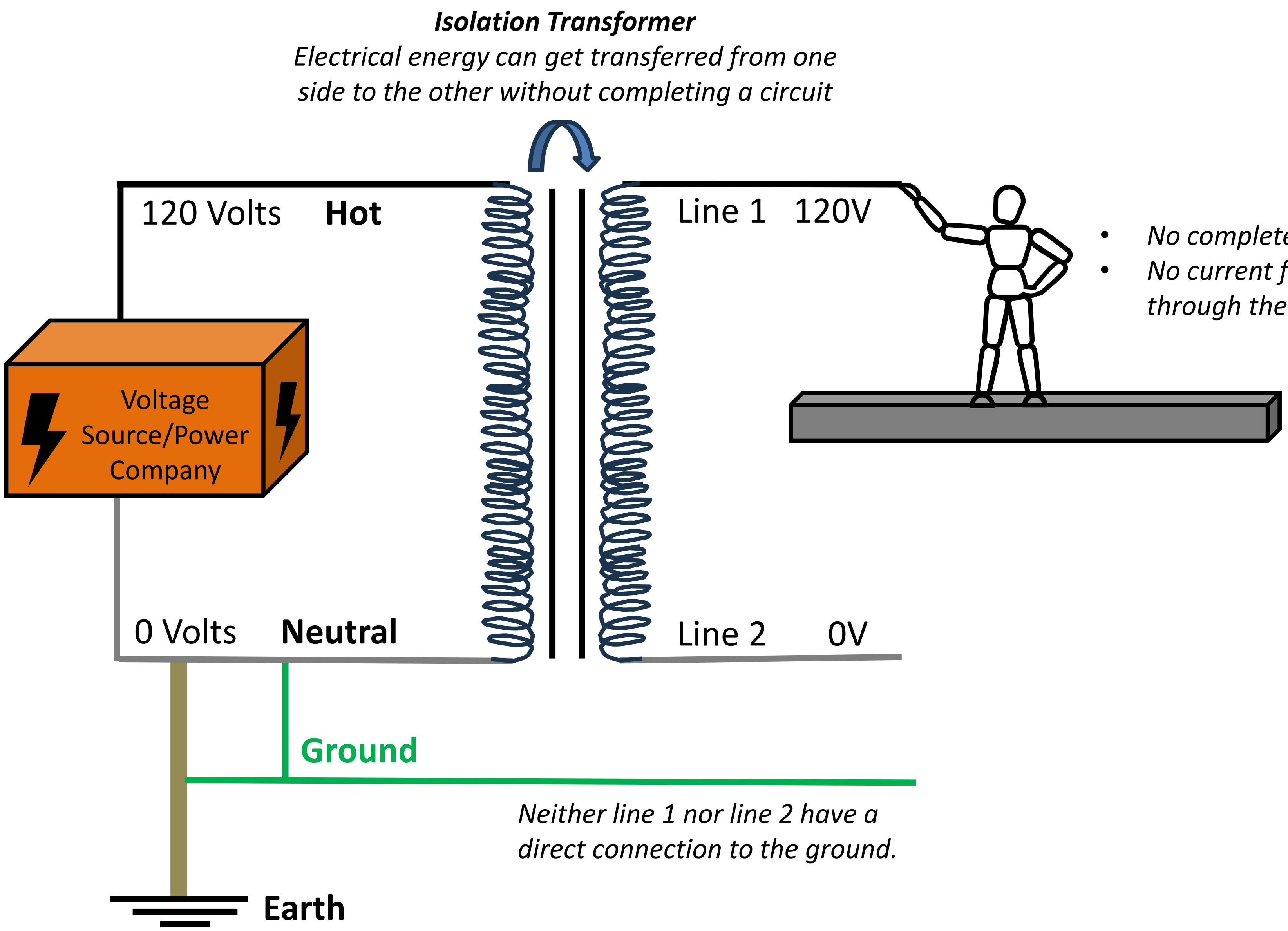
- "A GFCI continuously measures the current flow on the hot and neutral lines of the outlet, and if they are not closely in balance, the GFCI will disconnect the circuit."
- "In general, GFCI's can be expected to disconnect a circuit with between 5 and 6 mA of current leakage within 25 to 40 milliseconds."

Why not put GFCI's in all Operating Rooms?

- "This behavior [i.e., sudden disconnection of a circuit] may not be desirable for a piece of life support equipment in an OR environment."

Room for notes

Isolated Power System

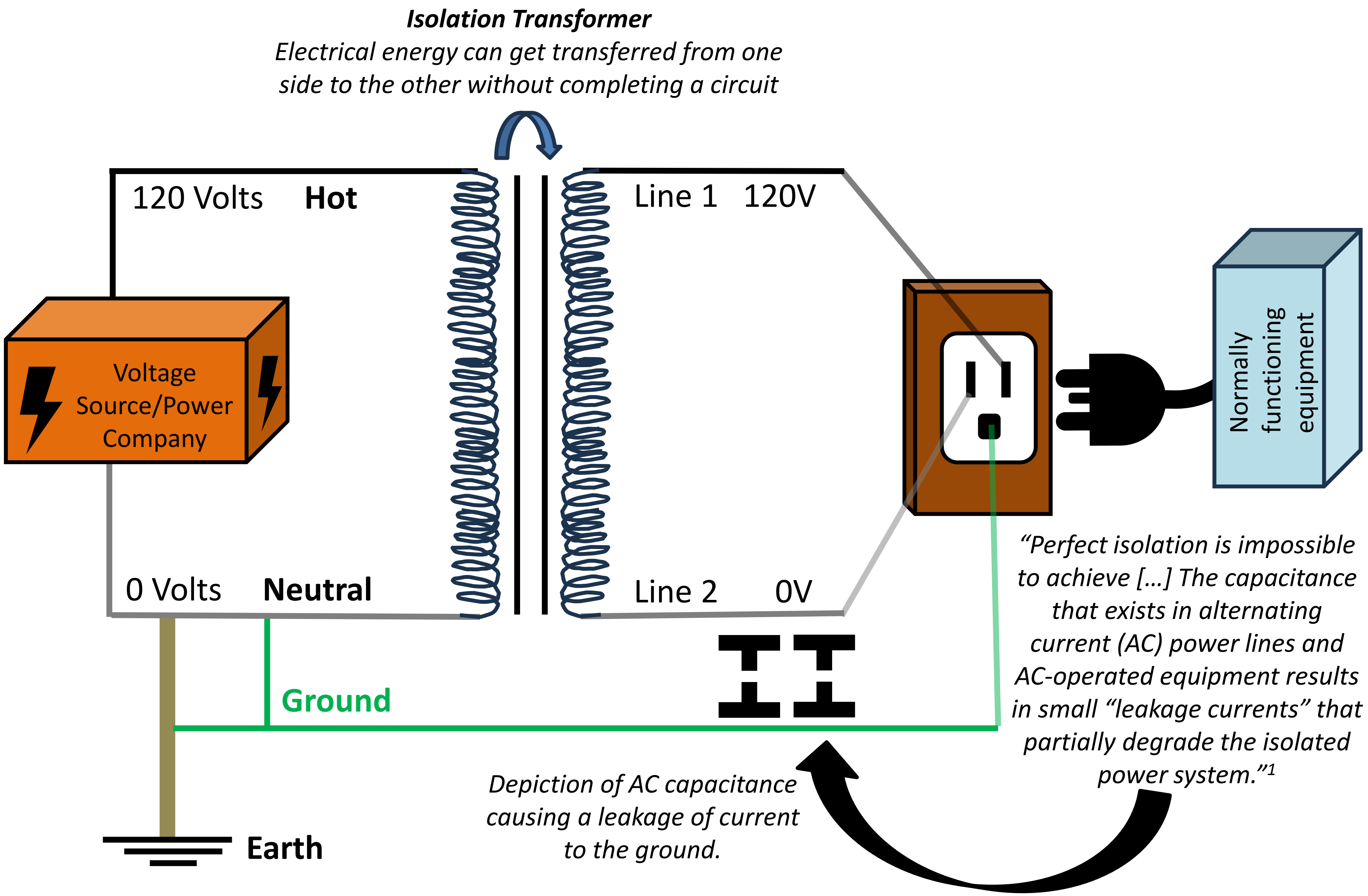


- *No completed circuit.*
- *No current flow through the individual.*

Room for notes

Refs: Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed.; Barash 9th Ed, Ch 5.

Leakage Currents in an Isolated Power System



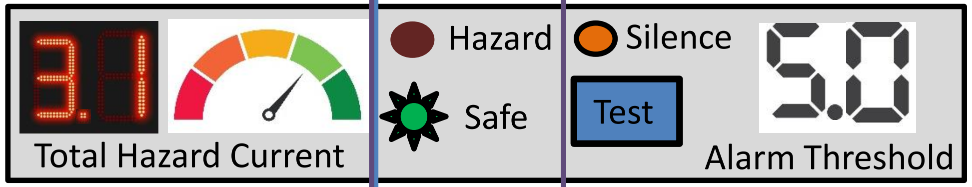
Refs: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // Barash 9th Ed, Ch 5.

Room for notes

The Line Isolation Monitor (LIM)

"Safe" light is on, and "Hazard" light is off, because the Total Hazard Current is below the Alarm Threshold

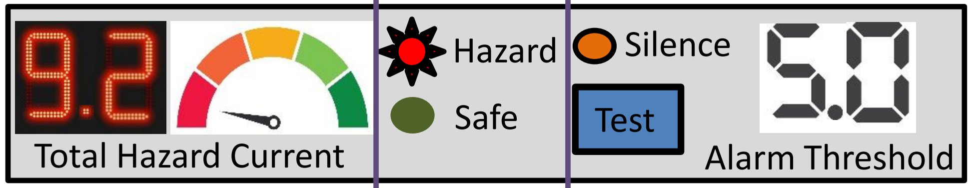
Alarm threshold, in milliamperes



Indication of how much leakage current (in milliamperes [mA]) has degraded the isolated power system

Buttons to Silence the alarm and test the monitor, respectively

"Hazard" light is on, and "Safe" light is off, because the Total Hazard Current is above the Alarm Threshold. This is typically accompanied by an audible alarm.

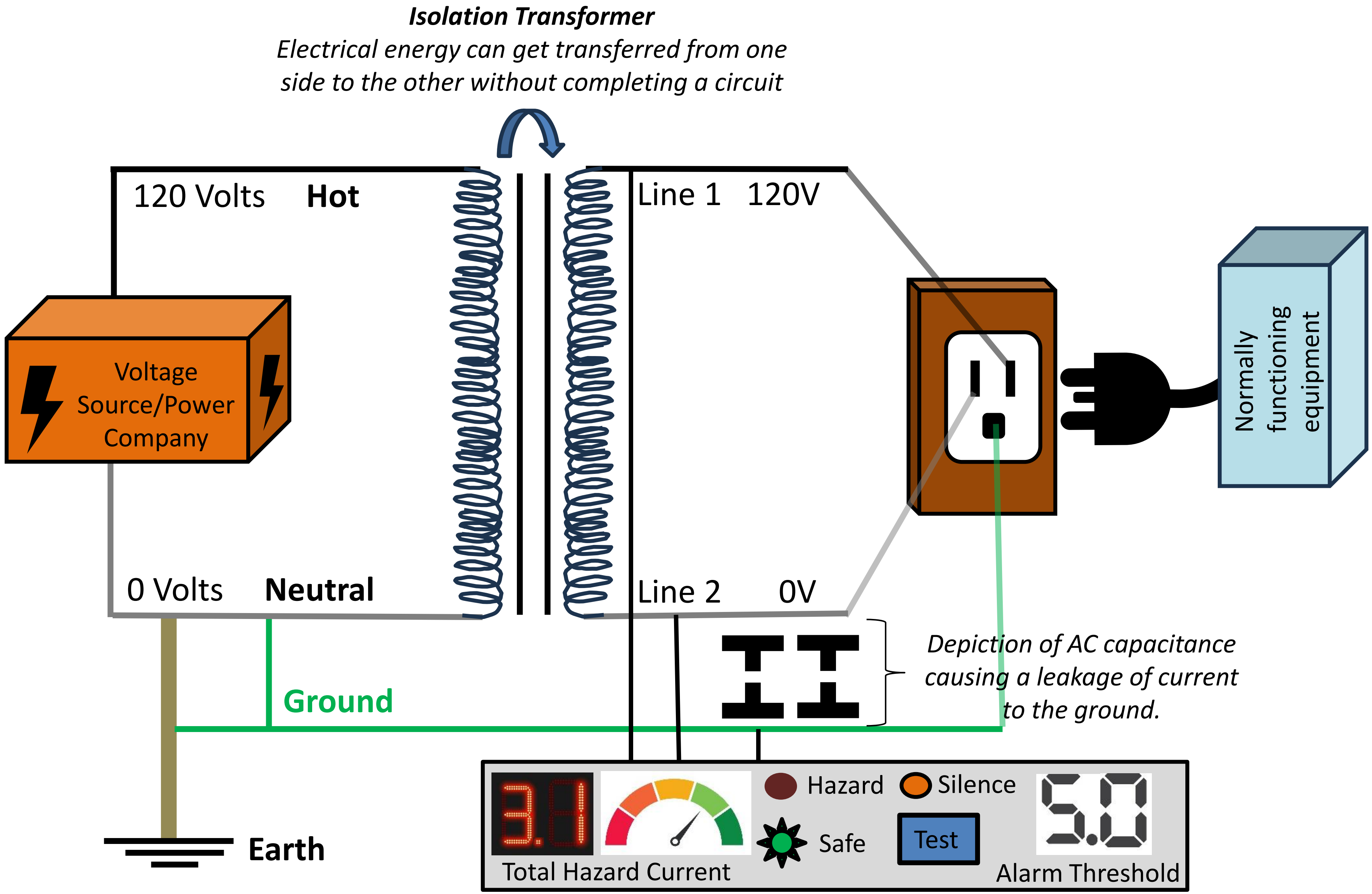


Refs: Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed.; Barash 9th Ed, Ch 5.

Room for notes

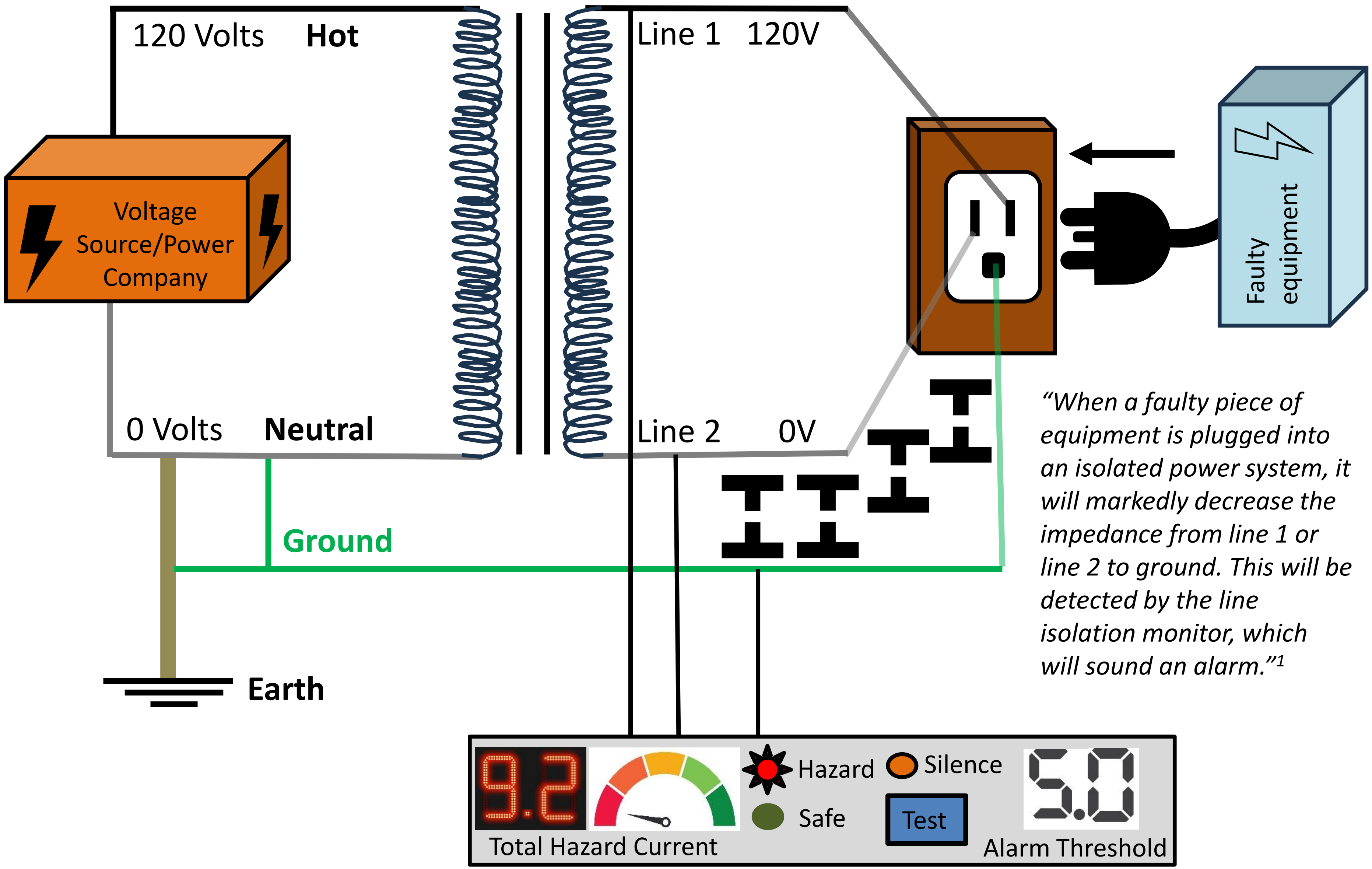
Line Isolation Monitor Integrated into an Isolated Power System

Room for notes



Refs: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // Barash 9th Ed, Ch 5.

Line Isolation Monitor Triggered by a Faulty Device



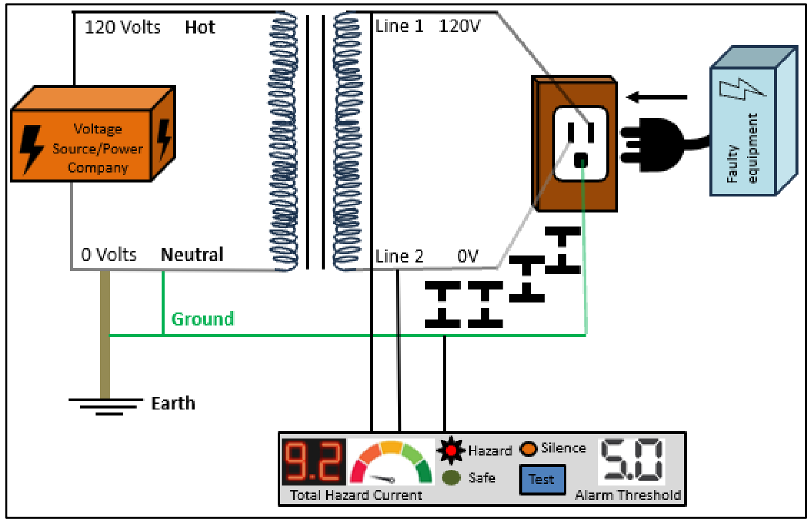
"When a faulty piece of equipment is plugged into an isolated power system, it will markedly decrease the impedance from line 1 or line 2 to ground. This will be detected by the line isolation monitor, which will sound an alarm."[1]

Refs: 1. Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // Barash 9th Ed, Ch 5.

Triggered Line Isolation Monitor

<u>If the LIM alarm is triggered</u>:

- **Check the gauge**
  - If over 5mA, there is likely a faulty device.
- **Identify the faulty device:**
  - Unplug each piece of equipment, unless critically vital (e.g., bypass machine), until alarm ceases (start with device most recently plugged in).
  - Remove any faulty non-critical equipment from the OR.

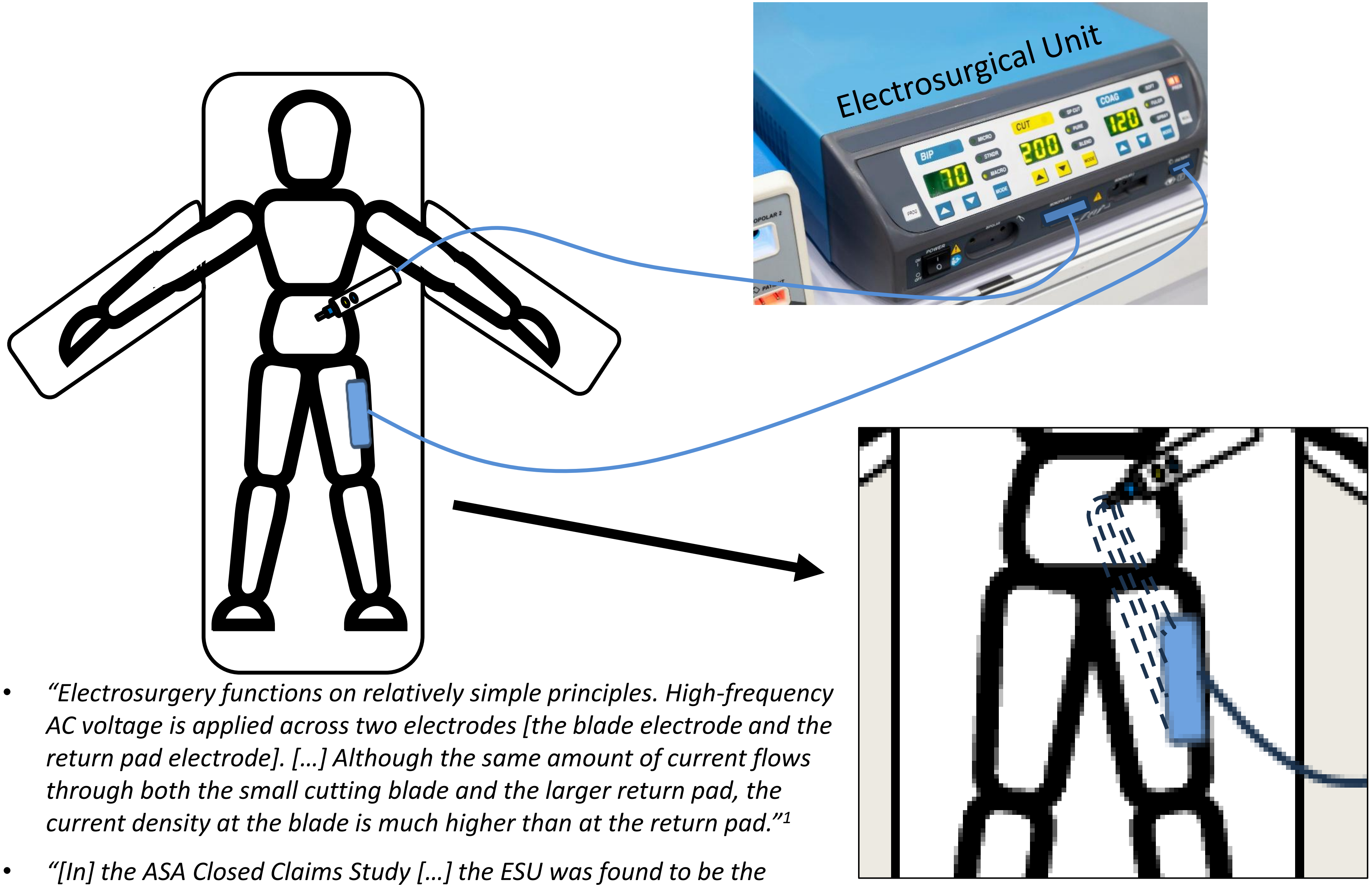


- **"If [the faulty device] is a vital piece of life-support equipment, it can be safely used**….[BUT] It must be remembered that the protection of the IPS and the LIM is no longer operative. Therefore, if possible, no other electrical equipment should be connected during the remainder of the case, or at least until the faulty piece of equipment can be safely removed. "
- A line isolation monitor ***does not*** directly prevent electric shock. Rather, it is a ***monitor*** that alerts you when current leakage is above a certain threshold.

Refs: Ehrenwerth J, Seifert HA. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed. // Barash 9th Ed, Ch 5.

Room for notes

The Electrosurgical Unit (ESU)



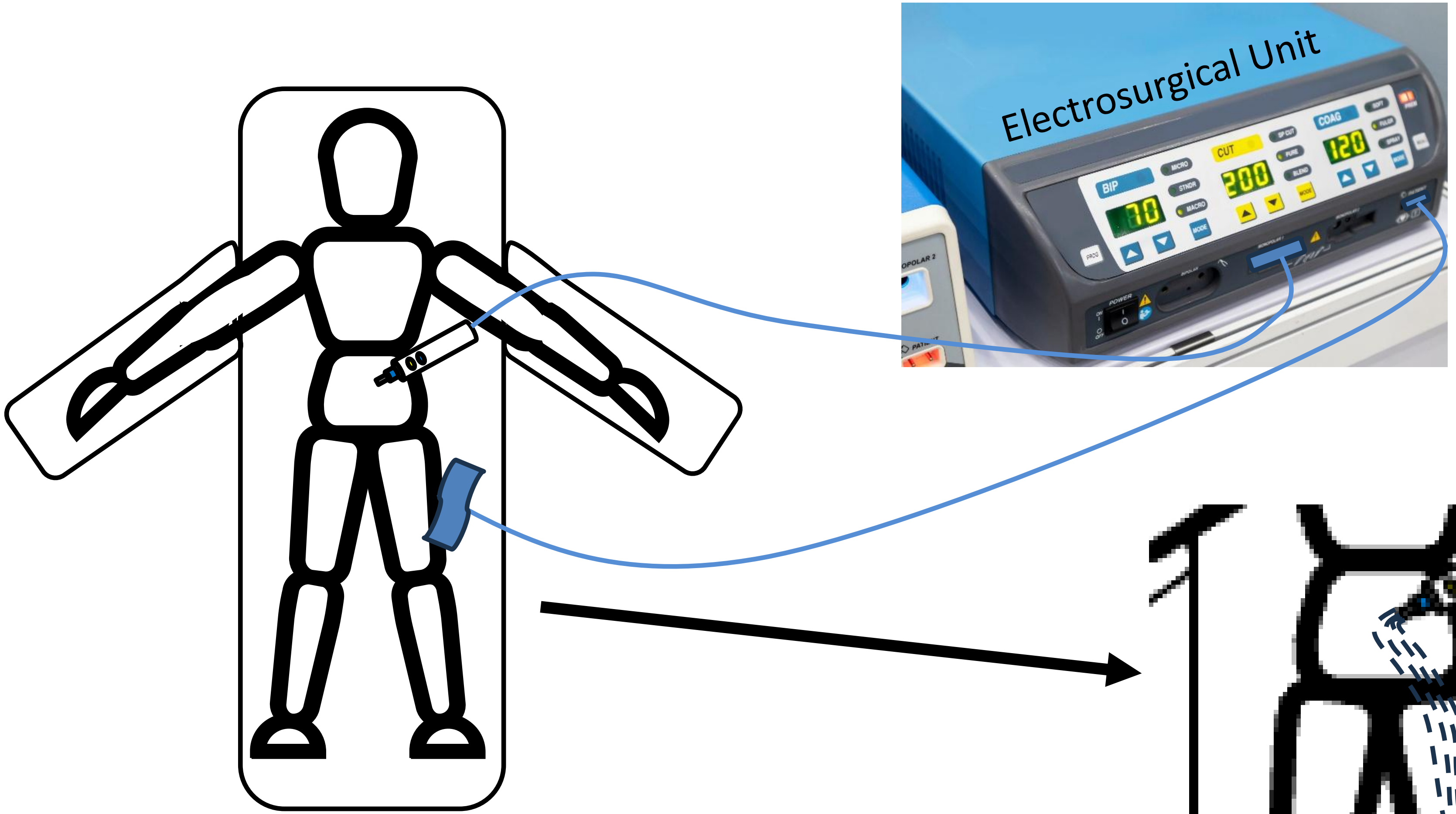
- *"Electrosurgery functions on relatively simple principles. High-frequency AC voltage is applied across two electrodes [the blade electrode and the return pad electrode]. […] Although the same amount of current flows through both the small cutting blade and the larger return pad, the current density at the blade is much higher than at the return pad."*[1]
- *"[In] the ASA Closed Claims Study […] the ESU was found to be the ignition source in 90% of the fire cases."*[2,3]

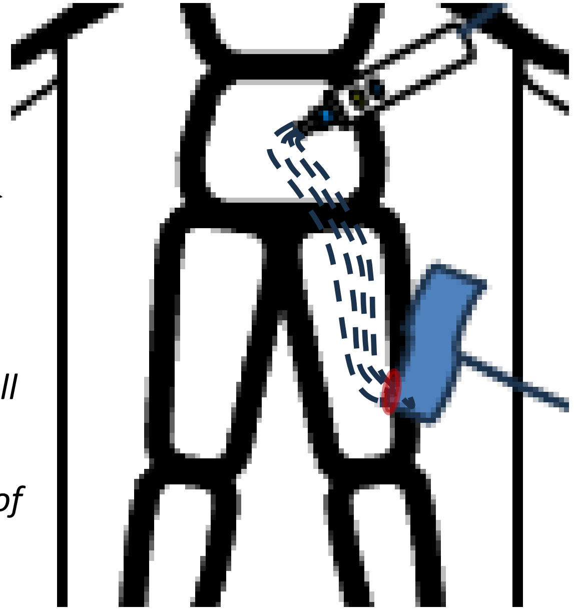
Refs: 1. Barash 9th Ed, Ch 5 // 2. Ehrenwerth, Anesthesia Equipment: Principles & Applications, 3rd Ed, Ch 24 // 3. PMID 23422795.

Room for notes

Improperly Placed ESU Return Pad

Room for notes



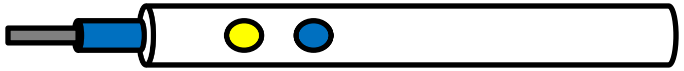


- *“An improperly placed, partially nonadherent, or faulty return pad with only a small contact area can create a high current density, which leads to burns at that site.”*[1]
- *<u>Regarding bipolar ESU</u>: “the current passes only between the two blades of a pair of forceps […] Because the active and return electrodes are the two blades of the forceps, it is not necessary to attach another dispersive electrode to the patient, unless a unipolar ESU is also being used. The bipolar ESU generates considerably less power than the unipolar.”*[2]

Refs: 1. Barash 9th Ed, Ch 5 // 2. Ehrenwerth J et al. Ch 24: Electrical and Fire Safety. In Anesthesia Equipment: Principles and Applications, 3rd Ed

Brief History/Trivia regarding the Electrosurgical Unit

Room for notes



<u>William T. Bovie, PhD</u>:[1-6]

- Bachelor's degree: University of Michigan in Ann Arbor. Master's degree from University of Missouri. PhD from Harvard (Plant Physiology). Harvard Assistant Professor (Biophysics). He later became the first Chair of the Dept of Biophysics at Northwestern.
- Collaborated with Dr. Harvey Cushing at the Peter Bent Brigham Hospital in Boston, Massachusetts, to first use his electrosurgical device in an operating room on October 1, 1926.
  - Dr. Cushing approached Prof Bovie after being unable to resect a tumor (suspected to be a highly vascularized sarcoma) on the right side of a patient's head on September 28, 1926. From Dr. Cushing's notes: "*On October 1, Dr. Bovie came to our rescue […] with Dr. Bovie's help I proceeded to take off most satisfactorily the remaining portion of tumor with practically none of the bleeding which was occasioned in the preceding operation*."[2]
- Prof Bovie patented his device, titled *Electrosurgical Apparatus*, "wherein the discharge of electric current from an electrode is used to dissect and/or dehydrate tissue, fat, cartilage, etc, in a surgical operation."[3]
  - Prof Bovie died of humble means in 1958. He sold his patent rights to the device's manufacturing company for $1. "Later in life, he maintained that he had had no interest in reaping personal reward from his invention."[1]

William T. Bovie, PhD

Dr. Harvey Cushing

Refs: 1. Carter et al. PMID 23592153 // 2. Voorhees et al. PMID 15871521 // 3. https://patents.google.com/patent/US1813902A/en // 4. Image of William Bovie: DeLeon, MS, Michelle F.; Yeo, MD, Charles J.; and Maxwell, IV, MD, Pinckney, "The evolution of cauterization: from the hot iron to the Bovie." (2011). Department of Surgery Gibbon Society Historical Profiles. Paper 35. Free and open access by the Jefferson Digital Commons // 5. Dr. Cushing painting: https://en.wikipedia.org/wiki/Harvey_Cushing. Public domain // 6. https://www.feinberg.northwestern.edu/about/notable/am-acad-arts-sci.html