Bio-Electricity

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Applied Bioelectricity, J.P. Reilly, 1998

- Responses to AC and DC voltage and current well understood
- Cardiac Stimulation and Fibrillation
  - Both AC and DC currents can disrupt heart rhythm
  - AC stimulus is a more efficient promoter of multiple ventricular responses
  - For 1 second exposure DC required 4 times more current (500 mA) than 20 Hz AC current (100 mA rms) to produce cardiac stimulation in dogs (page 215).
- Sensory and muscular Responses
  - In practice DC sensory and muscular thresholds are about equal to peak AC currents or about 1.4 times higher than AC rms values.

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Brief Overview of Human Exposures

- First neuro-electric studies done 100 years ago
  - Replicated hundreds of times
  - Reviewed by J.P. Reilly, 1998, Johns Hopkins University
- Main Topics
  - Beneficial Medical applications
    - Pace-Makers, Pain relief, paralysis mitigation
  - Startle response - accidents
  - Electrical Injuries
  - Death by Electrocution

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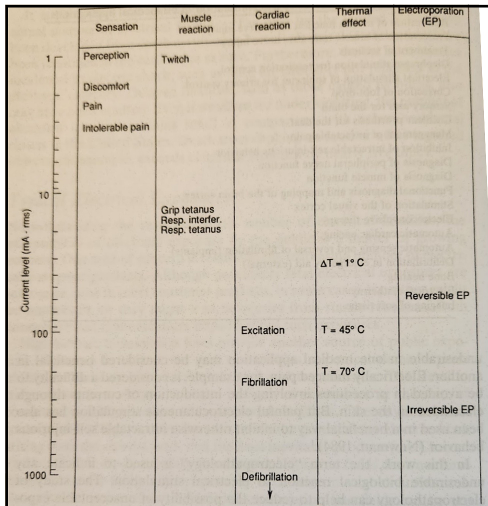
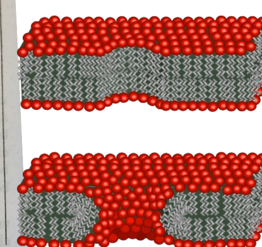


FIGURE 1.2. Potential short-term reactions to 60-Hz current. Assumed conditions: 5-s exposure; hand grip of large electrode; return electrode at feet; large adult subject; median response.

Electroporation, or **electro-permeabilization**, is a technique in which an electrical field is applied to cells in order to increase the permeability of the cell membrane. This may allow chemicals, drugs, electrode arrays or DNAto be introduced into the cell



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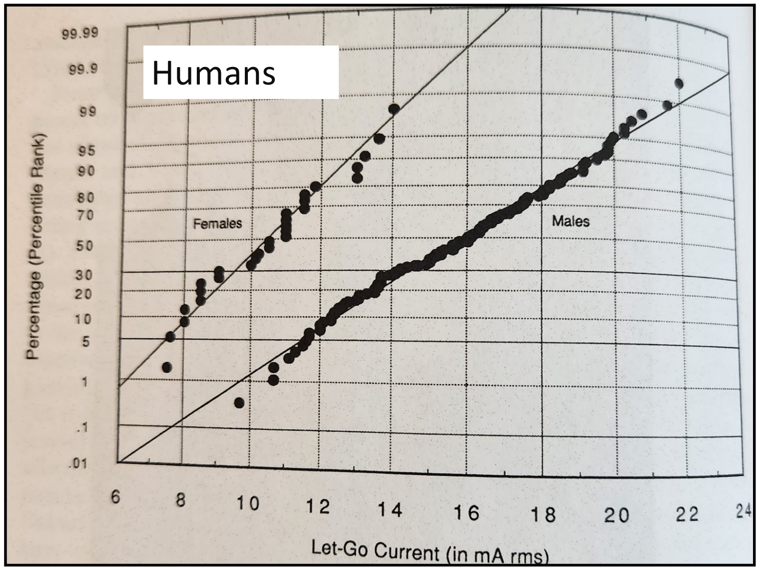

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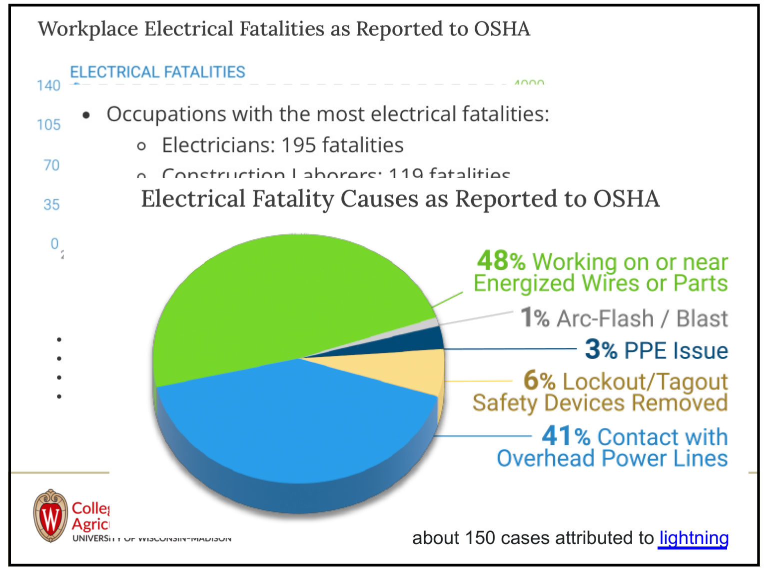

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TABLE 1.2. Examples of electrical stimulation in biomedical applications.

Restoration of muscle function after nerve injury
Preservation of muscle tone after nerve injury
Treatment of scoliosis
Diaphragm stimulation for respiration control
Electrical stimulation of sphincter for urinary control
Correction of foot-drop
Sensory aids for the blind
Cochlear prosthesis for the deaf
Management of intractable pain
Inhibition of intractable self-injurious behavior
Diagnosis of peripheral nerve function
Diagnosis of muscle function
Functional diagnosis and mapping of the brain cortex
Stimulation of the visual cortex
Electroconvulsive therapy
Automatic cardiac pacing
Automatic sensing and reversal of fibrillation (implants)
Defibrillation in emergency aid (external)
Bone healing
Electrical diathermy
Imaging of soft tissue

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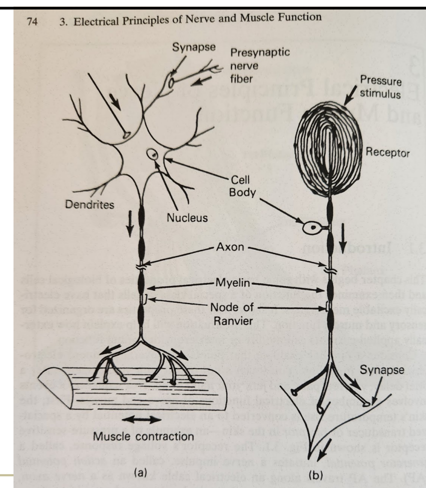

FIGURE 3.1. Functional components of (a) motor and (b) sensory neurons. Arrows indicate the direction of information flow. Signals are propagated across synapses through chemical neurotransmitters and elsewhere by membrane depolarization. Synapses are inside the spinal column. The sizes of the components are drawn on a distorted scale to emphasize various features.

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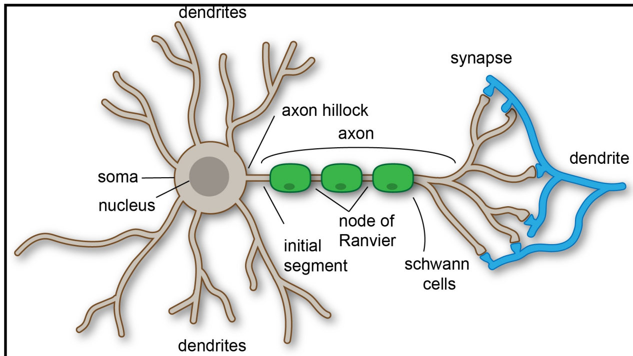

The neuron contains, a cell body called the soma,
dendrites that receives information
axon that sends information.
Synapses allow neurons to activate other neurons.

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All-or-none law

- Action potentials are all-or-none signals
  - either they occur fully or they do not occur at all
- Sensory receptor potentials amplitudes are dependent on the intensity of a stimulus
- frequency correlated with intensity of stimulus
  - About 1 to 100 Hz

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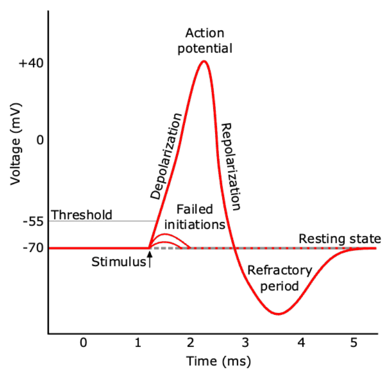
cell membranes maintain a voltage difference between the exterior and interior of the cell, called the membrane potential.

A typical voltage across an animal cell membrane is −70 mV. This means that the interior of the cell has a negative voltage relative to the exterior.

In neurons and muscle cells, rapid upward (positive) voltage spike followed by a rapid fall.

These up-and-down cycles are known as *action potentials*.



In neurons the entire up-and-down cycle takes place in 2 milliseconds.
In muscle cells, a typical action potential lasts about 200 milliseconds.

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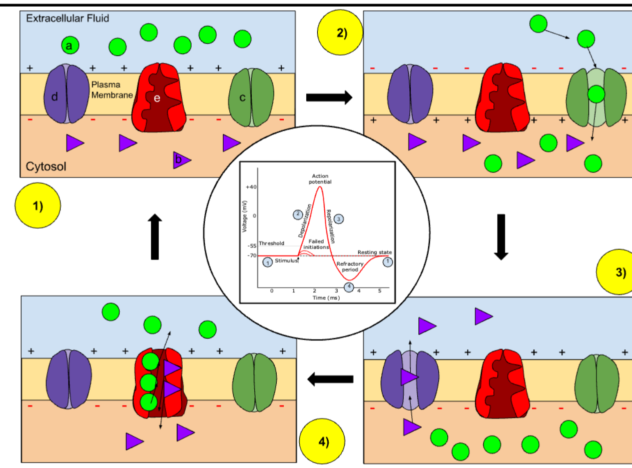

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a) Sodium (Na^+) ion. b) Potassium (K^+) ion.
c) Sodium channel. d) Potassium channel.
e) Sodium-potassium pump.

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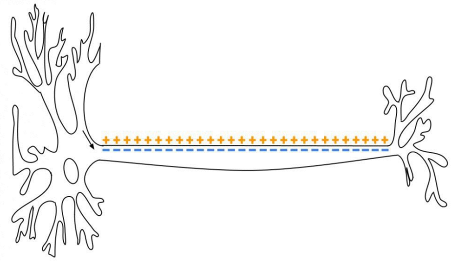
As an action potential (nerve impulse) travels down an axon there is a change in electric polarity across the membrane of the axon.

In response to a signal from another neuron, sodium- (Na^+) and potassium- (K^+)–gated ion channels open and close as the membrane reaches its threshold potential.



Na^+ channels open at the beginning of the action potential, and Na^+ moves into the axon, causing depolarization.

Repolarization occurs when K^+ channels open and K^+ moves out of the axon, creating a change in electric polarity between the outside of the cell and the inside.

The impulse travels down the axon in one direction only, to the axon terminal where it signals other neurons.

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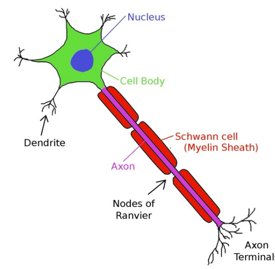

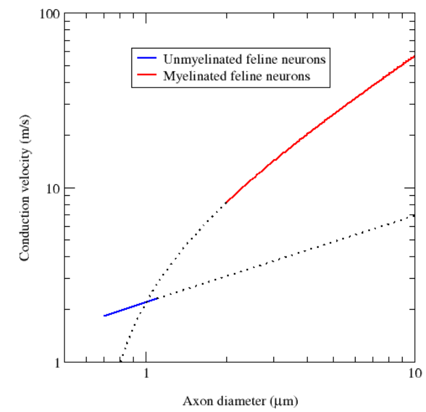

the action potential appears to "hop" from node to node

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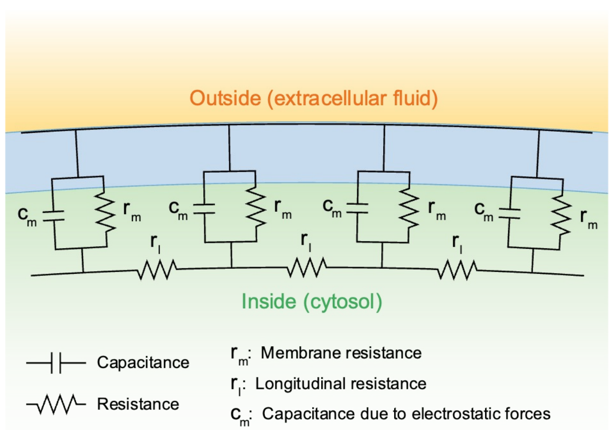

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The flow of currents within an axon can be described by Cable theory, developed in 1855 by Lord Kelvin to model the transatlantic telegraph cable

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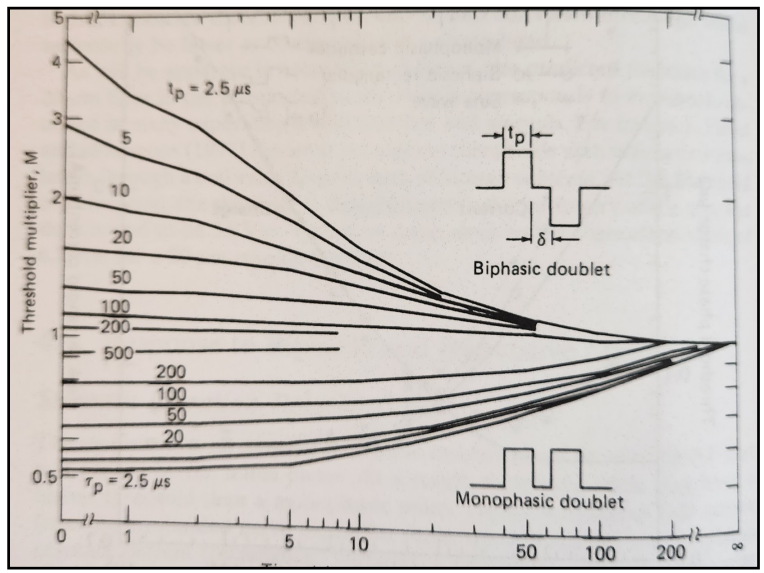

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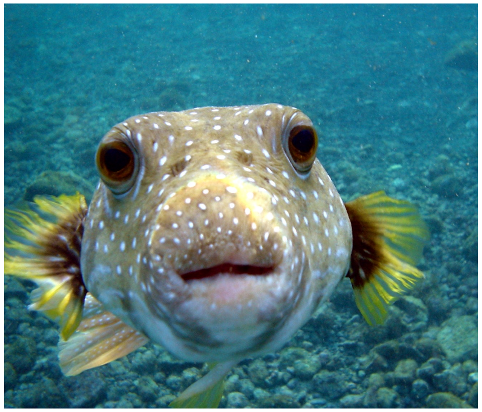

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Several neurotoxins, both natural and synthetic, function by blocking the action potential.

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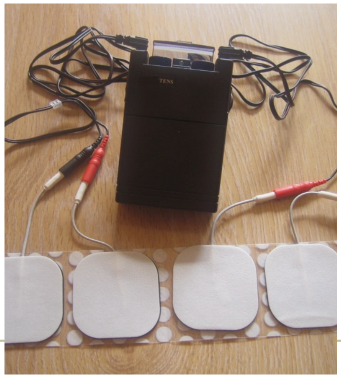
transcutaneous electrical nerve stimulation(TENS)

- produces electric current to stimulate the nerves for therapeutic purposes.
  - alleviate acute and chronic pain by reducing the sensitization of dorsal horn neurons



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Electrical muscle stimulation (EMS),

- elicitation of muscle contraction using electrical impulses.
  - strength training tool
  - rehabilitation and preventive tool for people who are partially or totally immobilized;

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Effects of electromagnetic radiation on human health

- health effects from extremely low frequency (ELF) electric and magnetic fields (0 to 300 Hz) generated by power lines,
- and radio/microwave frequencies (RF) (10 MHz - 300 GHz) emitted by radio antennas and wireless networks have been well studied
- documented effects from radiofrequency electromagnetic fields are limited to high power sources capable of causing significant thermal effects

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Magnetic Field Stimulation of Cows

- 1Magnetic flux density of 54 mT at 60 Hz required for nerve stiulation
- Several orders of magnitude reater than encountered on a farm

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AC Transmission Studies at McGill University

- Extreme level and duration of Electric and Magnetic Field exposure produced some physiological changes
  - Similar to changes in day length
  - Changes were within the normal range for healthy cattle.
- These changes do not represent a health hazard

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DC Transmission Studies

- Extensive 3-year study of beef cattle under a 500 kV DC transmission line
- exposure to air ions and EMF was far greater than typical
- from 5 to 11 percent fewer cattle occupied areas directly under DC conductors (not correlated with DC field or audible noise).
  - Such a small effect would not be noticeable
- no evidence that a +/-500-kV DC line caused any effects on cattle or crops that would impact commercial farming or ranching operations

- Raleigh, R. J. 1988. Joint HVDC Agricultural Study: Final Project Report. Bonneville Power Administration Report.

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Electrical and Biological Effect of Transmission Lines: A Review. J. M. Lee, 1996

- Minnesota Science Advisory Committee concluded no indication that the 400 kV DC line presented a risk to human health
- Overall, there appears to be no evidence that the electric fields and ions of DC lines pose and hazards to public health.
- It has been suggested that self reported health effects from some people in Minnesota may be related to stress, apparently associated with controversy over the line, or perceived hazards.

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Findings of the Minnesota Science Advisors to the Minnesota Public Utilities Commission: 1999

We have not found credible scientific evidence to verify the specific claim that currents in the earth or associated electrical parameters such as voltages, magnetic fields and electric fields, are causes of poor health and milk production in dairy herds

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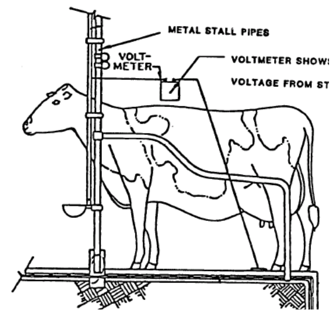

contact. For evaluation purposes, it is often sufficient to consider the worst case resistance, i.e., the lowest resistance likely to be encountered. We consider 500 Ω for the sum of contact and body resistances to be a very conservative estimate of the worst case, or minimum, resistance that is likely to be encountered.

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Impedance Model from J.P Reilly, 1998.
Applied Bioelectricity: From Electrical Stimulation to Electro-pathology. Springer-Verlag, New York.

- Impedance includes resistive and capacitive elements
- Measurement methods influence measured values

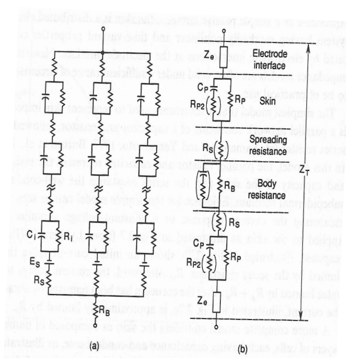

Figure 2.8 More complex impedance models: (a) multilayer model for skin impedance; (b) simplified body impedance model.

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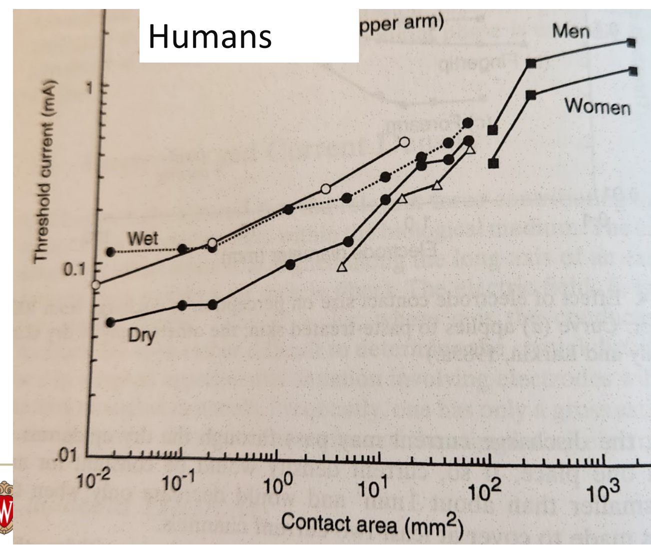

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USDA 696

- Chapter 3, Verse 1.2
  - it is the total series impedance that limits the current cows receive and not just body impedance.
  - The total series impedance is the sum of source, path, contact, and body impedances.

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USDA 696

- Chapter 3, Verse 1.5
  - The voltages needed to deliver these currents depend on
  - body impedance of the cow,
  - contact impedances between the cow and the conductive structures,
  - impedance of the conductive structures, and
  - impedance of the voltage source.

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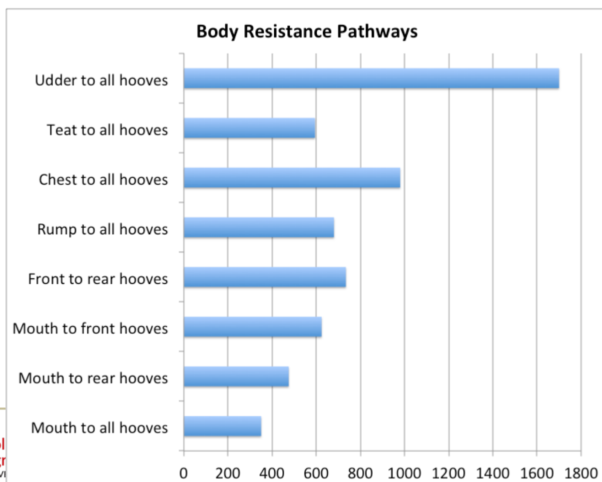
USDA 696 Values



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Calculated from Norell et al 1983

Head/Neck	183 ohms
Body	30 ohms
Front legs	882 ohms
Rear legs	525 ohms

Calculating Body Resistance
contact resistances need to be added

Standing on moist soil
'Body' = 472 Ohms
Lifting one foot = 549 Ohms
Front-rear hooves = 1,173 Ohms

Standing on a metal plate
(completely conductive surface)
'Body' = 358 Ohms

Impedance Model from J.P Reilly, 1998. Applied Bioelectricity: From Electrical Stimulation to Electro-pathology

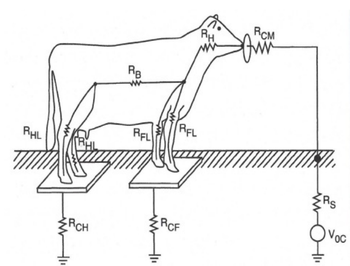

FIGURE 2.41. Cow impedance model for stray voltage application.

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R_{ch} and R_{cf} = 40 – 4000 Ohms Soil
= 40 – 1000 Ohms Concrete

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Cow body Impedance

- For moist soil conditions
  - Muzzle-all hoof = 472 Ohms
  - Excluding contact resistance
  - Lifting one foot = 549 Ohms
  - Front – rear feet = 1173 Ohms
- On perfectly conductive surface
  - Muzzle – all hoof = 358 Ohms

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Impedance Model from J.P Reilly, 1998.
Applied Bioelectricity: From Electrical Stimulation to Electro-pathology. Springer-Verlag, New York.

- relationship between the internal 'body resistance' (R_B) and the total impedance of a 'body'
  - including skin and electrode impedance
- For humans

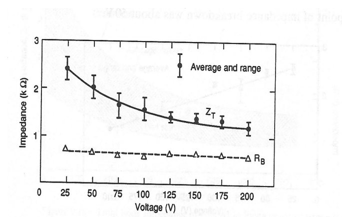

Figure 2.15 Impedance versus voltage for large-area hand-to-feet contacts. (From Biegelmeier, 1985b.)

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Effect of measurement method on muzzle-hoof 'body' resistance values

- Jagged metal plate versus concrete -100 ohms hoof contact resistance
- Nose clip versus waterer – 50 ohms muzzle contact resistance
  - Broken skin – ??? ohms

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The Problem of Contact Resistance

- The most variable part of the electrical circuit
- Contact resistances will increase with:
  - smaller contact surface area
  - reduced contact surface pressure
  - drier contact surfaces
  - the amount of debris on contact point
  - resistance value of the debris at the contact margin
- The accepted practice by researchers and regulators has been to assume worst-case (lowest practical values) for contact resistances.

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Animal Response to Stray Voltage

- Avoidance behavior
- Milk production

- Well documented
- Documented only for extreme exposure

- Somatic cells
- Reproduction
- Milkout problems

- Not documented
- Not documented
- Not documented

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Ways That Stray, or Tingle, Voltage Can Impact Farm Operations

- Direct effects
  - Mild behavioral reactions = sensation
  - Involuntary muscle contraction = twitching
  - Intense behavioral responses = pain
- Severity depends on
  - amount of electrical current (milliAmps) flowing through the animal's body
  - Body pathway
  - Individual animal Sensitivity

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Indirect effects

- Animals avoiding certain exposure locations
  - Reduced water intake if exposure is required for animals to access watering devices,
  - Reduced feed intake if exposure is required for animals to accesses feeding devices or locations.
- Difficulty of moving or handling animals in areas of voltage/current exposure
- Release of stress hormones produced by contact with painful stimuli

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Exposure Conditions Required to Produce an Effect

- Adverse effect requires BOTH annoying current AND forced exposure
- Contact resistance
  - 500 ohms is worst case
  - 1000 Ohms is typical
  - Dry contacts or bedding will increase contact resistance
- Location
  - Areas vital to normal daily activities
- Times / day
  - Annoying stimulus must occur frequently

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Levels That Affect Farm performance

- Current exposure < 3 mA may produce mild behavioral changes in a small percentage of cows
  - Corresponding to < 2 to 3 Volts
  - Aversive behaviors likely short-lived
  - No physiological changes
  - Changes likely undetectable on most farms

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Levels That Affect Farm performance

- Current exposure from 3 to 6 mA may produce observable behavioral changes in some cows
  - Corresponding to 3 to 6 Volts
  - May produce short term changes in eating/drinking for some cows depending on location and time of exposure
    - Likely difficult to detect
  - Aversive behaviors likely short-lived
  - May produce mild increase in 'stress' hormones in some cows

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Levels That Affect Farm performance

- Current exposure above 6 mA likely to produce some behavioral changes in most cows and pronounced behaviors in some cows
  - Corresponding to > 6 Volts
  - Likely to produce changes in eating / drinking for some cows depending on location and time of exposure
    - May be detectable on some farms
  - May produce increase in 'stress' hormones in some cows

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Diagnosis

- Animal behavior or other symptoms CANNOT be used to diagnose stray voltage problems
  - All known responses to stray voltage exposure can be produced by other causes
- The ONLY WAY to determine if stray voltage is a potential cause is to perform electrical testing

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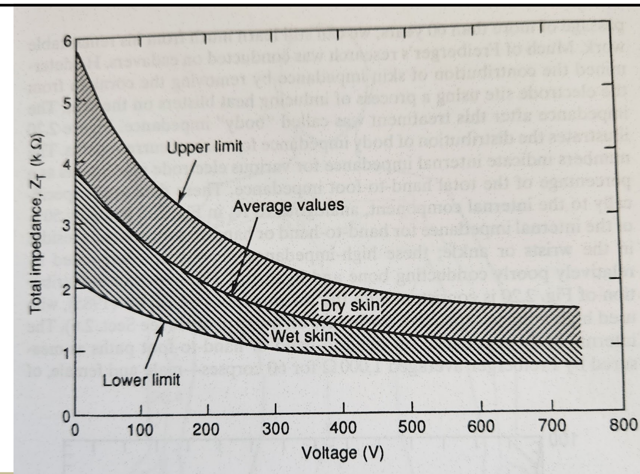

FIGURE 2.18. Total body impedance attributed to living persons; large-area hand-to-hand or hand-to-foot contacts. Measurements above 50 V conducted on cadavers, and corrected for living persons. (From Freiberger, 1934.)

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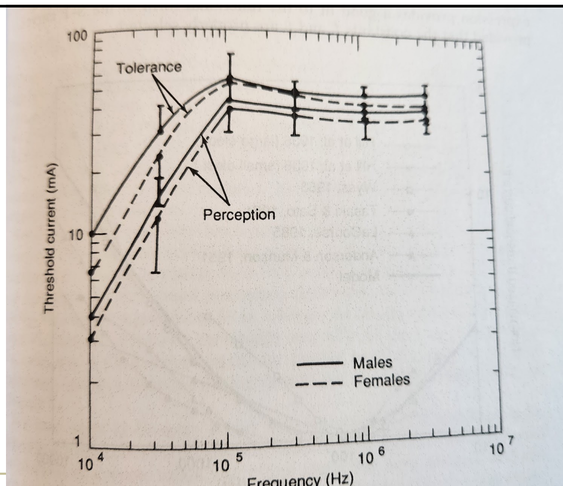

FIGURE 7.12. Perception and tolerance thresholds for AC stimulation of high frequency. Finger contact on 25-mm² plate. (Adapted from Chatterjee et al., 1986, © 1986 IEEE.)

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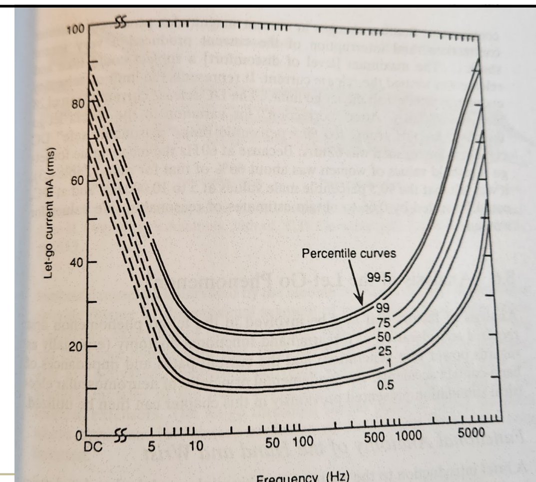

FIGURE 8.10. The effect of stimulus frequency on the let-go current threshold for adult males. Values on the left-hand axis are for DC. (Adapted from Dalziel, © 1972 IEEE, using some additional data from Dalziel et al., 1943.)

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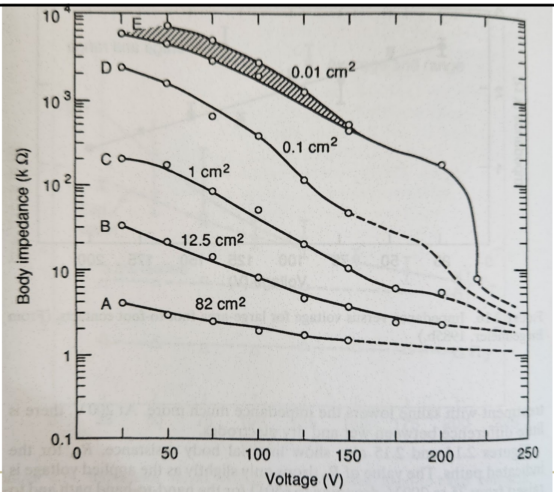

FIGURE 2.17. Total body impedance as a function of applied voltage for various contact areas; dry hand-to-hand electrodes. The various curves are identified by the contact area on each hand. (From Biegelmeier, 1985b.)

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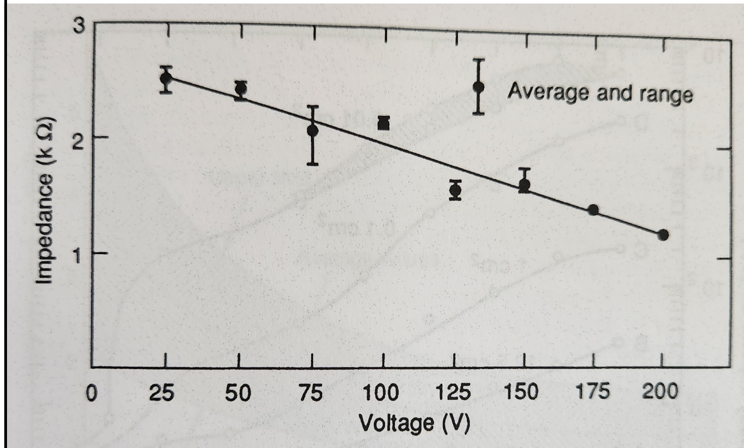

FIGURE 2.16. Impedance versus voltage for large-area foot-to-foot contacts. (From Biegelmeier, 1985b.)

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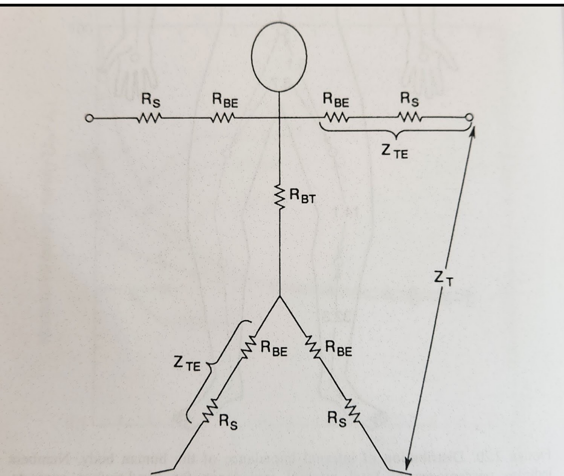

FIGURE 2.21. Simplified impedance model for current paths across extremities—wet skin, large-area contacts. Example values: Z_T = 1,000 Ω; Z_{TE} = 500 Ω; R_{BE} = 250–375 Ω; R_S = 125–250 Ω; R_{BT} = 50 Ω.

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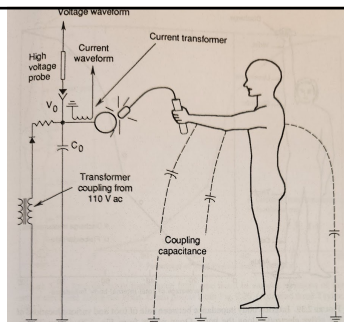

FIGURE 2.38. Body impedance measurement with capacitive coupling of body to ground. (From Taylor, 1985.)

TABLE 2.15. Initial total body impedance (Ω).

Path	Mean	Standard deviation
Dry skin		
Left hand/left foot	533	52
Right hand/left foot	521	37
Right hand/left hand	508	29
Treated skin		
Left hand/left foot	516	55
Right hand/left foot	507	36
Right hand/left hand	490	36

Source: Data based on measurements of seven individuals (from Taylor, 1985).

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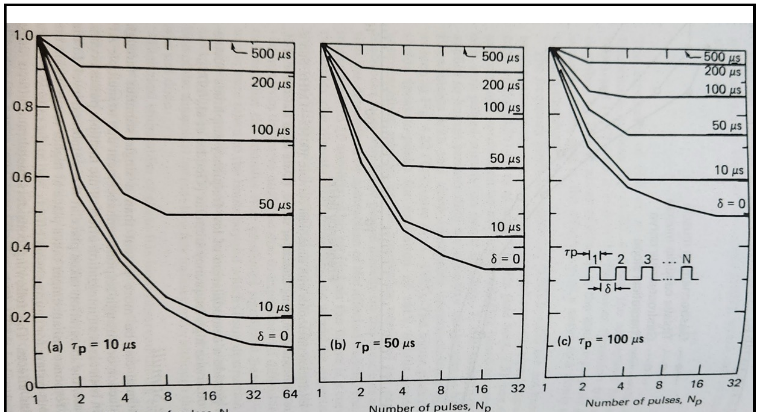

FIGURE 4.23. Threshold multiplier for repetitive pulse sequences—thresholds evaluated at N_p = 1, 2, 4, 8, 16, 32, and 64. Uniform field

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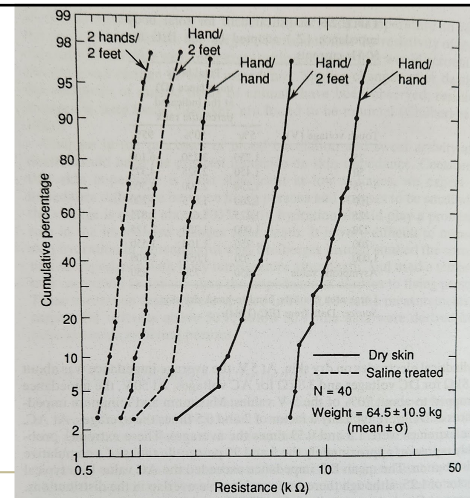

FIGURE 2.22. Cumulative distribution of DC resistance of adults, with various electrode paths. Hand electrodes = 2 No. 10 Awg twisted wires, feet on plate, I = 5 mA. (Data from Whitaker, 1939.)

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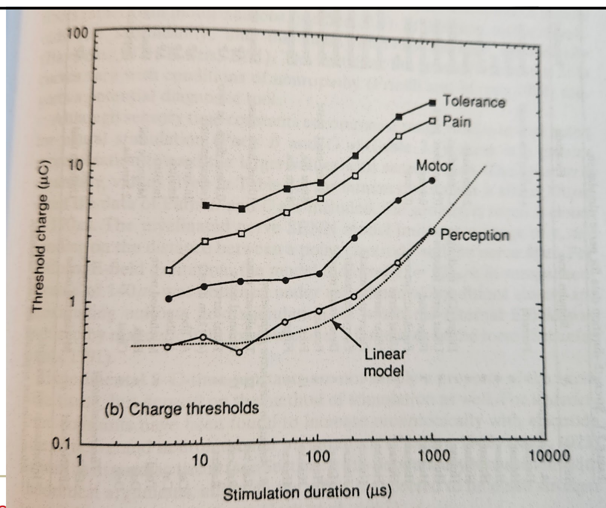

FIGURE 7.3. Strength-duration curves for sensory and motor reactions to square-wave pulses; forearm stimulation, 4-cm² electrode. (Data from Alon et al., 1983.)

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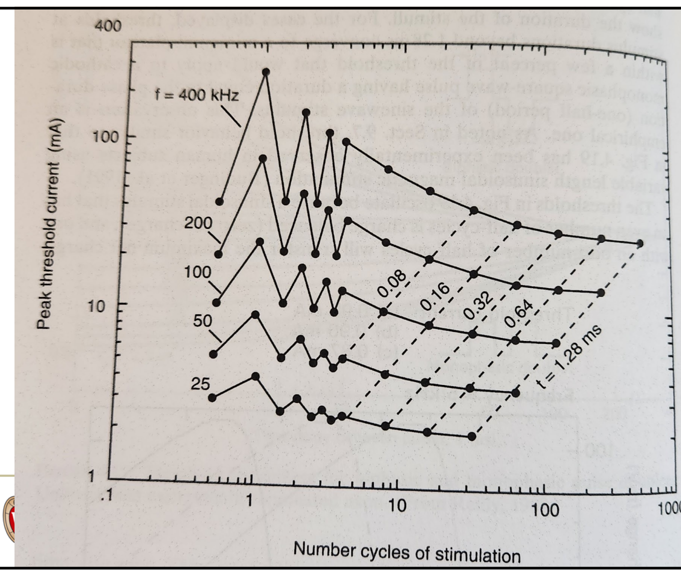

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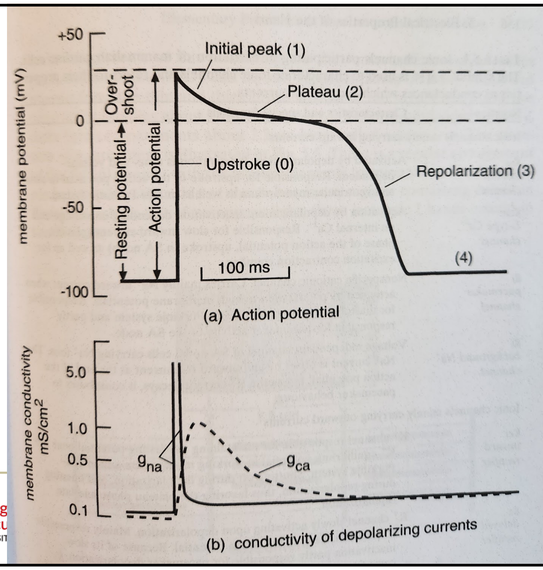

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TABLE 2.6. Statistical data for total body impedance (Z_T) adopted by the IEC for 50-Hz currents.

Touch voltage (V)	Total body impedance (Ω) at the indicated percentile rank 5%	50%	95%
25	1,750	3,250	6,100
50	1,450	2,625	4,375
75	1,250	2,200	3,500
100	1,200	1,875	3,200
125	1,125	1,625	2,875
220	1,000	1,350	2,125
700	750	1,100	1,550
1,000	700	1,050	1,500
Asymptotic value	650	750	850

Large area contacts, hand-to-hand, dry skin.
Source: Data from IEC (1984).

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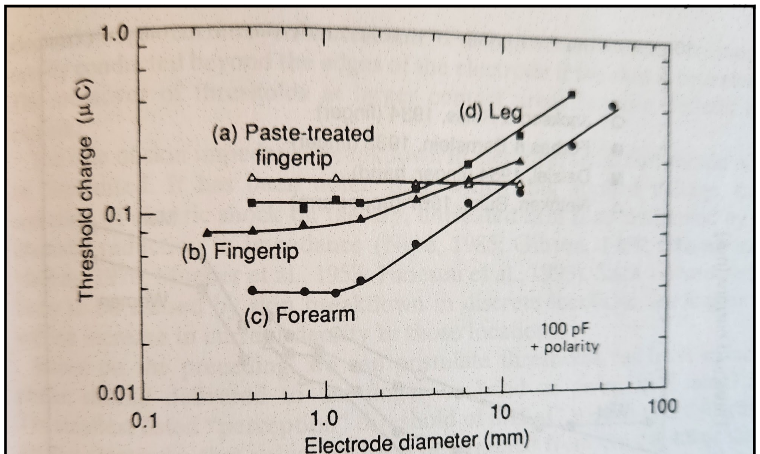

FIGURE 7.14. Effect of electrode contact size on perception of discharge from 100-pF capacitor. Curve (*a*) applies to paste-treated skin; the others apply to dry skin. (From Reilly and Larkin, 1985a.)

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TABLE 2.10. Resistivity of several materials—uniform composition.

Surface		Resistivity (Ωm)
Generic soil types		
Wet, loamy soil		10
Moist soil		100
Dry soil		1,000
Bed rock		10,000
Specific surface types		
Concrete,	moist	30–60
	air dry	910
Gravel,	dry	10^6
	wetted w/ground water	8,500
	wetted w/salt water	24

Source: IEEE (1986); Hammond & Robson (1955).

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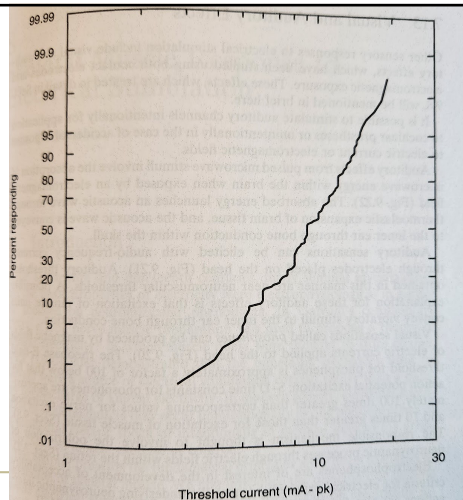

FIGURE 7.25. Cumulative frequency distribution for reaction threshold of 120 dairy cows for single-cycle, 60-Hz transient current. Threshold current refers to the peak of the stimulus waveform where an animal responded.

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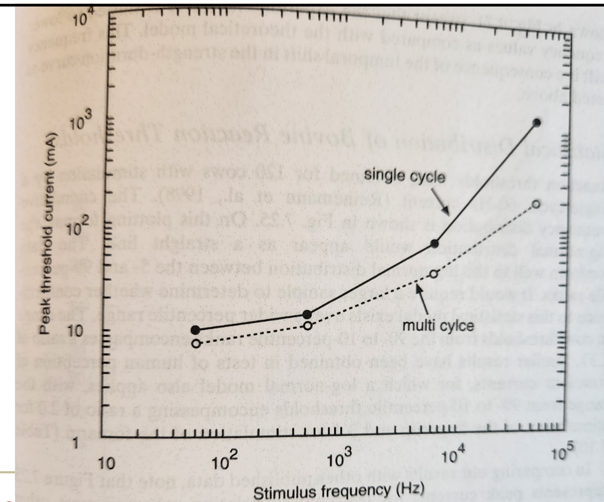

FIGURE 7.24. Strength-frequency data for reaction thresholds of dairy cows. Curves apply to single or multiple cycle sinusoidal currents. (From Reinemann et al., 1996.)

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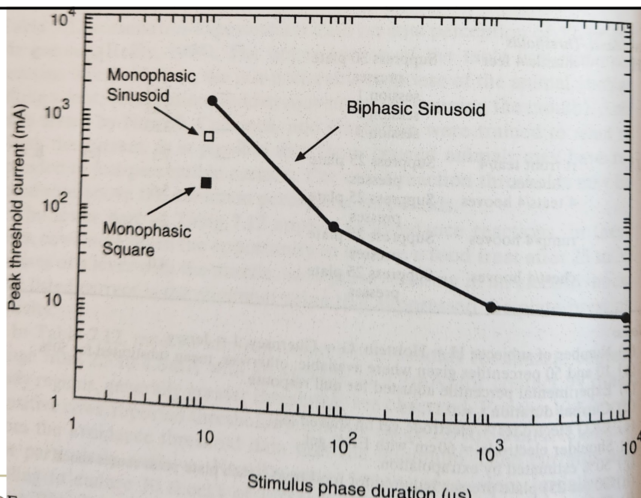

FIGURE 7.23. Strength-duration data for reaction thresholds of dairy cows. Curve applies to single sinusoidal cycle; points apply to monophasic stimuli. (From Reinemann et al., 1996)

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TABLE 2.17. Cow foot contact impedance.

Soil condition	Soil resistivity (Ωm)	*R* contact: One foot (Ω)	*R* contact: Two feet parallel (Ω)
Wet	10	40	22
Moist	100	400	220
Dry	1,000	4,000	2,200

Assumptions: Contact area each foot = 120 cm^2; distance between right and left feet = 0.4 m; distance between from and hind feet = 1.0 m.

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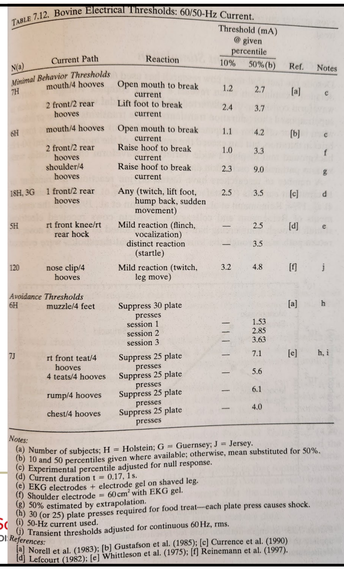

TABLE 7.12. Bovine Electrical Thresholds: 60/50-Hz Current.

N(a)	Current Path	Reaction	Threshold (mA) @ given percentile 10%	50%(b)	Ref.	Notes
Minimal Behavior Thresholds						
7H	mouth/4 hooves	Open mouth to break current	1.2	2.7	[a]	c
	2 front/2 rear hooves	Lift foot to break current	2.4	3.7		
6H	mouth/4 hooves	Open mouth to break current	1.1	4.2	[b]	c
	2 front/2 rear hooves	Raise hoof to break current	1.0	3.3		f
	shoulder/4 hooves	Raise hoof to break current	2.3	9.0		g
18H, 3G	1 front/2 rear hooves	Any (twitch, lift foot, hump back, sudden movement)	2.5	3.5	[c]	d
5H	rt front knee/rt rear hock	Mild reaction (flinch, vocalization)	—	2.5	[d]	e
		distinct reaction (startle)	—	3.5		
120	nose clip/4 hooves	Mild reaction (twitch, leg move)	3.2	4.8	[f]	j
Avoidance Thresholds						
6H	muzzle/4 feet	Suppress 30 plate presses			[a]	h
		session 1	—	1.53		
		session 2	—	2.85		
		session 3	—	3.63		
7J	rt front teat/4 hooves	Suppress 25 plate presses	—	7.1	[e]	h, i
	4 teats/4 hooves	Suppress 25 plate presses	—	5.6		
	rump/4 hooves	Suppress 25 plate presses	—	6.1		
	chest/4 hooves	Suppress 25 plate presses	—	4.0		

Notes:
(a) Number of subjects; H = Holstein; G = Guernsey; J = Jersey.
(b) 10 and 50 percentiles given where available; otherwise, mean substituted for 50%.
(c) Experimental percentile adjusted for null response.
(d) Current duration t = 0.17, 1 s.
(e) EKG electrodes + electrode gel on shaved leg.
(f) Shoulder electrode = 60 cm² with EKG gel.
(g) 50% estimated by extrapolation.
(h) 30 (or 25) plate presses required for food treat—each plate press causes shock.
(i) 50-Hz current used.
(j) Transient thresholds adjusted for continuous 60 Hz, rms.

References:
[a] Norell et al. (1983); [b] Gustafson et al. (1985); [c] Currence et al. (1990)
[d] Lefcourt (1982); [e] Whittleson et al. (1975); [f] Reinemann et al. (1997).

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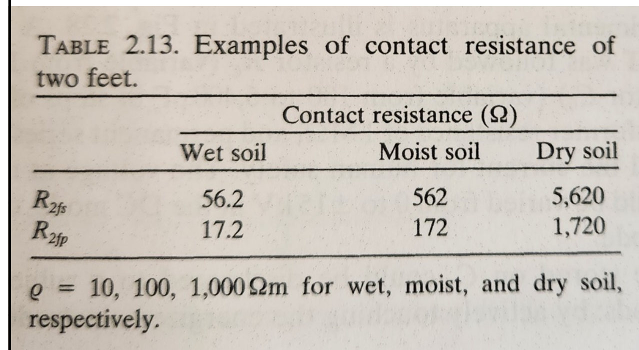

TABLE 2.13. Examples of contact resistance of two feet.

	Contact resistance (Ω) Wet soil	Moist soil	Dry soil
R_{2fs}	56.2	562	5,620
R_{2fp}	17.2	172	1,720

ϱ = 10, 100, 1,000 Ωm for wet, moist, and dry soil, respectively.

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