Electrical Safety in Hospitals

Safety in Clinical Environment

- Electrical hazards
  - Electrical shocks (micro and macro) due to equipment failure, failure of power delivery systems, ground failures, burns, fire, etc.
- Mechanical hazards
  - mobility aids, transfer devices, prosthetic devices, mechanical assist devices, patient support devices
- Environmental hazards
  - Solid wastes, noise, utilities (natural gas), building structures, etc.
- Biological hazards
  - Infection control, viral outbreak, isolation, decontamination, sterilization, waste disposal issues
- Radiation hazards
  - Use of radioactive materials, radiation devices (MRI, CT, PET), exposure control
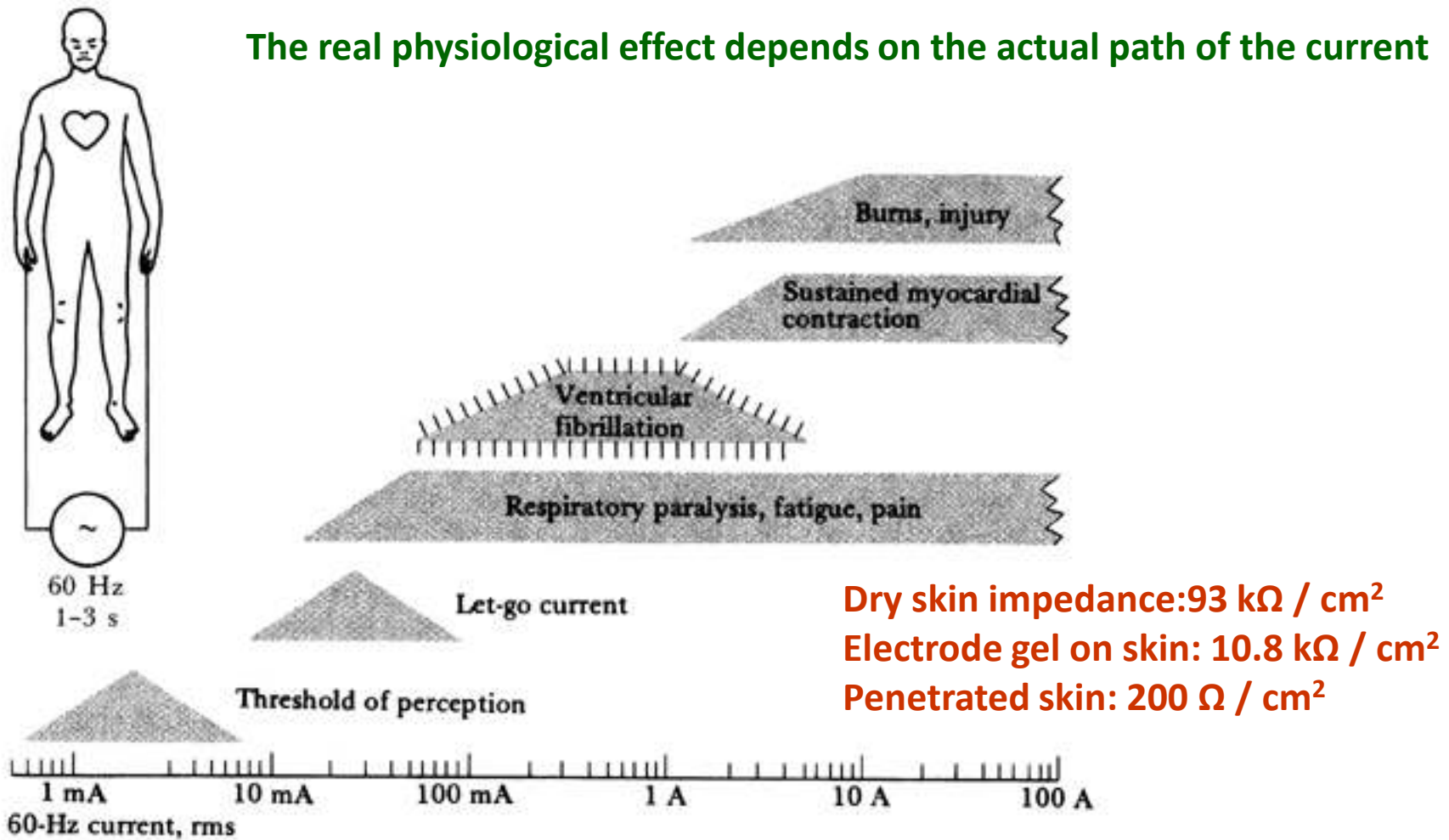
Electrical Safety

- Many sources of energy, potentially hazardous substances, instruments and procedures
  - Use of fire, compressed air, water, chemicals, drugs, microorganisms, waste, sound, **electricity**, radiation, natural and unnatural disaster, negligence, sources of radiation, etc.
- Medical procedures expose patients to increased risks of hazards due to skin and membranes being penetrated / altered
- 10,000 device related injuries in the US every <u>year</u>! Typically due to
  - Improper use
  - Inadequate training
  - Lack of experience
  - Improper (lack of) use of manuals
  - Device failure

Physiological Effects of Electricity

- For electricity to have an effect on the human body:
  - An electrical potential difference must be present
  - The individual must be part of the electrical circuit, that is, a current must enter the body at one point and leave it at another.
- However, what causes the physiological effect is NOT voltage, but rather ***CURRENT***.
  - A high voltage (KV,(10^3V)) applied over a large impedance (rough skin) may not cause much (any) damage
  - A low voltage applied over very small impedances (heart tissue) may cause grave consequences (ventricular fibrillation)
- The magnitude of the current is simply the applied voltage divided by the total effective impedance the current faces; skin : largest.
- Electricity can have one of three effects:
  - Electrical stimulation of excitable tissue (muscles, nerve)
  - Resistive heating of tissue
  - Electrical burns / tissue damage for direct current and high voltages

Physiological Effects of Electricity

The real physiological effect depends on the actual path of the current

Burns, injury

Sustained myocardial contraction

Ventricular fibrillation

Respiratory paralysis, fatigue, pain

Dry skin impedance: 93 kΩ / cm²
Electrode gel on skin: 10.8 kΩ / cm²
Penetrated skin: 200 Ω / cm²

Let-go current

Threshold of perception

60 Hz
1–3 s

| 1 mA | 10 mA | 100 mA | 1 A | 10 A | 100 A |

60-Hz current, rms

Physiological effects of electricity. Threshold or estimated mean values are given for each effect in a 70 kg human for a 1 to 3 s exposure to 60 Hz current applied via copper wires grasped by the hands.

PHYSIOLOGICAL EFFECTS OF ELECTRICITY

- **Threshold of perception:** The minimal current that an individual can detect. For AC (with wet hands) can be as small as 0.5 mA at 60 Hz. For DC, 2 ~10 mA

- **Let-go current:** The maximal current at which the subject can voluntarily withdraw. 6 ~ 100 mA, at which involuntary muscle contractions, reflex withdrawals, secondary physical effects (falling, hitting head) may also occur

- **Respiratory Paralysis / Pain / Fatigue** At as low as 20 mA, involuntary contractions of respiratory muscles can cause asphyxiation / respiratory arrest, if the current is not interrupted. Strong involuntary contraction of other muscles can cause pain and fatigue

- **Ventricular fibrillation** 75 ~ 400 mA can cause heart muscles to contract uncontrollably, altering the normal propagation of the electrical activity of the heart. HR can raise up to 300 bpm, rapid, disorganized and too high to pump any meaningful amount of blood ➔ ventricular fibrillation. Normal rhythm can only return using a defibrillator

- **Sustained myocardial contraction / Burns and physical injury** At 1 ~6 A, the entire heart muscle contracts and heart stops beating. This will not cause irreversible tissue damage, however, as normal rhythm will return once the current is removed. At or after 10A, however, burns can occur, particularly at points of entry and exit.

Important Susceptibility Parameters

- Threshold and let-go current variability
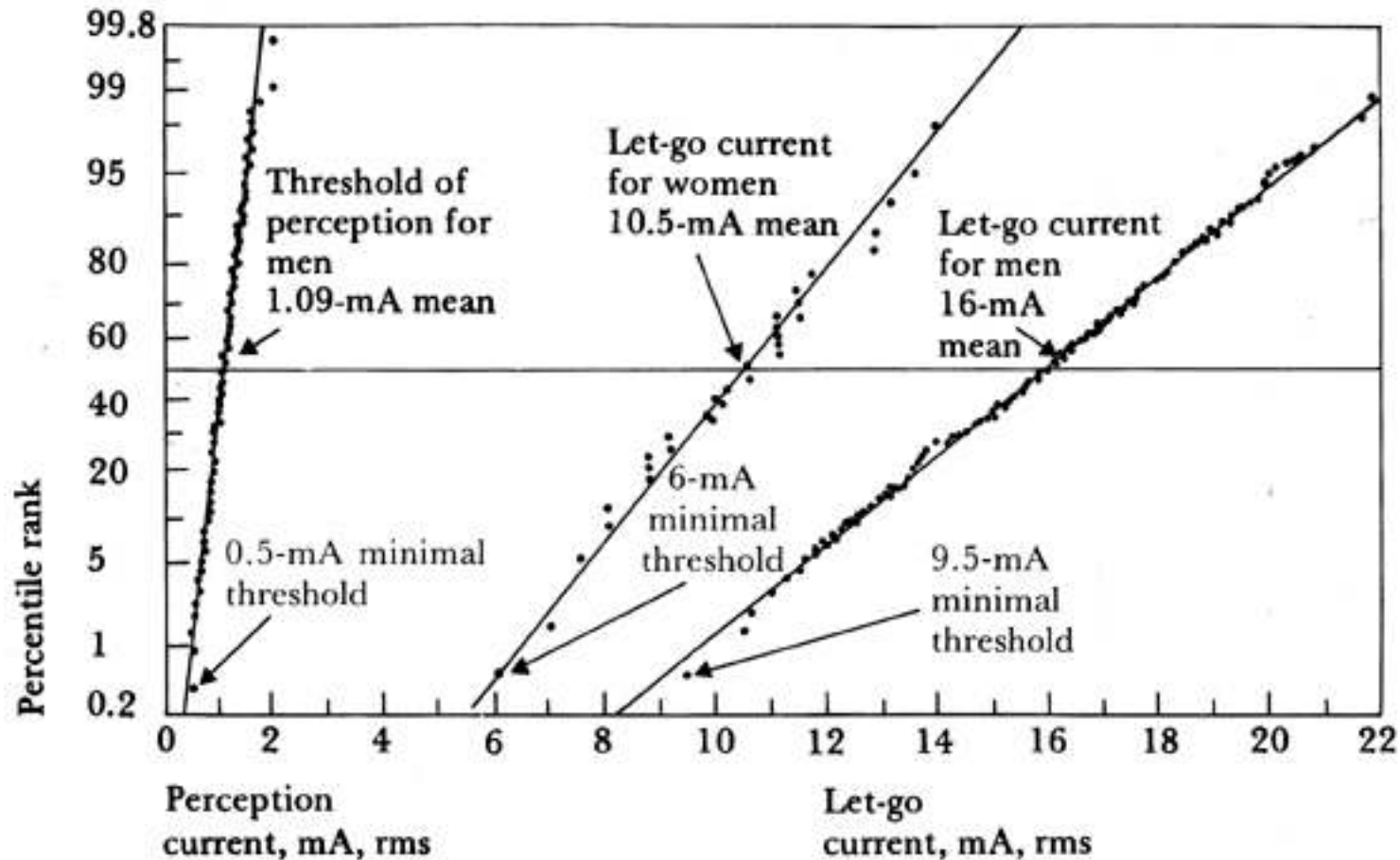
Distributions of perception thresholds and let-go currents These data depend on surface area of contact, moistened hand grasping AWG No. 8 copper wire, 70 kg human, 60Hz, 1~3 s. of exposure

Important Susceptibility Parameters

- Frequency
  - Note that the minimal let-go current happens at the precise frequency of commercial power-line 50-60Hz.
  - Let-go current rises below 10 Hz and above several hundred Hz.

Let-go current versus frequency
Percentile values indicate variability of let-go current among individuals. Let-go currents for women are about two-thirds the values for men.
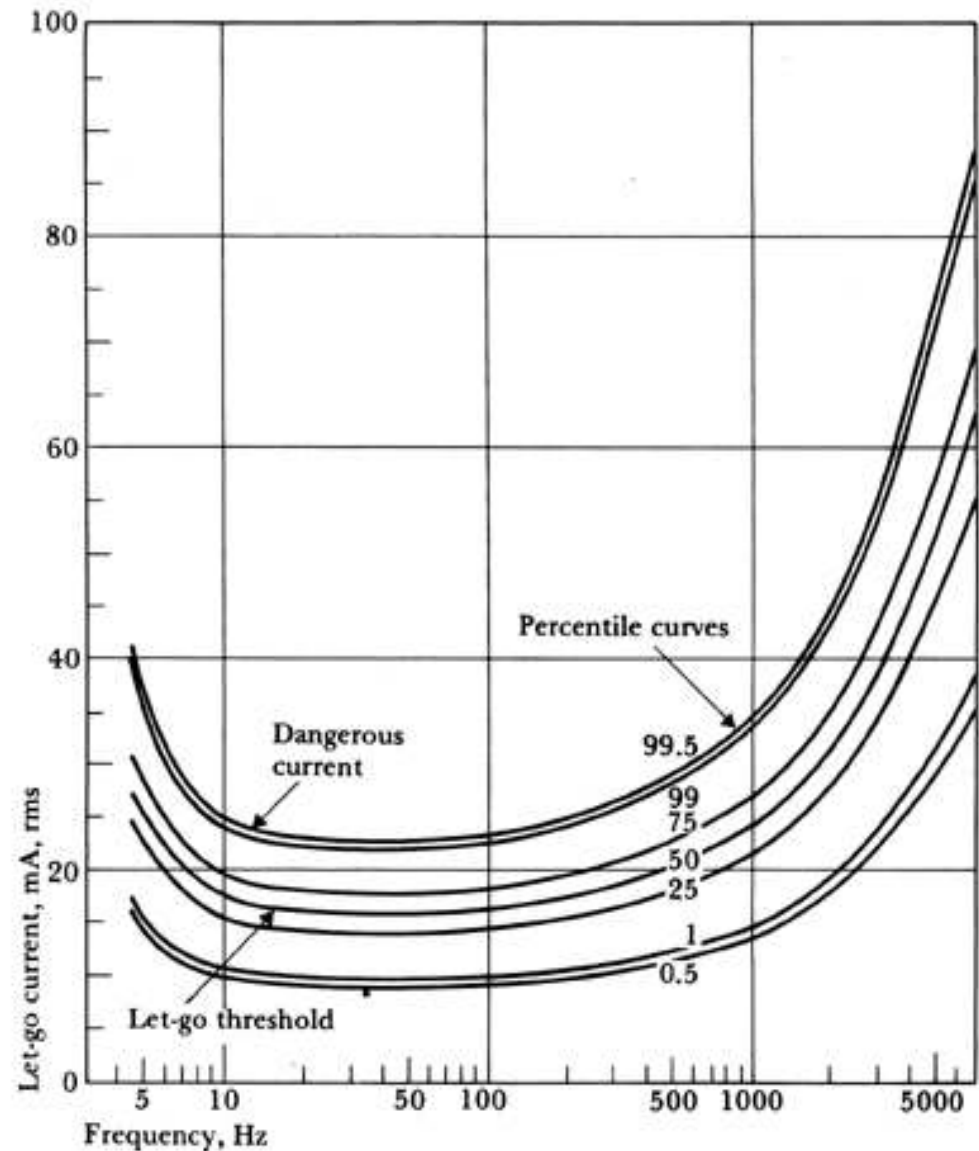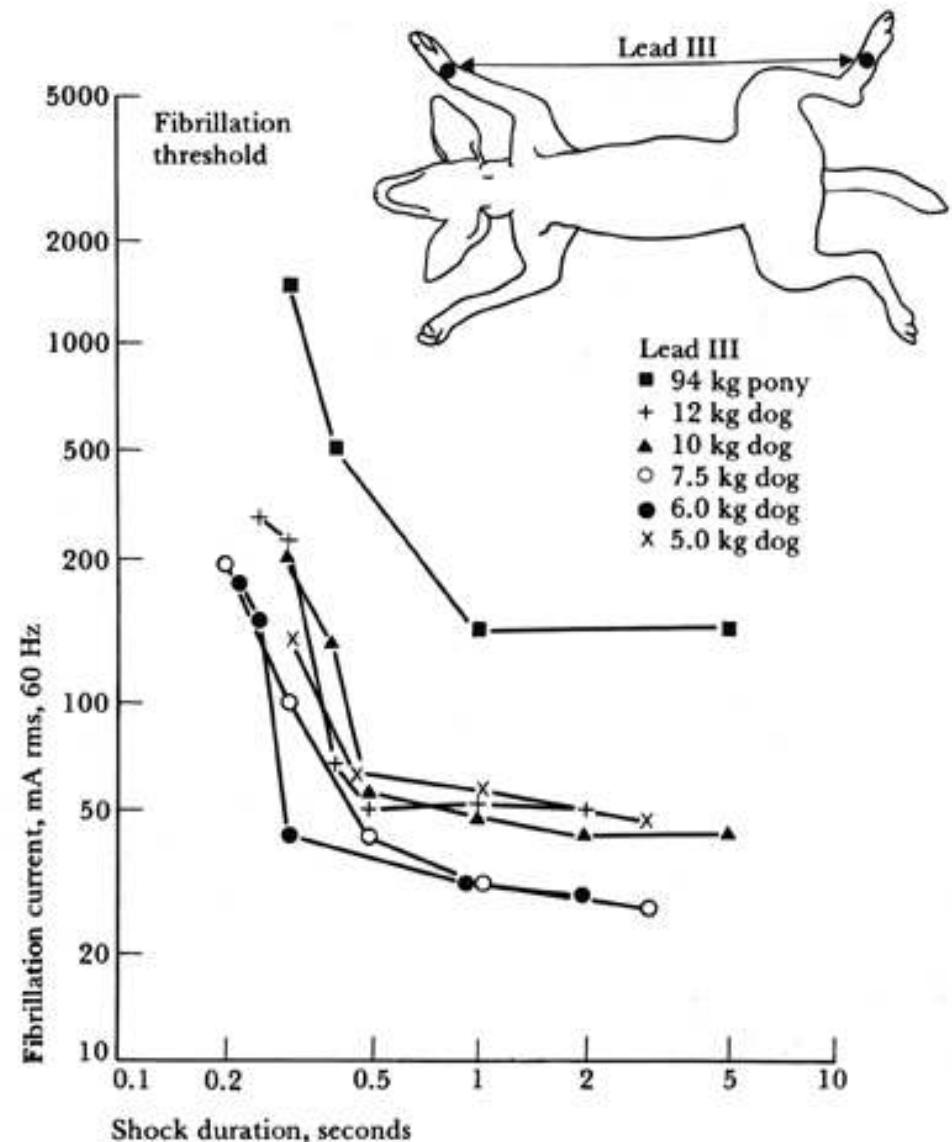
Important Susceptibility Parameters

- Duration
  - The longer the duration, the smaller the current at which ventricular fibrillation occurs
  - Shock must occur long enough to coincide with the most vulnerable period occurring during the T wave.

- Weight
  - Fibrillation threshold increases with body weight (from 50mA for 6kg dogs to 130 mA for 24 kg dogs.

Fibrillation current versus shock duration. Thresholds for ventricular fibrillation in animals for 60 Hz AC current. Duration of current (0.2 to 5 s) and weight of animal body were varied.

Important Susceptibility Parameters

- Points of entry

  - The magnitude of the current required to fibrillate the heart is far greater if the current is applied directly to heart; externally applied current loses much of its amplitude due to current distributions. Large, externally applied currents cause *macroshock*.

  - If catheters are used, the natural protection provided by the skin 15 kΩ ~ 2 MΩ) is bypassed, greatly reducing the amount of current req'd to cause fibrillation. Even smallest currents (80 ~ 600 μA), causing *microshock*, may result in fibrillation. Safety limit for microshocks is 10 μA.

  - The precise point of entry, even externally is very important: If both points of entry and exit are on the same extremity, the risk of fibrillation is greatly reduced even at high currents (e.g. the current req'd for fibrillation through Lead I (LA-RA) electrodes is higher than for Leads II (LL-RA) and III (LL-LA).

# Important Susceptibility Parameters
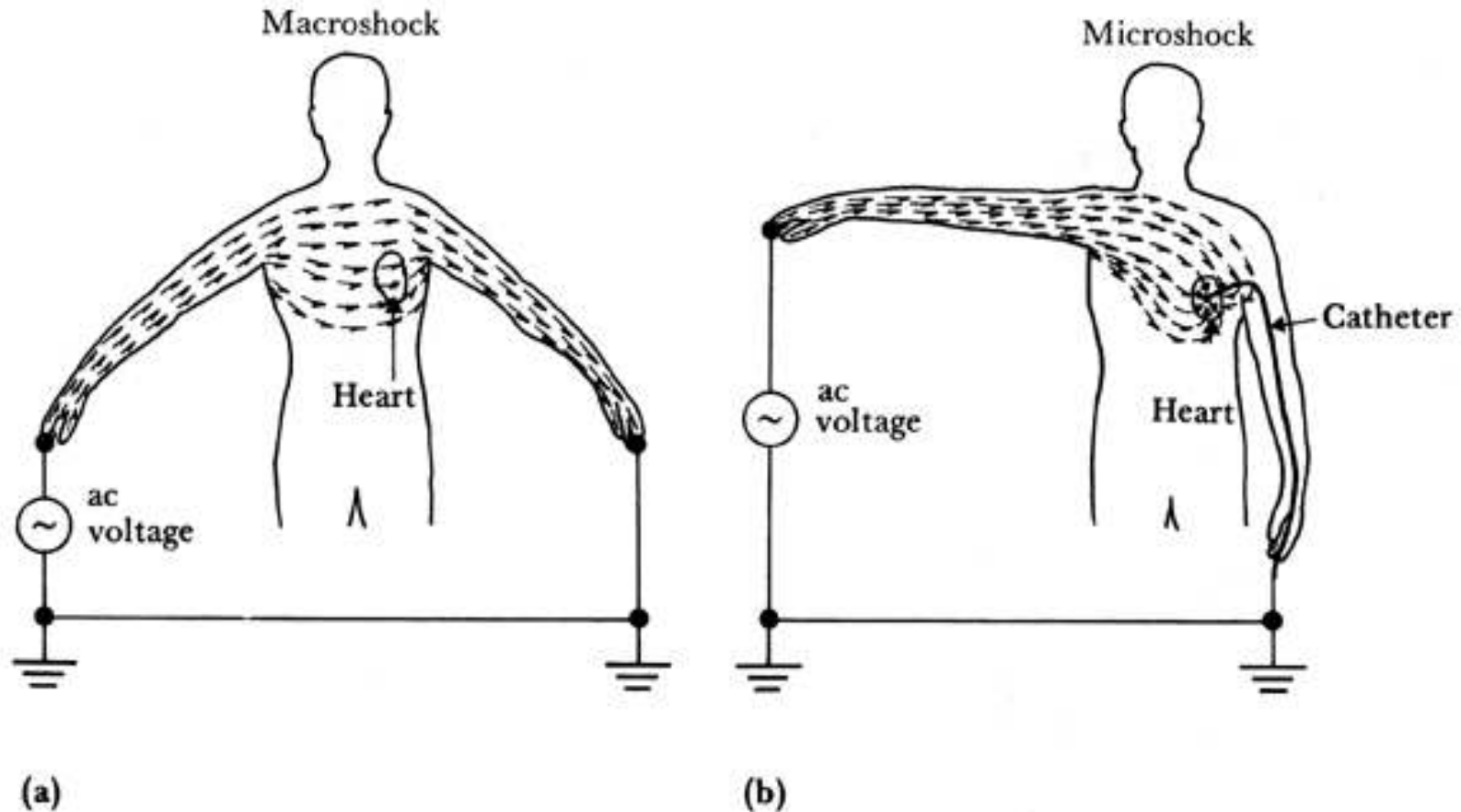
- Points of entry

Effect of entry points on current distribution (a) *Macroshock*, externally applied current spreads through-out the body. (b) *Microshock*, all the current applied through an intracardiac catheter flows through the heart.

Macroshock

- Most electrical devices have a metal cabinet, which constitutes a hazard, in case of an insulation failure or shortened component between the hot power lead and the chassis. There is then 115 ~ 230 V between the chassis and any other grounded object.
- The first line of defense available to patients is their skin.
  - The outer layer provides 15 kΩ to 1 MΩ depending on the part of the body, moisture and sweat present, 1% of that of dry skin if skin is broken,
  - Internal resistance of the body is 200Ω for each limb, and 100Ω for the trunk, thus internal body resistance between any two limbs is about 500Ω (somewhat higher for obese people due to high resistivity of the adipose tissue)!
  - Any procedure that reduces or eliminates the skin resistance increases the risk of electrical shock, including biopotential electrode gel, electronic thermometers placed in ears, mouth, rectum, intravenous catheters, etc.
- A third wire, grounded to earth, can greatly reduce the effect of macroshock, as the resistance of that path would be much smaller then even that of internal body resistance!
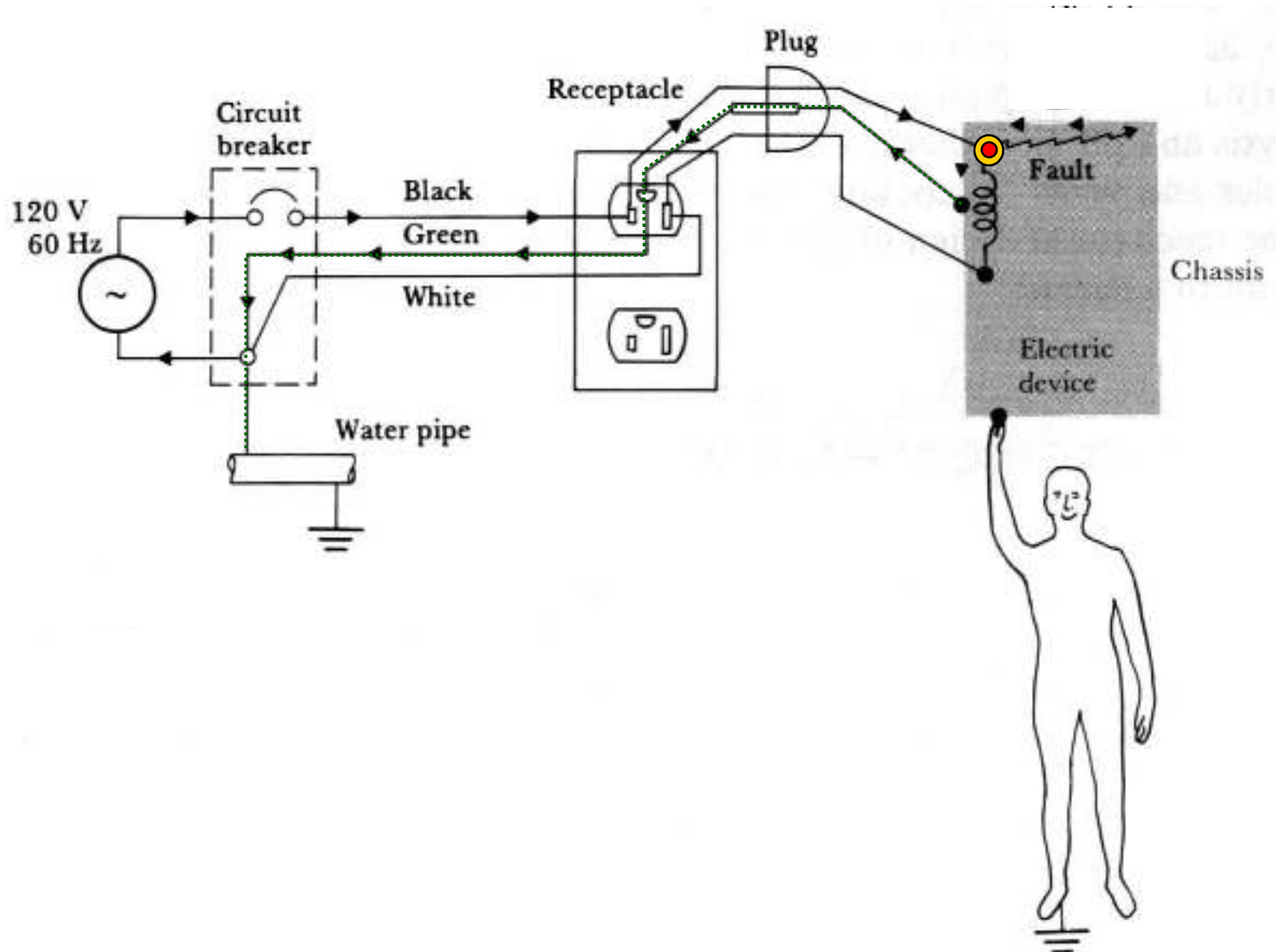
Macroshock Hazards
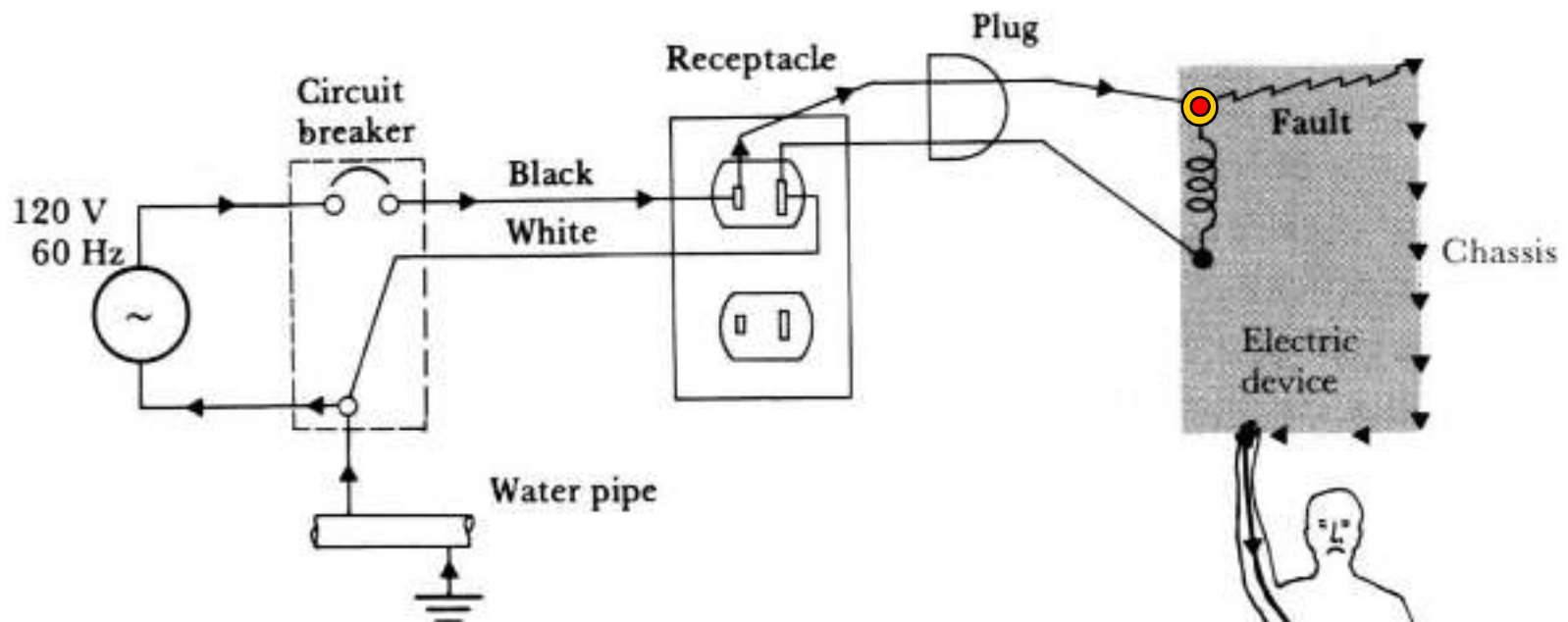
- Direct faults between the hot conductor and the ground is not common,
  and technically speaking, ground connection is not necessary during normal operation.

- In fact, a ground fault will not be detected during normal operation of the device, only when someone touches it, the hazard becomes known.
  Therefore, ground wire in devices and receptacles must be periodically tested

Macroshock Hazards

Microshock Hazards
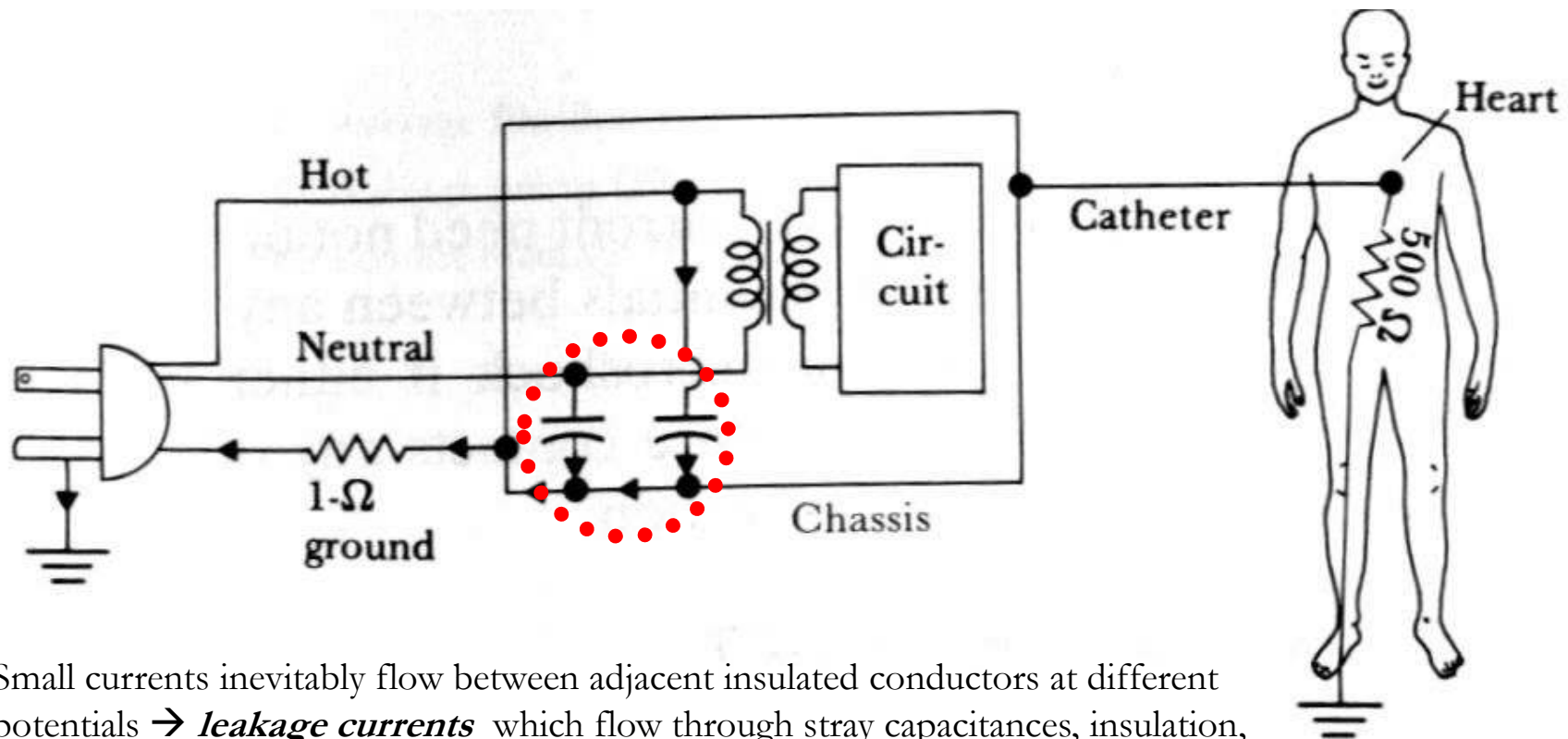

Small currents inevitably flow between adjacent insulated conductors at different potentials ➔ *leakage currents* which flow through stray capacitances, insulation, dust and moisture

Leakage current flowing to the chassis flows safely to the ground, if a low-resistance ground wire is available.

Microshock Hazards

• If ground wire is broken, the chassis potential rises above the ground; a patient who has a grounded connection to the heart (e.g. through a catheter) receives a microshock if s/he touches the chassis.
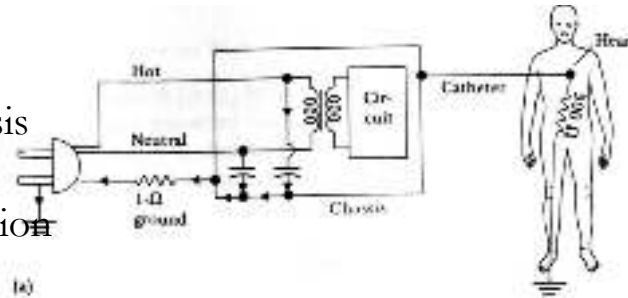
• If there is a connection from the chassis to the patient's heart, **and** a connection to the ground anywhere in the body, this also causes microshock.
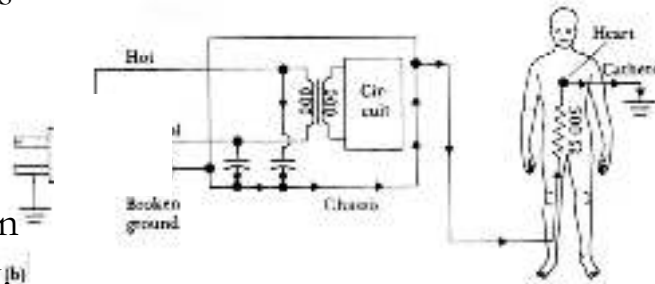
• Note that the hazard for microshock only exists if there is a direct connection to the heart. Otherwise, even the internal resistance of the body is high enough top prevent the microshocks.
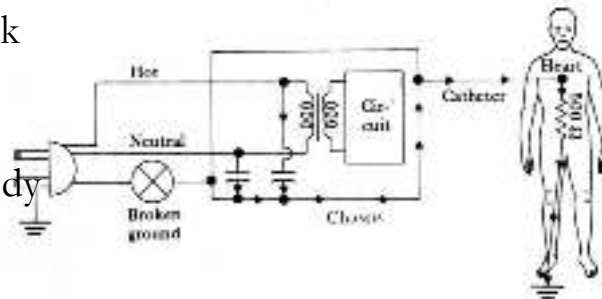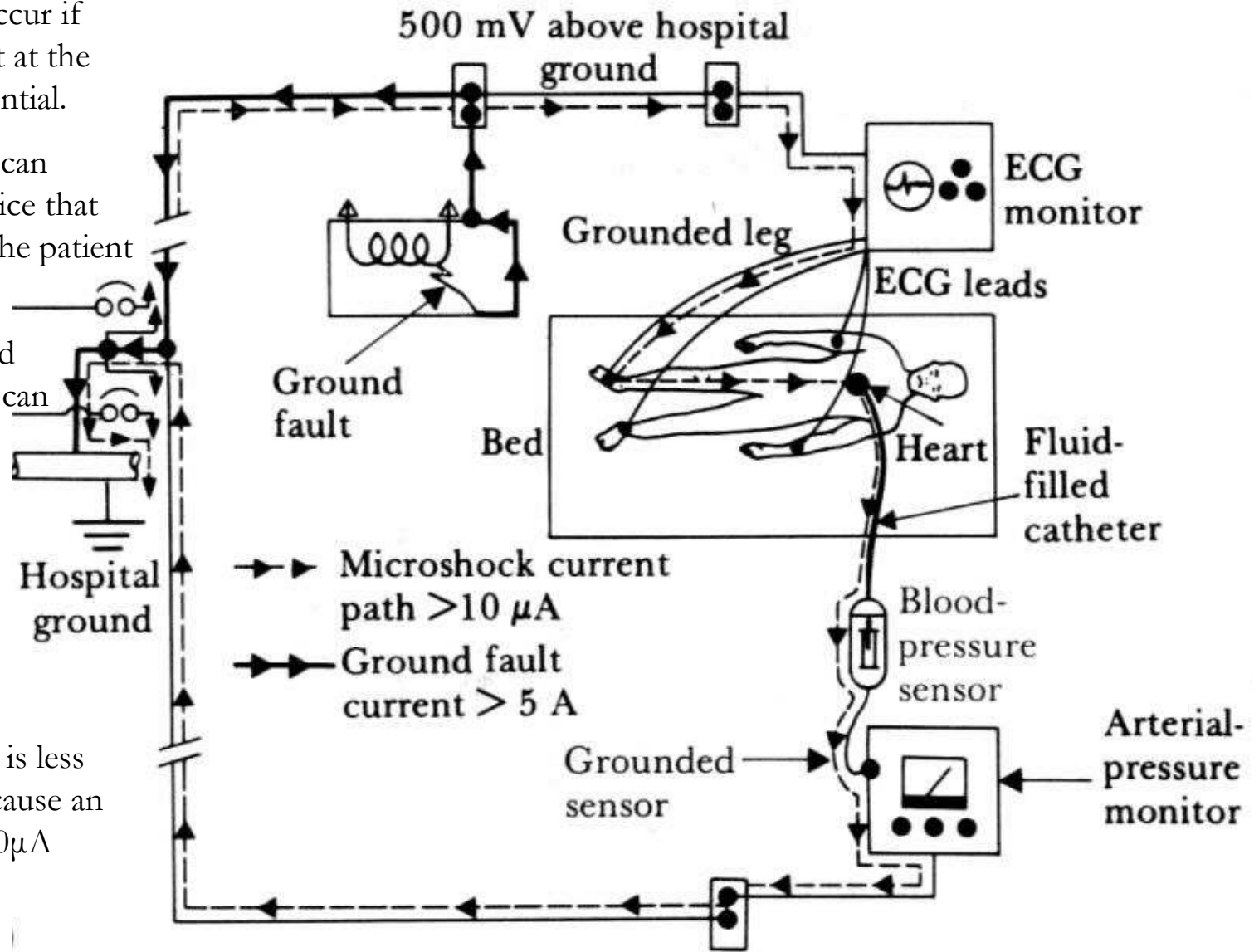
Microshock via Ground Potentials

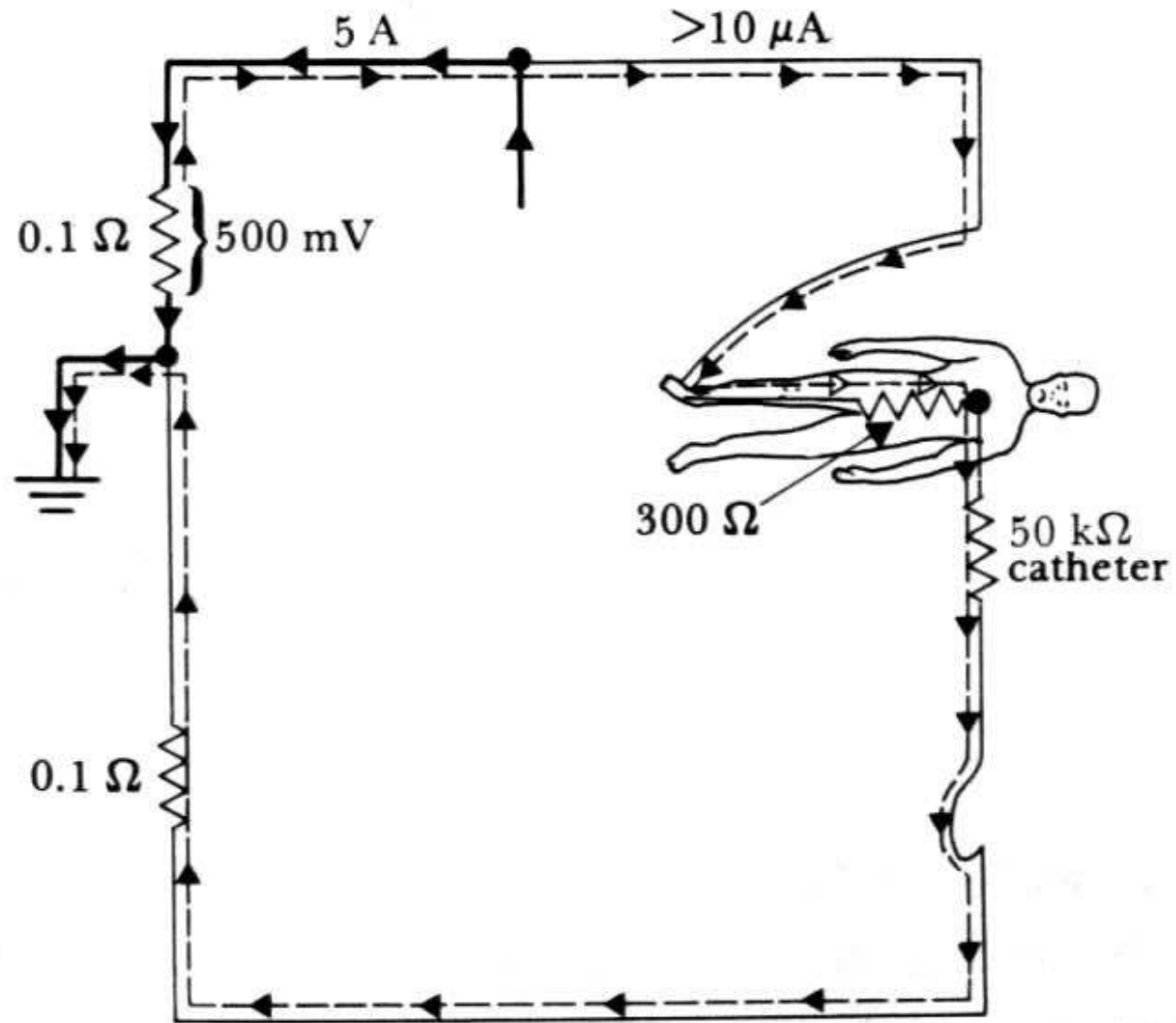Microshocks can also occur if different devices are not at the exact same ground potential.

In fact, the microshock can occur **even when** a device that does not connected to the patient has a ground fault!

A fairly common ground wire resistance of 0.1Ω can easily cause a a 500mV potential difference if initiated due to a, say 5A of ground fault.

If the patient resistance is less then 50kΩ, this would cause an above safe current of 10μA

500 mV above hospital ground

Grounded leg

ECG monitor

ECG leads

Ground fault

Bed

Heart

Fluid-filled catheter

Hospital ground

→▶ Microshock current path >10 μA

▶▶ Ground fault current > 5 A

Blood-pressure sensor

Grounded sensor

Arterial-pressure monitor

Microshock Via Ground Potentials

5 A >10 μA

0.1 Ω 500 mV

300 Ω

50 kΩ
catheter

0.1 Ω

Safety Codes & Standards

- Limits on leakage current are instituted and regulated by the safety codes instituted in part by the National Fire Protection Association (NFPA), American National Standards Institute

Electric Appliance	Chassis Leakage, μA	Patient-lead Leakage, μA
Appliances not intended to contact patients	100	NA
Appliances not intended to contact patients and single fault	500	NA
Appliances with *nonisolated* patient leads	100	10
Appliances with *nonisolated* leads and single fault	300	100
Appliances with *isolated* patient leads	100	10
Appliances with *isolated* leads and single fault	300	50

Basic Approaches to Shock Protection

- There are two major ways to protect patients from shocks:
  - Completely isolate and insulate patient from all sources of electric current
  - Keep all conductive surfaces within reach of the patient at the same voltage

- Neither can be fully achieved ➜ some combination of these two
  - Grounding system
  - Isolated power-distribution system
  - Ground-fault circuit interrupters (GFCI)
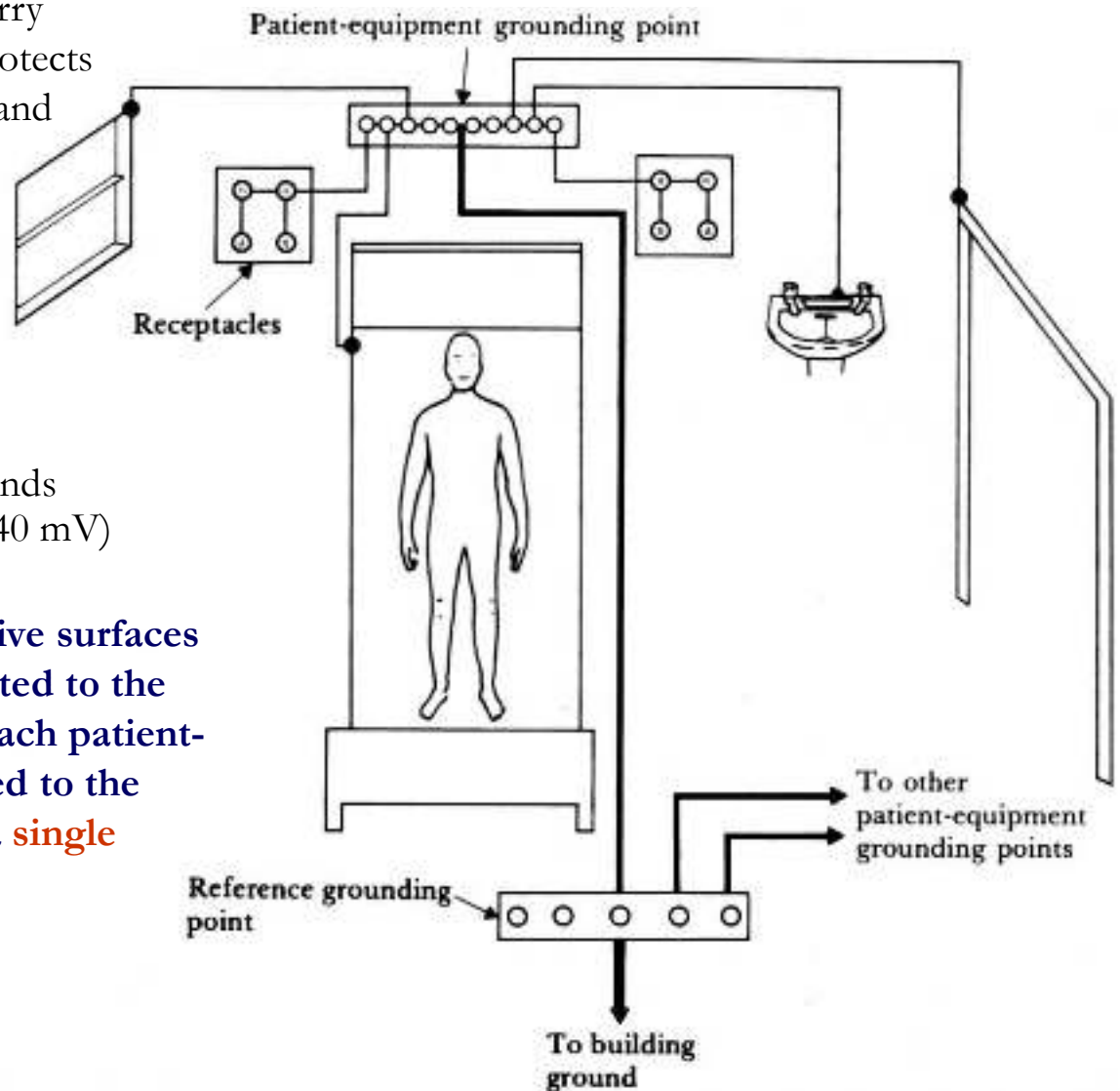
Grounding Systems

Low resistance (0.15 Ω) ground that can carry currents up to the circuit-breaker ratings protects patients by keeping all conductive surfaces and receptacle grounds at the same potential.

Protects patients from

- Macroshocks
- Microshocks
- Ground faults elsewhere (!)

The difference between the receptacle grounds and other surface should be no more then 40 mV)

All the receptacle grounds and conductive surfaces in the vicinity of the patient are connected to the patient-equipment grounding point. Each patient-equipment grounding point is connected to the reference grounding point that makes a single connection to the building ground.

Patient-equipment grounding point

Receptacles

Reference grounding point

To building ground

To other patient-equipment grounding points

Isolated Power Systems

- A good equipotential grounding system cannot eliminate large current that may result from major ground-faults (which are rather rare).
- Isolated power systems can protect against such major (single) ground faults
  - Provide considerable protection against macroshocks, particularly around wet conditions
  - However, they are expensive !
  - Used only at locations where flammable anesthetics are used. Additional minor protection against microshocks does not justify the high cost of these systems to be used everywhere in the clinical environment

Protection through Equipment Design

- Strain-relief devices for cords, where cord enters the equipment and between the cord and plug

- Reduction of leakage current through proper layout and insulation to minimize the capacitance between all hot conductors and the chassis

- Double insulation to prevent the contact of the patient with the chassis or any other conducting surface (outer case being insulating material, plastic knobs, etc.)

- Operation at low voltages; solid state devices operating at <10V are far less likely to cause macroshocks

- Electrical isolation in circuit design

Testing Electrical Appliances

- Leakage current in patient leads:
  - Potentially most damaging leakage is the one with patient leads, since they typically have low impedance patient contacts
  - Current should be restricted to 50µA for non-isolated leads and to 10 µA for isolated leads (used with catheters / electrodes that make connection to the heart)
  - Leakage current **between** any pair of leads, or between a single lead and other patient connections should also be controlled
  - Leakage in case of line voltage appearing on the patient should also be restricted.