HUMAN RESPONSES TO ELECTRICITY: A LITERATURE REVIEW

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INTRODUCTION

This manuscript was prepared for the National Aeronautics and Space Administration to aid the Office of Medical Research and Operations in establishing standards for current limiting devices for biomedical sensors, such that the safety and comfort of the wearers will be insured while signal quality is not unduly compromised.

Specific information was requested in four major areas:

1. What are the human threshold levels for sensation, pain, muscular contraction and ventricular fibrillation when exposed to direct current and 60 Hz and 400 Hz alternating currents?

2. What variations might be expected in the above thresholds with different electrode placements?

3. What are the above thresholds when a current is passed from the head and/or hands through an electrode positioned on the chest?

4. What is the effect on the thresholds of such variables as electrode size, skin temperature, heart phase and other physiologic states?

The information contained in this manuscript represents an effort to answer these questions based on an extensive literature review of appropriate research reports over many years duration. In addition, a section is devoted to examining in some detail the passive electrical properties of cells and tissues. It is felt

that such information may prove useful in future, more advanced designs of biomedical instrumentation systems.

Special acknowledgement is in order for the assistance of several persons. The suggestions from Dr. H. V. Ellingson of The Ohio State University, Department of Preventive Medicine, and from Doctors J. F. Tomashefski and J. F. Foster of the Battelle Memorial Institute as to which information should be included and their suggestions as to the format and preparation of the final manuscript were invaluable.

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PHYSIOLOGICAL AND PATHOLOGICAL RESPONSES OF THE HUMAN WHEN EXPOSED TO ELECTRICITY

The Threshold for the Perception of Electricity

When one considers the application of electricity to the surface of the body - be this through a "true" electrode positioned to detect a biopotential but which offers a path for extrinsic electrical energy to reach the body, or be it an "electrode" of a bare wire touching the skin - it is apparent that the initial perception of current flow will arise from stimulation of cutaneous receptors immediately under the electrodes, since this is the region of greatest current density[31]. Thus the first physiological response to electric current can be measured as the threshold of perception, or as worded slightly differently by Conrad, et al., minimal response occurs in human tissue when the potential across the tissue reaches a certain threshold value[10].

Dalziel and Mansfield have determined the threshold of perception of the hand[20]. Studies were accomplished on 115 males whose hands were moistened with a saturated salt solution. The subjects either grasped or simply touched a copper wire through which the current was provided and the investigators noted that testing by these two different methods compared well. Using a direct current, the mean threshold for perception was 5.2 mA, with a median of 5.0 mA and a range from 2.1 mA to 12.6 mA. With alternating current at 60 Hz, the threshold mean was 1.072 mA, with a median of 1.05 mA and a range from 0.44 mA to 1.92 mA. In attempting to correlate the currents required for perception with different physical characteristics, inconclusive results were found when the subjects were

grouped according to build or complexion. However, a suggestion was noted that an age differential exists, with older subjects requiring slightly more current to perceive the stimulus.

Based on the above and related studies, Dalziel and Mansfield made the following observations[20]. The predominant sensation produced by gradually increasing direct current is warmth in the palm of the hand or wrist. With alternating current, the sensation at less than 10K Hz is tingling at the area adjacent to the contact point except at very low frequencies, when the muscles tend to follow alternations of the current wave. From 10K to 100K Hz the sensations produced are similar to those at the lower frequencies but less intense and perceived over a larger area around the contact point. From 100K to 200K Hz, the sensation becomes one only of heating and this probably applies to frequencies greater than 200K Hz. Further, it was observed that the current required for perception increases with increasing frequency and between about 1K and 100K Hz, the current is nearly proportional to the frequency. In later discussing this same problem, Dalziel made several additional obersvations[15]. Except at point contracts, the current required to produce a sensation increases with the area in contact with normal skin; however, this area effect is fairly small. Secondly, the crest of the wave form - not the effective or average value of the AC wave - is responsible for the sensation. Thirdly, the threshold for women is approximately two-thirds that for men.

A study somewhat similar to that of Dalziel and Mansfield's was performed by Carter and Coulter[7]. In this study, the "fleshy" parts of the thumb and index finger were each placed on one square centimeter brass electrodes. Sixty males and 47 females were tested. Results obtained from subjects with calloused or

scarred fingers or from subjects who had "wet" or "sweaty" hands were excluded. Table 1 gives the results for direct current thresholds as well as the skin resistance at these thresholds.

Table 1: Threshold for Perception of Direct Current-59 Subjects*

Ages	#ss	Mean Threshold mA/cm^2	Mean Resistance Kohms
17-24	13	.252	72.720
25-35	21	.304	116.660
36-45	11	.360	111.360
46-55	8	.346	105.710
56-65	4	.331	92.500
66-75	2	.157	110.000
Average 59 yrs.		.291	101.000

*From Carter and Coulter[7]

Table 2 gives similar data by the same investigators for alternating current at several different frequencies.

Table 2: Threshold for Perception of Alternating Current-mA/cm^2*

Age	100 Hz	500 Hz	1000 Hz	2000 Hz	6000 Hz	15000 Hz	35000 Hz	48000 Hz
17-24	.204	.290	.373	.542	1.380	3.300	7.80	12.00
25-35	.184	.284	.401	.658	1.388	2.907	6.63	11.35
36-45	.226	.338	.469	.679	1.539	3.205	8.33	12.43
46-55	.237	.404	.563	.828	1.934	3.800	9.01	13.89
56-65	.260	.375	.550	.884	1.800	3.590	11.0	15.90
66-75	.387	.550	.750	1.2	2.37	5.0	15.0	21.25

*From Carter and Coulter[7]

Carter and Coulter continued their studies and investigated the effects of variation in electrode size on perception thresholds[7]. In these studies electrodes were placed on the medial and lateral aspects of the distal upper arm with the skin having previously been moistened with normal saline. Table 3 gives the results as noted with direct currents on 15 subjects aged 20-50 years and Table 4 gives the results from studies with alternating current.

Table 3: Effect of Electrode Size on Perception of Direct Current*

Electrode Diameter	Area-In^2	Area-Cm^2	Avg. Threshold mA	Avg. Threshold per Cm^2-mA	Resistance Kohms
5/8"	.31	2.0	.261	1.30	47.5
1.0"	0.79	5.1	.475	0.94	28.2
2 1/4"	3.9	25.2	.801	0.032	14.0

*From Carter and Coulter[7]

Table 4: Effect of Electrode Size on Perception of Alternating Current*

Electrode Diameter	200 Hz	500 Hz	1000 Hz	2000 Hz	6000 Hz	10000 Hz	15000 Hz	35000 Hz	48000 Hz
5/8"	.26	.43	.67	.98	1.81	2.58	3.65	8.50	11.05
1.0"	.44	.69	1.08	1.42	2.82	1.1	5.27	13.2	17.8
2 1/4"	.87	1.39	2.04	2.92	5.01	7.98	11.65	26.30	34.30

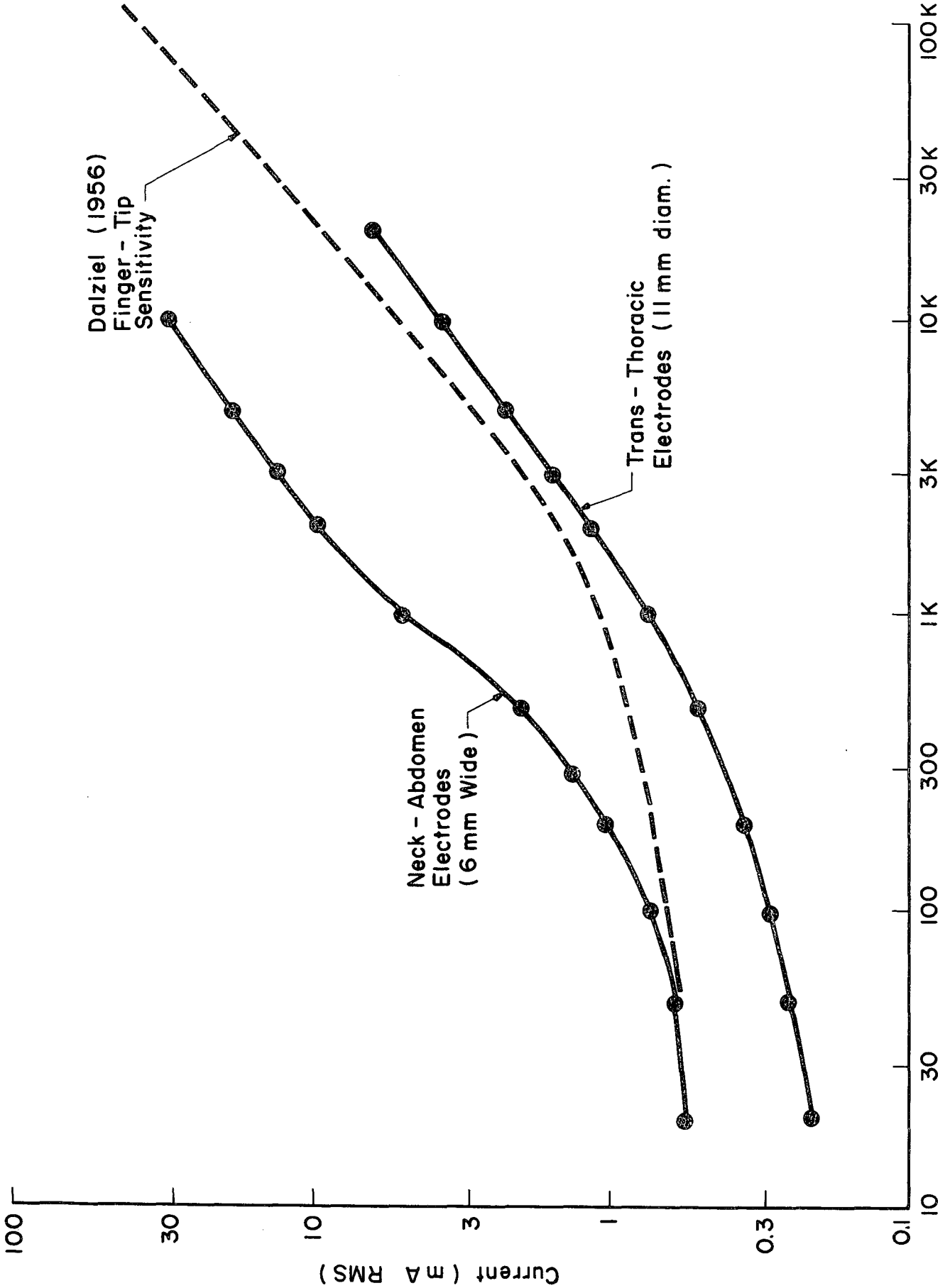
*From Carter and Coulter[7]

These investigators concluded that for alternating current, as the frequencies increase, the threshold increases, provided that the electrode location, size and same degree of electrode pressure on the skin exist.

Geddes, et al., recently performed a study to evaluate the threshold of sensation for eight human subjects using sinusoidal currents over a frequency range of 10 to 3,000 Hz[31]. Two electrode configurations were used: the first consisted of a pair of trans-thoracic electrodes, similar to the arrangement commonly used for impedance pneumography. The second configuration was a neck-abdomen arrangement. Their results are shown in Figure 1. With either electrode configuration low frequency currents (in the 20 to 50 Hz range) of less than 1 mA are perceptible. This figure is in agreement with the data of Dalziel, Thompson and Wood[20,31,65]. Again, as in studies previously mentioned in this paper, it was demonstrated that as the frequency is increased, more current is required for perception, and that above 100 Hz the current for sensation rises sharply with increasing frequency.

A study was performed by Green to determine the threshold for sensation for electric shock under 12 conditions[34]. The independent variables were as follows: three "types" of electrical flow - constant current, constant voltage, constant power; three electrode sizes - 0.075", 0.15", 0.3" diameter. Nine separate conditions were thus examined in this manner. The additional three conditions were added by using electrode jelly in combination with the 0.15" diameter electrodes. The results of this study are shown graphically in Figure 2. All tests were made using a rectangular DC stimulus of one second duration to the ball of the thumb and the index finger of the left hand. The investigator made the observation that the threshold for dry electrodes in terms of power, was approximately 50 mW regardless of the area of contact[33]. It was also noted that the current threshold increased as the electrode size increased while the voltage threshold fell as the electrode size increased. In addition, he observed that the threshold did not increase as the skin temperature was lowered[34].

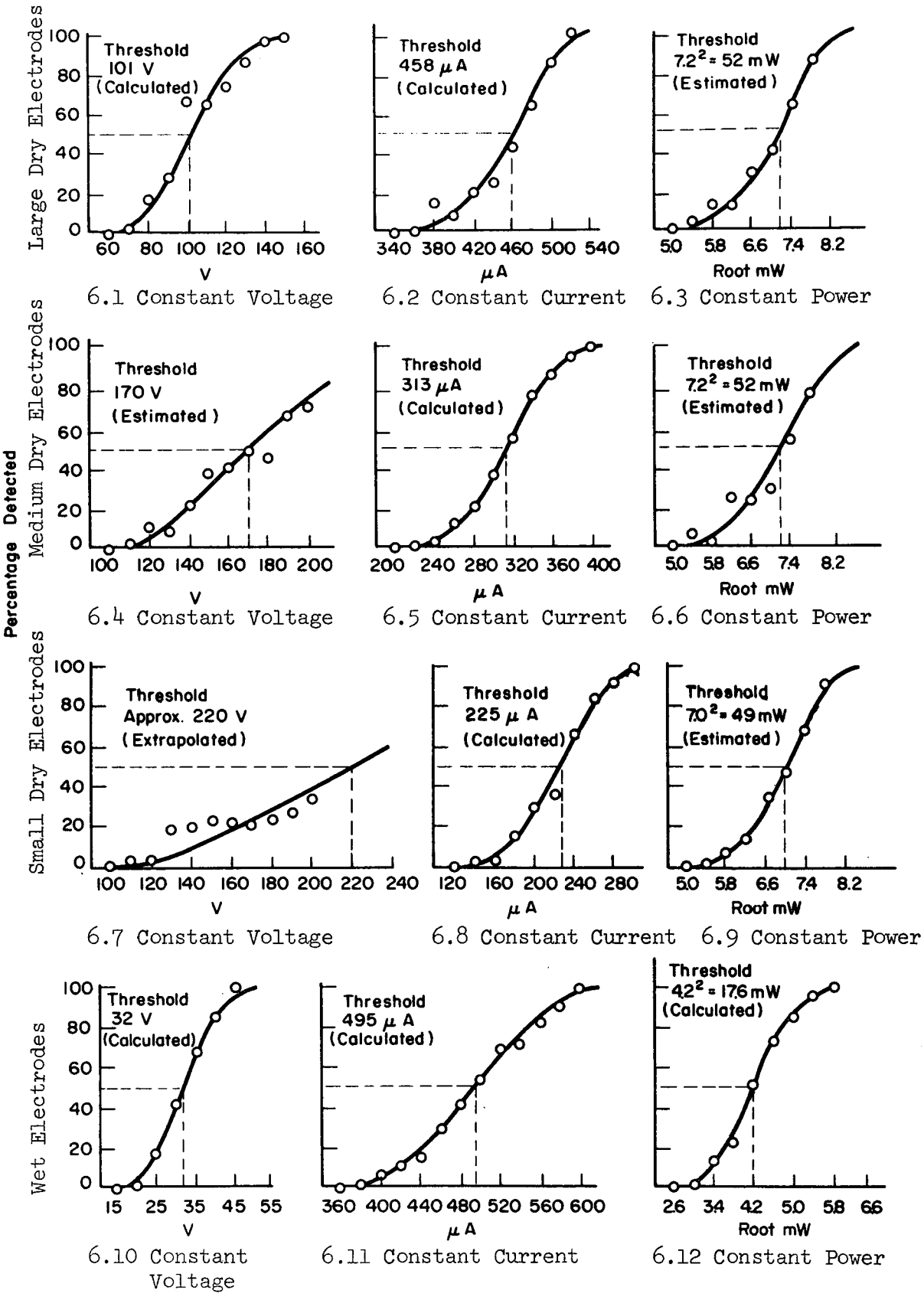
Figure 1*



Sensation Threshold *

*From Geddes et al 31

Figure 2*



*Redrawn from Green[34]

Six subjects with the first and second fingers of one hand immersed in saline solution were studied by Conrad, et al.[11]. A rectangular wave form was applied and simultaneous measurements of voltage, current and skin resistance were made. They noted that a steady state resistance was not reached until 15 to 40 minutes after the fingers were immersed, at which point the average skin resistance for the six subjects was 7.1 Kohms. The simultaneous voltage measurements demonstrated considerable capacitance effect in the skin. The investigators summated their findings graphically (Figure 3), relating the time-intensity values for current impulses required to produce minimal responses in human fingers.

Brown, et al., examined the varying temporal parameters involved in the threshold of stimulation on hairy areas of the body using DC pulses of 1, 4 and 8 pulses per train[5]. Using 0.5 msec and 1.0 msec trains, it was noted that both as the number of pulses per train increased, and at the longer train duration, the threshold for sensation decreased slightly. (See Figure 4.) In addition, they noted that with progressive experimental sessions, the subjects' threshold for sensation increased. (Figure 5.)

Gibson measured touch thresholds in two experiments as a function of (1) the number of brief electric pulses, from 1 to 20 and (2) the rate of pulse repetition, 10-25 pulses per second, on eight body regions, including hairy and hairless tissues[32]. Anodal pulses were delivered through a constant current stimulator and were 0.5 msec duration at half-peak.

Touch thresholds were found to be a decreasing hyperbolic function of the number of pulses in a stimulus train, indicating nearly linear integration of current pulses at different rates. In addition, touch thresholds were found to be nearly the same on hairy and non-hairy skin areas. In the report of the study, no report was given of the actual current flows required to produce a threshold response.

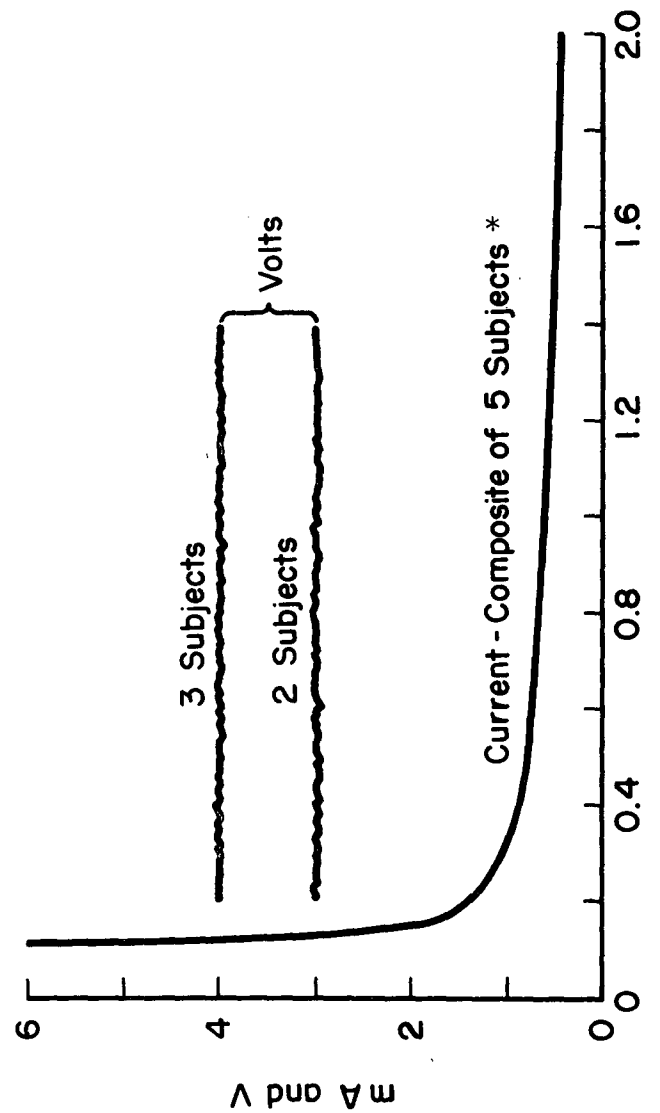


Figure 3*

*Redrawn from Conrad et al 11

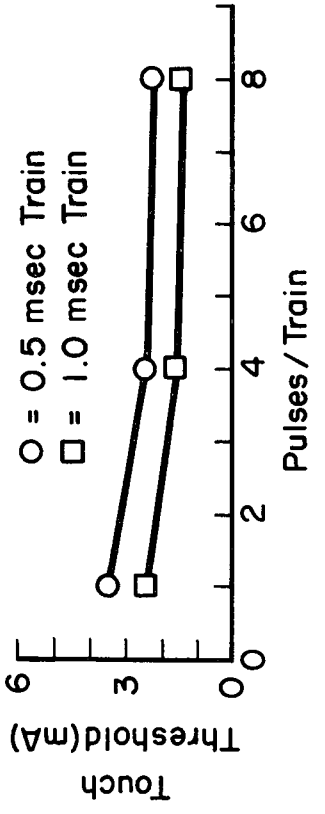
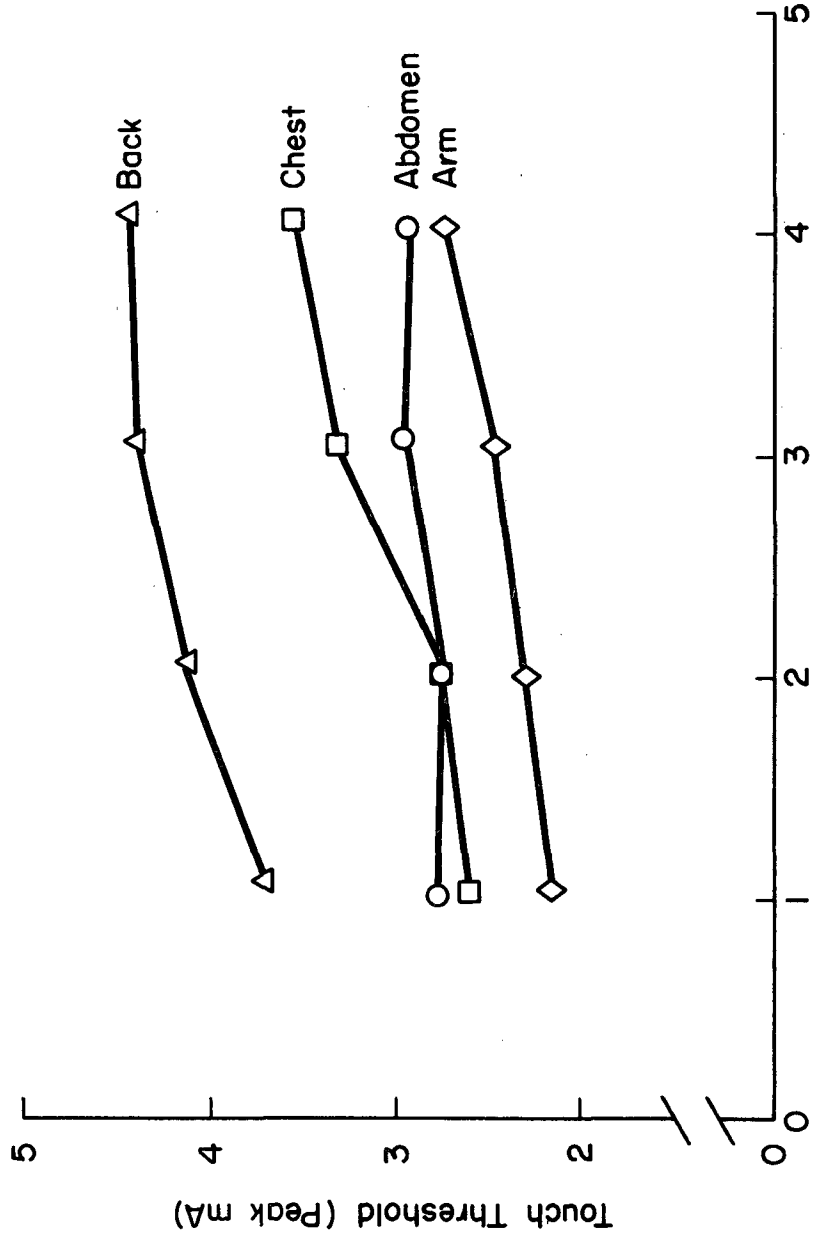


Figure 4*

*Redrawn from Brown et al[5]

Figure 5*



Touch and Pain Thresholds for Body Areas Across Experimental Sessions*

*Redrawn from Brown et al[5]

Thompson investigated the perception thresholds for 60 Hz AC of 70 adult subjects[61]. Each subject's left hand was immersed in a weak saline solution. The subject's right hand made contact with the appropriate end of the circuit in four different methods: (1) tapping a metallic surface with the tip of the forefinger, (2) pinching a metallic surface between the thumb and forefinger, (3) grasping a 1" diameter metal rod with the hand, (4) immersing the hand in salt water. The results of the study are shown in Table 5.

Table 5: Threshold Values (mA) for perception of 60 Hz AC*

Type of Contact	28 Women			42 Men			Avg. for All
	Avg.	Max.	Min.	Avg.	Max.	Min.	
Tap	0.27	0.40	0.20	0.40	0.80	0.20	0.35
Pinch	0.59	1.20	0.20	0.87	2.40	0.25	0.76
Grip	0.84	1.40	0.50	1.19	3.00	0.28	1.05
Immersion	0.88	1.80	0.80	1.39	3.00	0.44	1.19

*From Thompson[61]

These findings are compatible with Dalziel's observation previously referred to: that with increased contact area, the current required to produce sensation increases.

The Threshold for Pain Produced by Electric Current

Pain is a subjective matter, "known to us by experience and described by illustration."[52] No objective criteria exist for measuring the actual experience of pain. Hall has said, "Pain may be studied as a sensation in one experiment, as a perception and as involving attitudes in another and as related to emotional behavior in a third."[52] Thus, although the pain threshold of a given individual in response to a given stimulus may be rather constant, it does not hold that this same stimulus may produce a similar response in another person. It must therefore

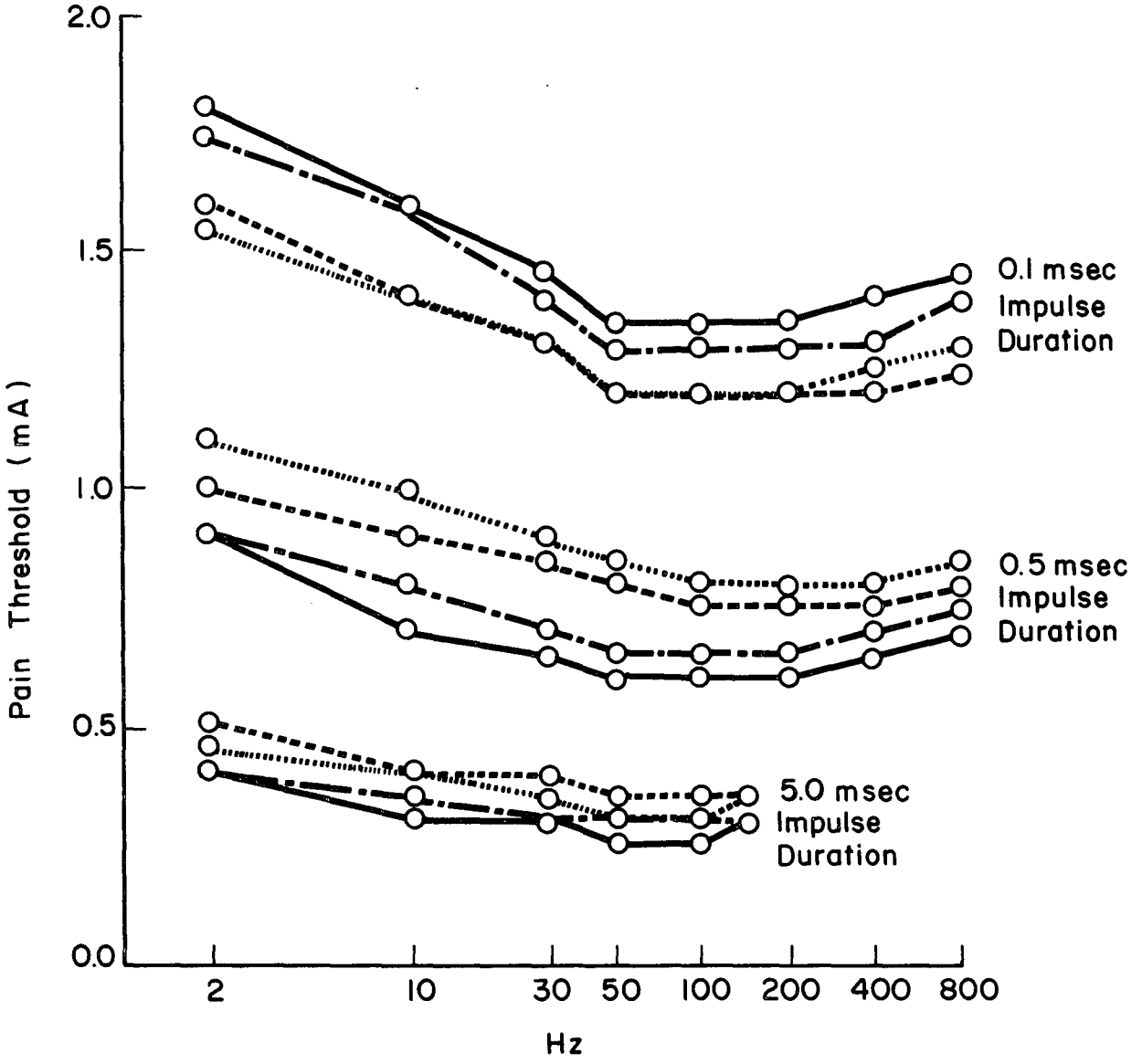
be recognized that for any true evaluation of a pain threshold, any individual must be his own control. Further, any study measuring pain thresholds must be considered with the subjective nature of "pain" in mind.

It is thus apparent that no ideal "pain threshold" level can be determined which is generally applicable. Rather it is necessary to postulate a range of stimuli which may be expected to produce pain under a given set of circumstances. A number of the following mentioned studies, while performed quite well in and of themselves, give some idea as to the problem of variability in this area.

Using a 2 mm diameter stainless steel stimulating electrode and a conduction medium of electrode paste, Notermans performed a rather extensive study measuring pain thresholds[52]. The subjects were instructed to report as soon as they experienced a painful sensation. Figure 6 demonstrates the pain thresholds for different frequencies and different impulse durations. It was observed that when frequencies less that 10 Hz were used, the sensations were first described by all subjects as tapping or pulsating rather than painful. As the stimulating current was increased, the sensations became more painful and were described as unpleasant, but not perceived as a "pricking" sensation. Between approximately 30-200 Hz a fairly reliable threshold measurement associated with a "pin-prick" sensation was not felt. Figure 6 also demonstrates that as the duration of the current is increased, the threshold for pain sensation falls at all frequencies.

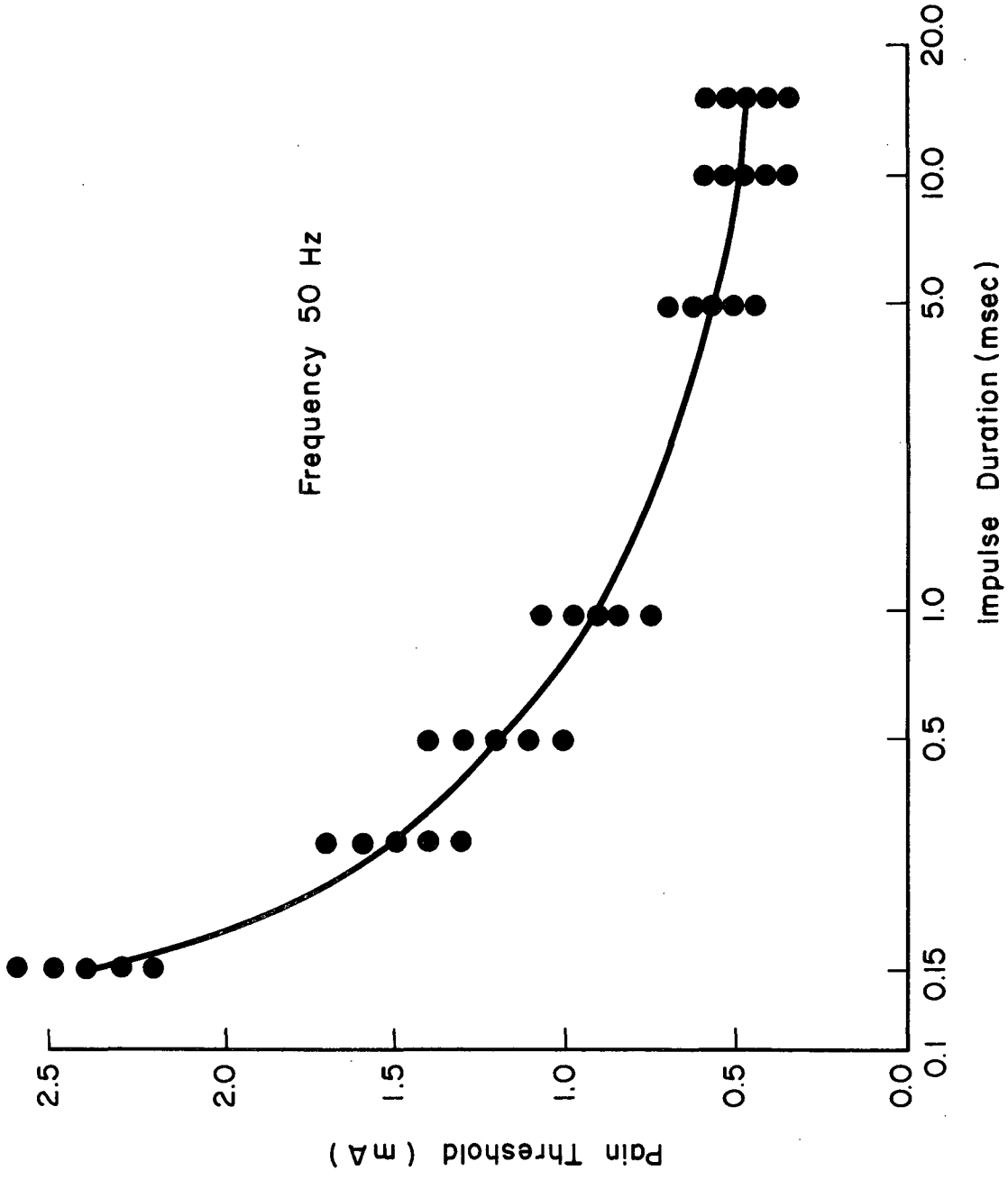
A study was then performed to evaluate further the effect of impulse duration upon pain threshold. This study was carried out using a constant frequency (50 Hz) where it has previously been determined that a rather constant "pin-prick" sensation of pain could be measured. The results of the investigation are shown in Figure 7. It was observed that with impulse durations of 0.1 msec

Figure 6*



*Redrawn from Notermans[52]

Figure 7*



*Redrawn from Noterman's[52]

or less, the subjects perceived "vibratory" sensations but could not exactly describe a constant "pain" sensation. Figure 7 demonstrates that thresholds established with an impulse duration of 5 msec give nearly the same values as those measured with impulses of longer durations.

Using a frequency of 50 Hz and an impulse duration of 5 msec, both derived from preceding phases of the study, the effect of the number of pulses within the 5 msec impulse period upon the pain threshold was measured. These results are shown in Figure 8. At less than 10 pulses per 5 msec, no reliable constant pain thresholds could be measured. However, above 20 pulses, the threshold value did not alter significantly.

To estimate the reliability of pain thresholds, 12 individuals were studied, using a fixed electrode and a gradual increase of the stimulating current. Every measurement was repeated 40 times with a minimal interval of 20 seconds. The results are shown in Table 6. The same procedure using 20 pulses per impulse gave nearly similar results.

Continuing his study, Notermans measured pain thresholds in 64 subjects over multiple body sites. On every dermatome, the threshold was measured at three different places at distances of 2 cm from one another. These results are shown in Figure 9. It was noted that the pain threshold is nearly uniform over the entire body, with most individuals showing the lowest values in the face and neck. Further, it was observed that the measured pain threshold values varied from one person to another over a range of nearly $\pm$ 50% from the mean value. The pain threshold was always lower than 1 mA, and it appeared that the mean pain threshold was about 0.5 mA. Variations in the pain threshold between corresponding places on the left and right sides of the body of the same individual were never more than 0.1 mA with a mean threshold of 0.55 mA.

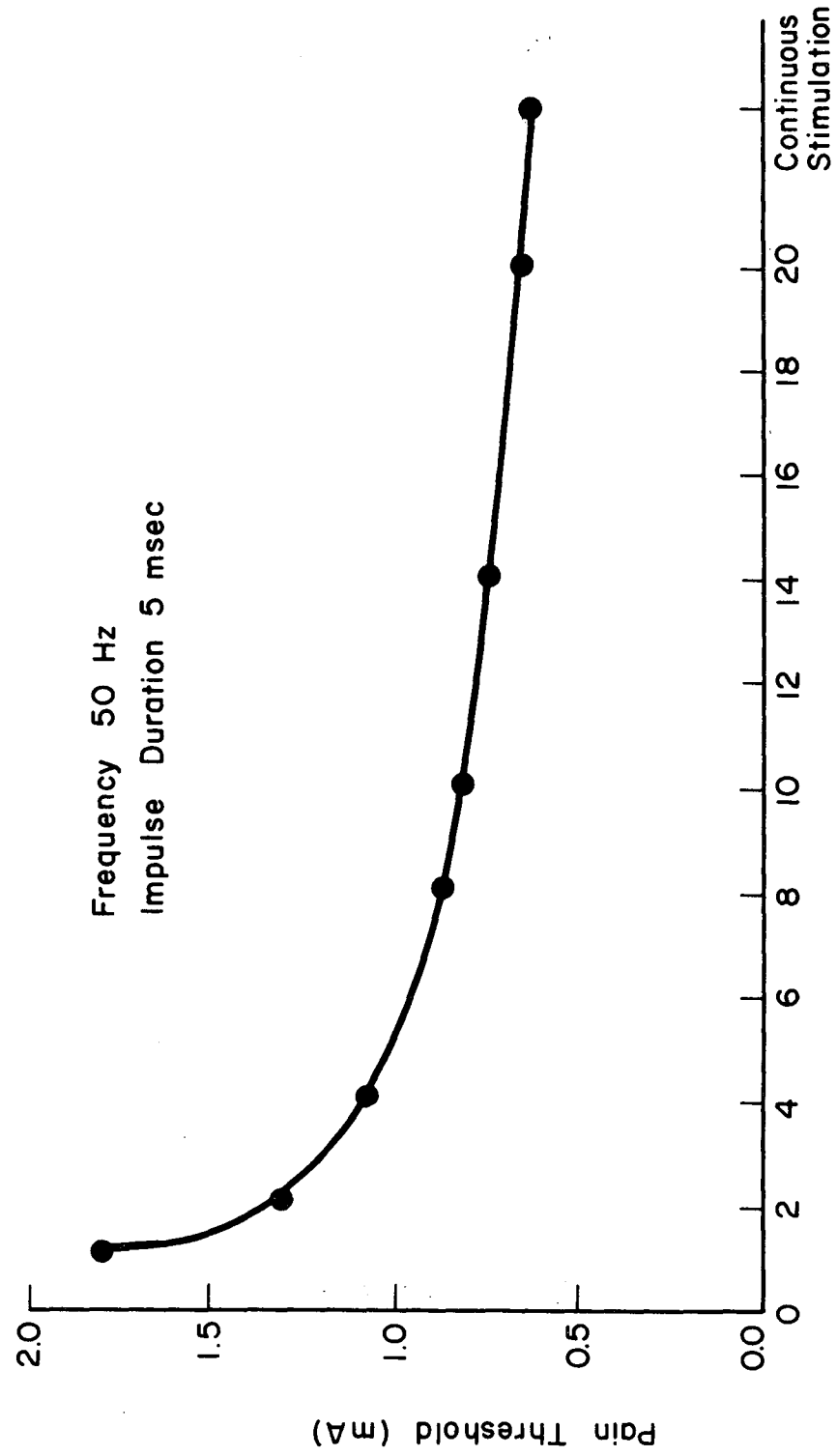
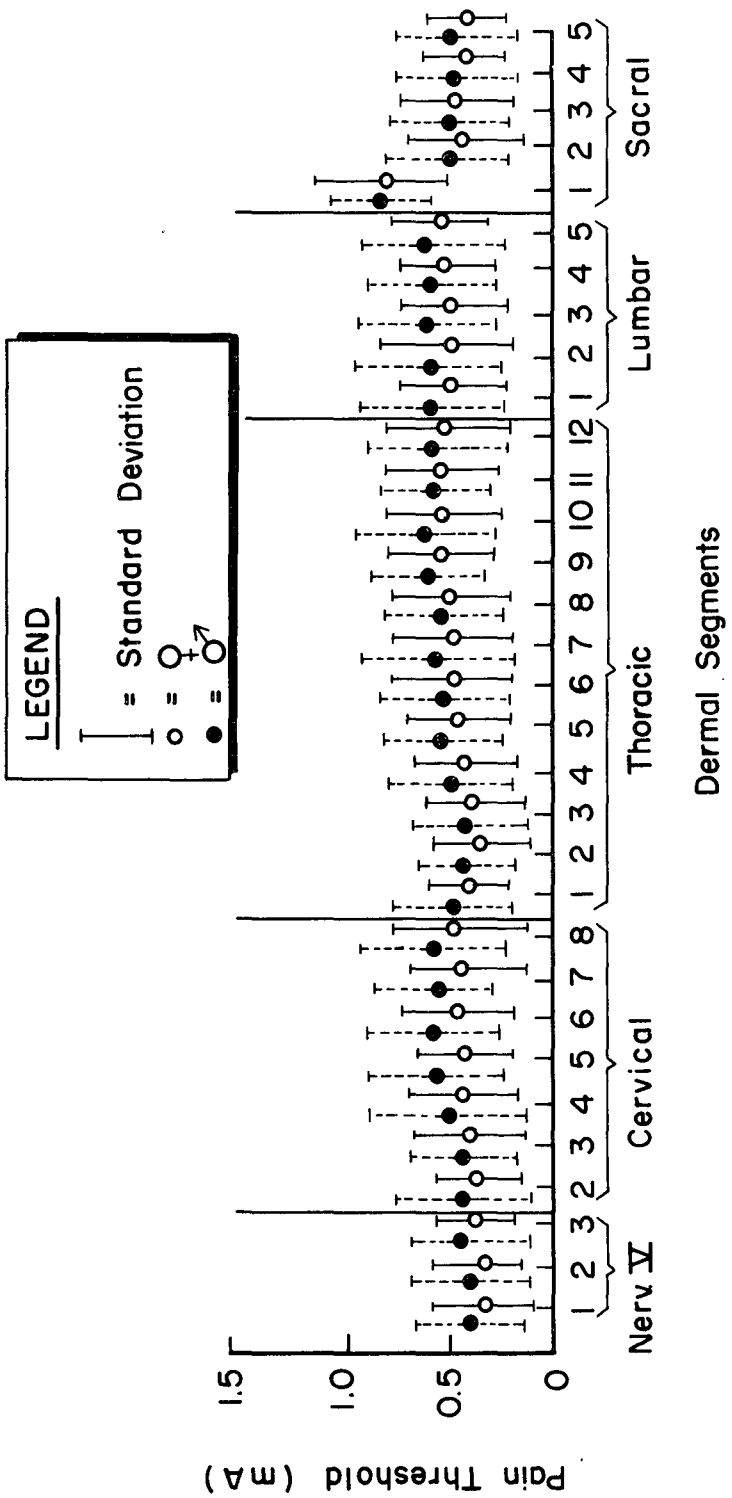


Figure 8*

*Redrawn from Notermans[52]

Figure 9*



*Redrawn from Noterman's[52]

Table 6: Variation in Pain Thresholds on the Dorsal Surface of the Middle Finger of 12 Subjects*

Subject (age in years)	Mean pain threshold value in mA	Highest and lowest threshold measured in mA	Number of pulses	Range in mA
Male				
32 years	0.43	0.40-0.45	40	0.05
34 years	0.39	0.35-0.40	40	0.05
30 years	0.50	0.48-0.54	40	0.06
35 years	0.45	0.42-0.50	40	0.08
37 years	0.40	0.38-0.43	40	0.05
27 years	0.50	0.48-0.55	40	0.07
Female				
20 years	0.42	0.39-0.45	40	0.06
21 years	0.60	0.50-0.65	40	0.15
22 years	0.65	0.60-0.70	40	0.10
27 years	0.42	0.40-0.45	40	0.05
27 years	0.48	0.45-0.52	40	0.07
22 years	0.55	0.50-0.58	40	0.08

*From Notermans[52]

Ten individuals were studied to determine the possibility of alterations in pain thresholds during a day; significant diurnal variation was not found. These same individuals were evaluated daily over the course of four months and again it was concluded that in the course of time, little variation in pain thresholds occurs in the same individual.

Pain thresholds were measured on ten control individuals with and without distraction and/or pain sensation elsewhere. When the individual was distracted by being required to inflate a blood pressure cuff placed around a bar to 300 mm Hg, consistently higher thresholds were measured. When the cuff was placed around the subject's own arm and inflated by an assistant to 300 mm Hg (thus inducing pain remote from the site of electrical stimulus) a 40-50% increase was seen in the pain threshold.

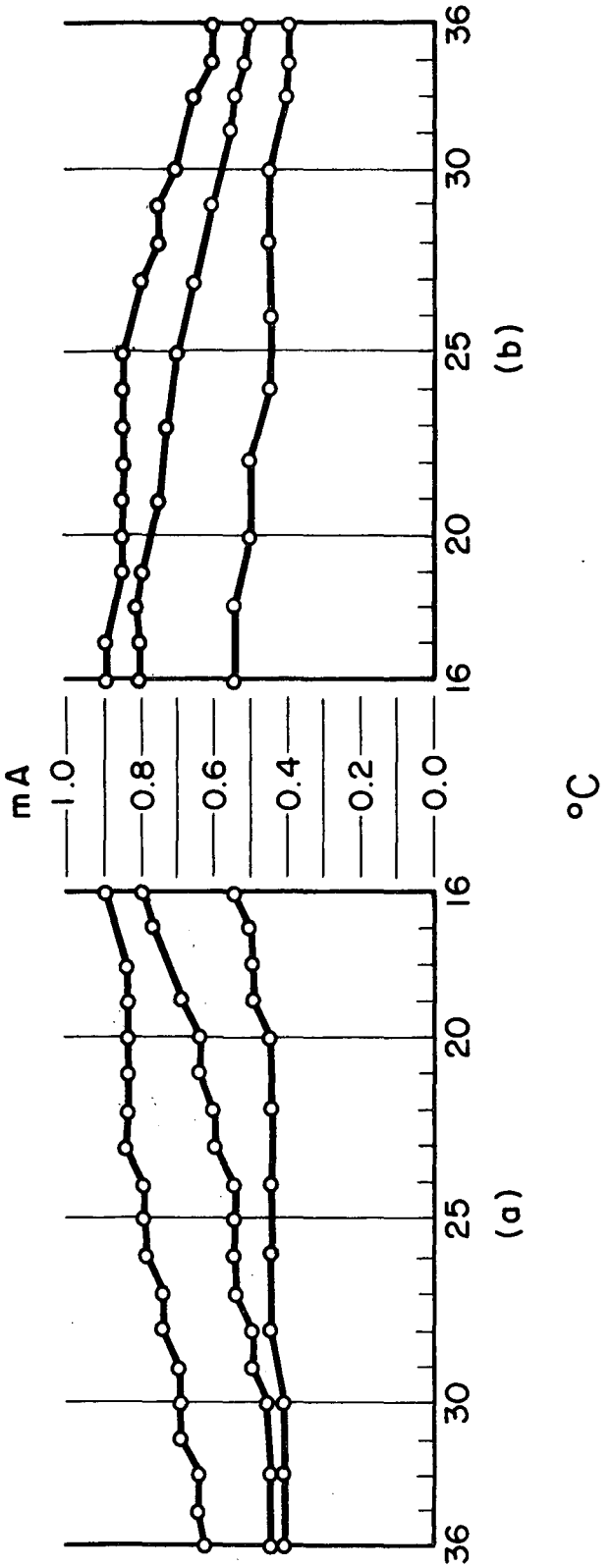
Notermans performed additional studies to determine the effect of skin temperature on pain thresholds, as measured on the distal phalanx of the middle finger. These results are shown in Figure 10 and indicate that the influence of skin temperature on the pain threshold is minimal. Only with a drop of 10°C did the threshold increase by about 30% of the original value and at 16°C the increase was about 50%.

In comparing his findings with those of other investigators, Notermans makes several observations. First, he points out that while many investigators agree with his negative findings as to diurnal variation, that others have suggested that the pain threshold may be higher in the evening than in the morning. Secondly, he notes that many studies have suggested that the pain threshold for women is lower than that for men, while his study did not demonstrate this finding.

Nonetheless, a later study by Notermans and Tophoff was performed to investigate the sex difference in pain threshold[53]. Although males were found to have a greater pain tolerance threshold than females (i.e., they could tolerate a painful stimulus longer, Figure 11) no sex difference was found in the threshold of pain perception. (Figure 12.)

An example of findings on sex difference is demonstrated by the study of Plutchik and Bender[54]. Twenty college students were tested, with electrodes of 1 cm diameter placed on the digital pads of the first and fourth fingers of the right hand. No electrode paste was used. The subjects were subjected to stimulations by 5 second impulse trains of 1, 3, 6, 10, and 15 pulses per second with each pulse lasting 50 msec. The results of the study are shown in Figure 13. The different responses of males as opposed to females are clearly shown. Further,

Figure 10*



Pain Threshold in Relation to Skin Temperature in 3 Persons*

*Redrawn from Notermans[52]

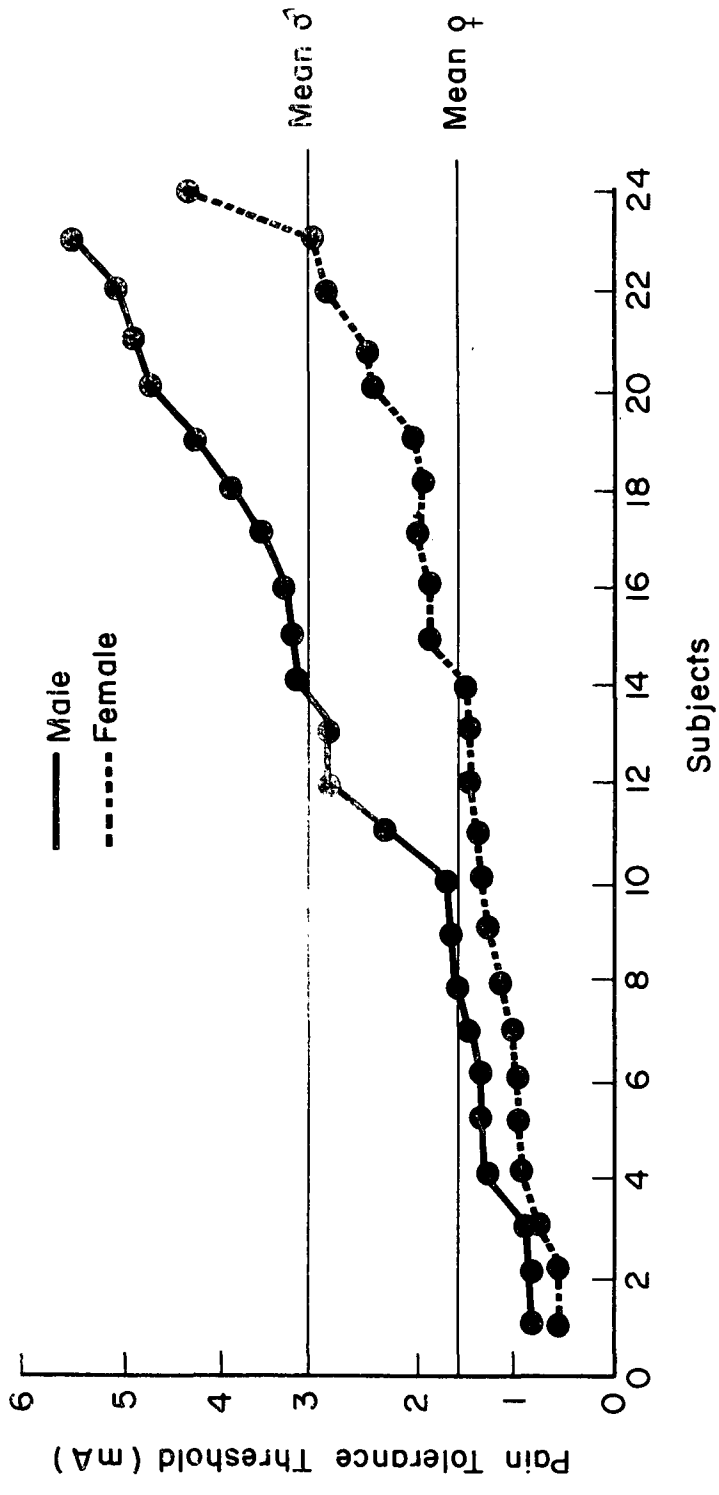
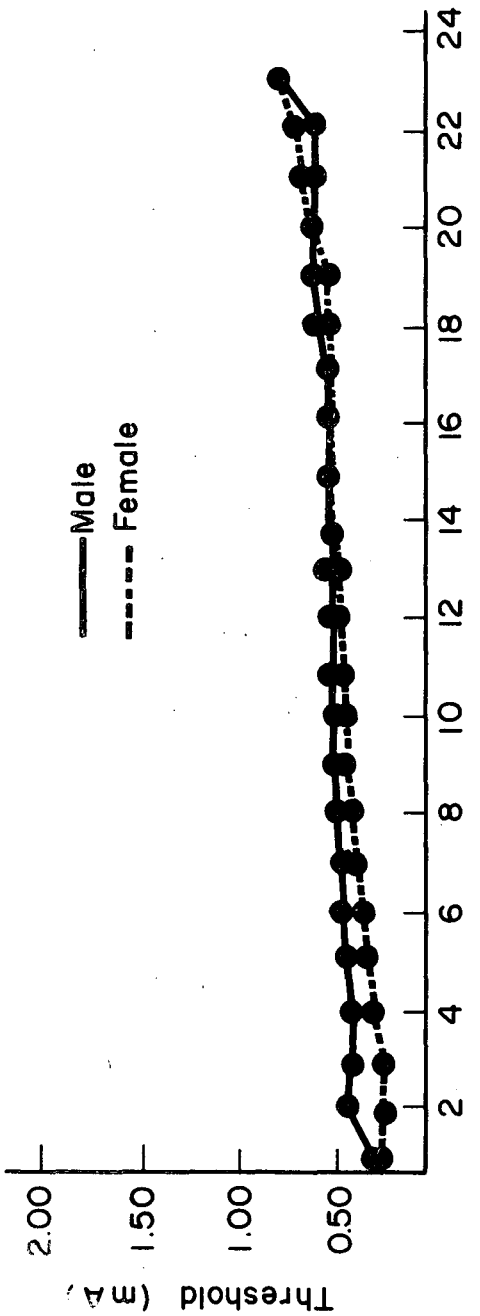


Figure 11*

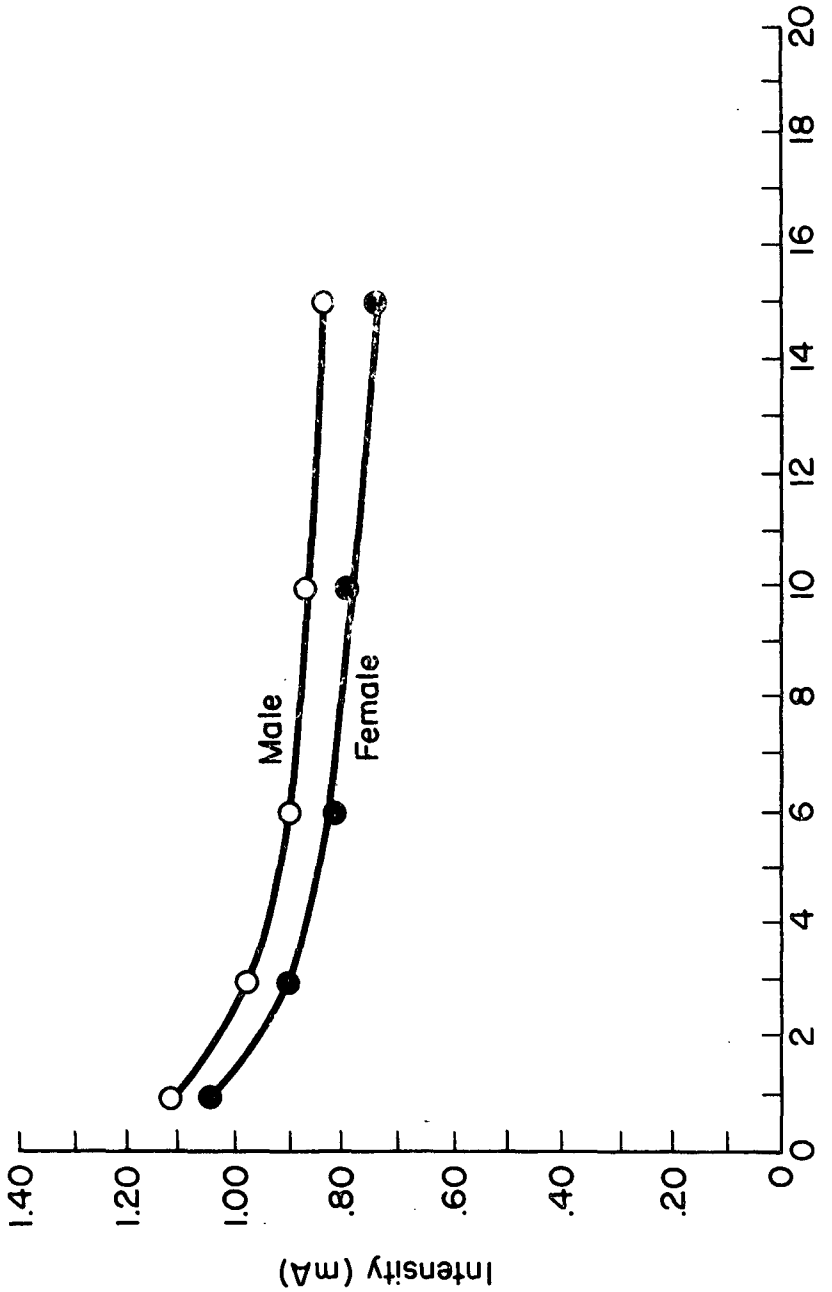
*From Noterman & Tophoff[53]

Figure 12*



*From Notermans & Tophoff[53]

Figure 13*



Mean Pain Thresholds for 10 Male and 10 Female Subjects As A Function of Pulse Rate*

*From Plutchik and Bender[54]

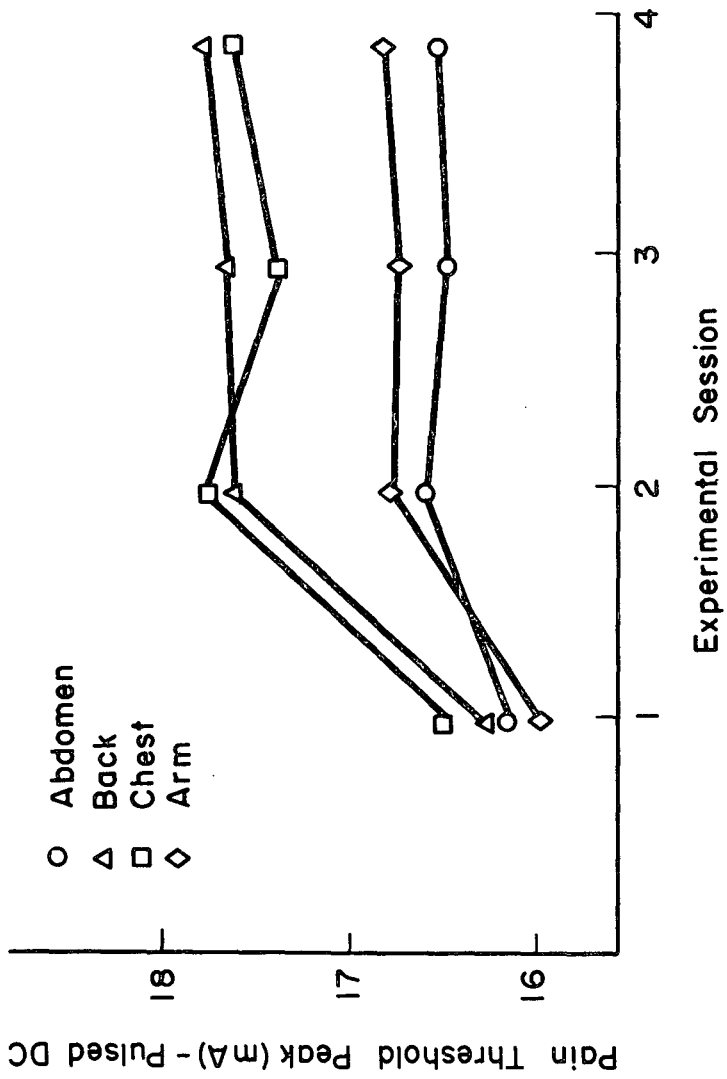
it is shown that as the amount of energy reaching the skin is increased (i.e., more pulses) the threshold falls, suggesting an integrated response of the skin to the stimulus.

This agrees with the findings of Gibson who reports that the pain threshold is a decreasing hyperbolic function of the number of pulses in a stimulus train, and that, in general, the threshold for hairy tissue is higher than that for hairless[32]. Gibson also points out that with repeated testing the pain threshold is raised considerably in hairy tissue, while pain threshold on hairless tissue does not show this elevation[32].

This difference in pain threshold for hairy and hairless tissue is demonstrated by the findings of Brown, et al., as shown in Figure 14, and it is also shown that across experimental sessions, the threshold increases[5]. It should be noted, however, that the actual levels of current are higher than those previously mentioned, and are, in general, considerably higher than the levels usually mentioned in the literature.

More generally accepted levels for threshold pain are those suggested by Lee based upon data from Kouwenhoven and Milnor, Dalziel, and Morse[28]. He suggests a range of three to ten mA as annoying or painful. This range is in agreement with the data of Farmer which show an average current of 8.0 mA as the painful level for 42 men being tested with 60 Hz current and is also in agreement with Hackman and Glascow, who suggest 9.0 mA as a level for moderate pain with 60 Hz current[27,35]. At the other end of this range, Davidson and McDougall found an average level of 3.37 mA when studying the responses of 65 female subjects ranging in age from 17 to 49 years[22].

Figure 14*



*Redrawn from Brown et al[5]

A study performed by Blitz, et al., suggested that the pain perception level may be affected by vibration[4]. The results of this study are shown in Table 7. It should be noted, however, that only the mean voltage at the thresholds for sensation, for pain and for the "quit point" were recorded and that data on actual current flows are not available.

Table 7: Mean Voltage at Perception, Moderate Pain, Quit Point*

	Vibrating	Non-Vibrating	P
Threshold	76.43	69.56	.001
Moderate Pain	124.89	118.89	.001
Quit	177.09	175.64	N. S.

*From Blitz, et al.[4]

An interesting study measuring the pain threshold of the teeth to electrical stimuli was done by Mumford[50]. The investigation was performed to measure the pain perception through normal young teeth. The results of the study are shown in Table 8. It was demonstrated that as the duration of the stimulus increased from 0-3 msec the threshold decreased. From 3 to 1000 msec no further decrease in the threshold was noted. Further, the subjects exhibited an "adaptation" to the painful stimulus such that the current could be increased. The average time required for this adaptation was 11.6 sec. It was also demonstrated that as the electrode area was increased (from the 9.5 mm^2 used for the baseline studies) the threshold value was also increased. In addition, with an increased frequency, the threshold also increased. These latter two findings are similar to the responses seen with electrical stimulation of the skin, as previously noted in this paper.

Table 8: Pain Perception Through Teeth*

	Upper Teeth			Lower Teeth		
	#	Mean Pain Threshold μamps	S.D.	#	Mean Pain Threshold μamps	S.D.
Central Incisors	40	6.4	2.53	20	5.6	2.36
Lateral Incisors	40	6.3	2.50	20	7.0	2.31
Canines	40	8.9	2.96	20	8.3	3.24
1st Premolar	20	7.5	3.37	20	8.8	3.48
2nd Premolar	20	7.9	3.35	20	8.7	3.01
1st Molar	10	14.0	4.95	6	10.1	3.33
2nd Molar	9	13.8	3.99	12	11.8	2.68

*From Mumford[50]

The Threshold for the Induction of Muscular Contraction by Electric Shock

To this point we have discussed amounts of electricity which, when applied to man, are not dangerous. As the amount of current is increased, however, a point is reached where involuntary muscle spasm is produced. If the "electrodes" are in contact with the hands, then it is not possible to free oneself from the electricity, since voluntary muscle activity is no longer possible. The maximum current at which an electrode can be released by voluntary muscular control has been called the "let-go" current by Dalziel, et al.[18].

The let-go current was determined by Dalziel, et al., on 120 individuals for frequencies ranging from 5 to 10,000 Hz[18]. Direct current was also investigated. Table 9 demonstrates the results obtained using 60 Hz alternating current, while Table 10 shows the results for direct current. A summary of the statistical data for all frequencies studied is shown in Table 11, with derived current versus frequency curves shown graphically in Figure 15.

Table 9: Let-Go Current for 60 Hz AC*

Subject Number	Voltage (Volts)	Current (Milli-amperes)	Resistance (Ohms)	Percentile Rank (Per Cent)	Subject Number	Voltage (Volts)	Current (Milli amperes)	Resistance (Ohms)	Percentile Rank (Per Cent)
73	26	9.7	2,680	99.6	51	30	15.6	1,920	50.0
7	45	10.7	4,210	98.3	67	34	15.7	2,170	47.8
19	26	10.7	2.430	98.3	100		15.8		46.5
62	32	11.1	2,880	97.0	6	37	15.8	2,340	46.5
5		11.3		96.1	119		16.0		43.8
118		11.5		95.2	42	43	16.0	2,690	43.8
104		11.6		94.3	21		16.0		43.8
12	43	11.7	3,680	93.0	94		16.0		43.8
33		11.7		93.0	8	34	16.1	2,110	42.1
82		12.0		91.2	44	31	16.1	1,930	42.1
16	53	12.0	4,420	91.2	96		16.3		39.0
20	30	12.3	2,440	89.5	48	55	16.3	3,370	39.0
75	20	12.3	1,630	89.5	85		16.3		39.0
88		12.4		87.7	106		16.4		36.8
10		12.4		87.7	36		16.4		36.8
2	44	12.5	3,520	85.9	101		16.5		35.5
26	27	12.5	2,160	85.9	57	35	16.6	2,110	33.8
69	31	12.6	2,460	84.7	87		16.6		33.8
53	26	12.7	2,050	83.8	23	36	16.6	2,170	33.8
90		12.8		82.9	121		16.7		32.0
91		13.0		82.0	37		16.9		31.1
11	30	13.1	2,290	80.7	61	48	17.1	2,810	29.8
70		13.1		80.7	114		17.1		29.8
89		13.3		79.4	60	75	17.3	4,330	28.1
83		13.5		77.6	120		17.3		28.1
15	43	13.5	3,190	77.6	56		17.4		26.3
84		13.5		77.6	55		17.4		26.3
38	28	13.6	2,060	75.0	92		17.5		24.1
46	32	13.6	2,350	75.0	34	38	17.5	2,170	24.1
68	30	13.6	2,200	75.0	93		17.5		21.9
13	34	13.7	2,480	71.5	35	36	17.6	2,040	21.9
102		13.7		71.5	65	32	17.6	1,820	21.9
25	23	13.7	1,680	71.5	117		18.0		19.7
113		13.7		71.5	71		18.0		19.7

41	22	13.7	1,610	71.5	95		18.0		19.7
47		13.9		68.9	49	31	18.1	1,710	18.0
27		14.0		68.0	109		18.2		17.1
52		14.1		66.7	54	51	18.4	2,770	16.2
79		14.1		66.7	108		18.5		14.9
1	63	14.2	4,430	64.9	81		18.5		14.9
58	31	14.2	2,180	64.9	97		18.6		13.6
30	48	14.4	3,330	63.6	111		18.7		12.7
45	38	14.7	2,580	62.7	22	30	19.1	1,570	10.5
77		14.9		61.8	98		19.1		10.5
74	44	15.0	2,930	59.7	110		19.1		10.5
72	34	15.0	2,270	59.7	80		19.1		10.5
78		15.0		59.7	112		19.2		8.3
29	32	15.0	2,130	59.7	64	44	19.5	2,250	7.0
59	31	15.1	2.050	57.4	103		19.5		7.0
39	29	15.2	1,910	56.1	40	58	19.8	2,930	5.3
32	28	15.2	1,840	56.1	99		19.8		5.3
116		15.3		53.9	50	38	20.0	1,900	3.9
28		15.3		53.9	107		20.3		3.1
86		15.3		53.9	14		20.5		2.2
43	44	15.4	2,860	52.2	3	53	20.8	2,550	1.3
31	33	15.6	2,120	50.0	105		21.6		0.4
76		15.6		50.0					
4	38	15.6	2,430	50.0	115**		13.2		

*From Dalziel, et al.[18]
**Female, not used in the statistical analysis.

Table 10: Let-Go Current for Direct Current*

Subject Number	Voltage (Volts)	Current (Milli amperes)	Resistance (Ohms)
1	113	75.0	1,510
8	127	75.5	1,680
10	130	71.0	1,830
12	116	61.0	1,900
21	129	83.0	1,560
22		80.0	
23		71.0	
28	130	75.0	1,740
30	116	80.0	1,450
31	128	73.0	1,750
32	115	72.0	1,600
33	109	65.0	1,680
36	122	70.0	1,740
37	109	75.0	1,450
40	126	71.0	1,780
45		62.0	1,440
47	129	81.0	1,590
54	117	75.0	1,560
55	131	67.0	1,960
57	117	76.0	1,540
60		79.0	
61	130	72.5	1,790
62	123	75.0	1,640
64	128	70.0	1,830
69		80.0	
70	124	75.0	1,650
74	126	75.0	1,680
75	121	76.0	1,590
115**		56.0	

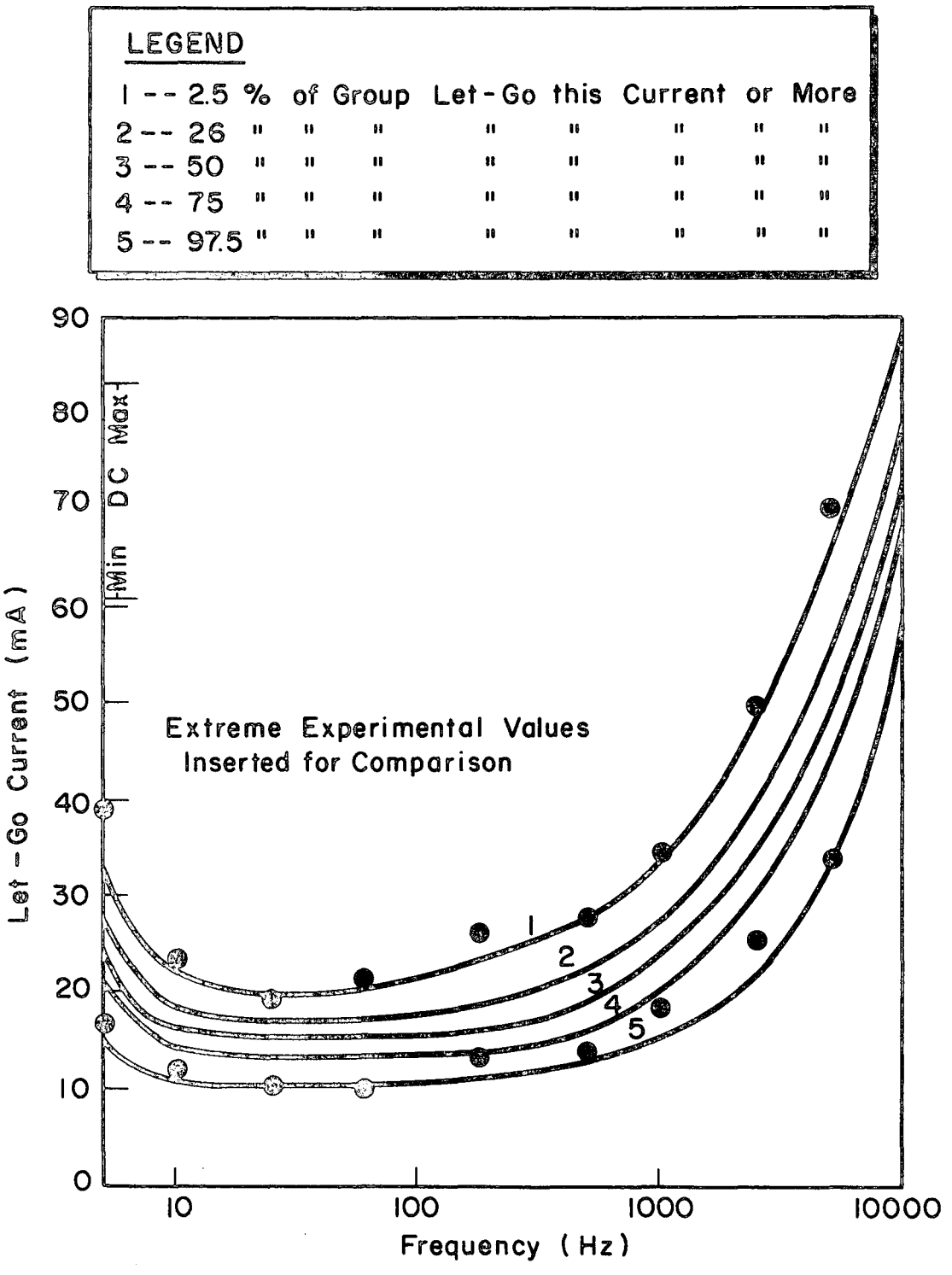
*From Dalziel, et al.[18]
**Female, not used in the statistical analysis

Table 11: Statistical Data and Measures of Validity for Studies on Let-Go Currents*

Frequency	Direct Current	5	10	25	60	180	500	1,000	2,500	5,000	10,000
Number Subjects	28	25	27	27	114	30	27	26	27	26	28
Voltage											
Maximum volts	131	80	68	56	75	60	46	49	61	76	82
Minimum volts	109	29	24	24	20	22	18	18	22	31	45
Impedance											
Maximum ohms	1,960	3,810	3,330	3,910	4,430	3,140	2,150	2,000	1,970	1,310	1,010
Minimum ohms	1,430	1,340	1,610	1,620	1,570	1,380	1,040	923	706	720	634
Current											
Maximum milliamperes	83	39.1	23.2	19.3	21.6	21.6	27.7	34.4	49.6	70.0	92.5
Minimum milliamperes	61	17.0	12.1	10.1	9.7	13.2	13.7	18.2	25.2	33.8	57.6
Mean milliamperes	74	24.05	16.30	15.14	15.55	17.80	18.90	24.20	34.60	49.30	73.00
Probable errors											
Mean		0.604	0.376	0.32	0.166	0.378	0.595	0.588	0.871	1.106	0.911
2.5 and 97.5 percentile		1.61	1.01	0.857	0.443	1.01	1.59	1.57	2.32	2.96	2.43

*From Dalziel, et al.[18]

Figure 15*



*Redrawn from Dalziel et al[18]

In addition to the data presented in the tables, several observations were made by the investigators. First, it was noted (using #6 copper wire and brass rods of 1/2, 3/4 and 1" diameter with a stimulating current of 60 Hz) that the let-go current is independent of electrode size. Secondly, in testing the effects of different wave forms, the let-go current was dependent upon the crest value of the current and not on the rms value.

Following these initial studies, Dalziel, et al., expanded their studies on the effects of frequency on let-go currents[21]. A total of 134 males and 28 females were evaluated. Based upon the findings the following conclusions were drawn:

1. A reasonably safe electric current for normal healthy adults is the let-go current which 99 1/2% of a large group can release by using muscles directly affected by that current.

2. The reasonably safe 60 cycle current for normal healthy adult men is about 9 mA; for adult women about 6 mA.

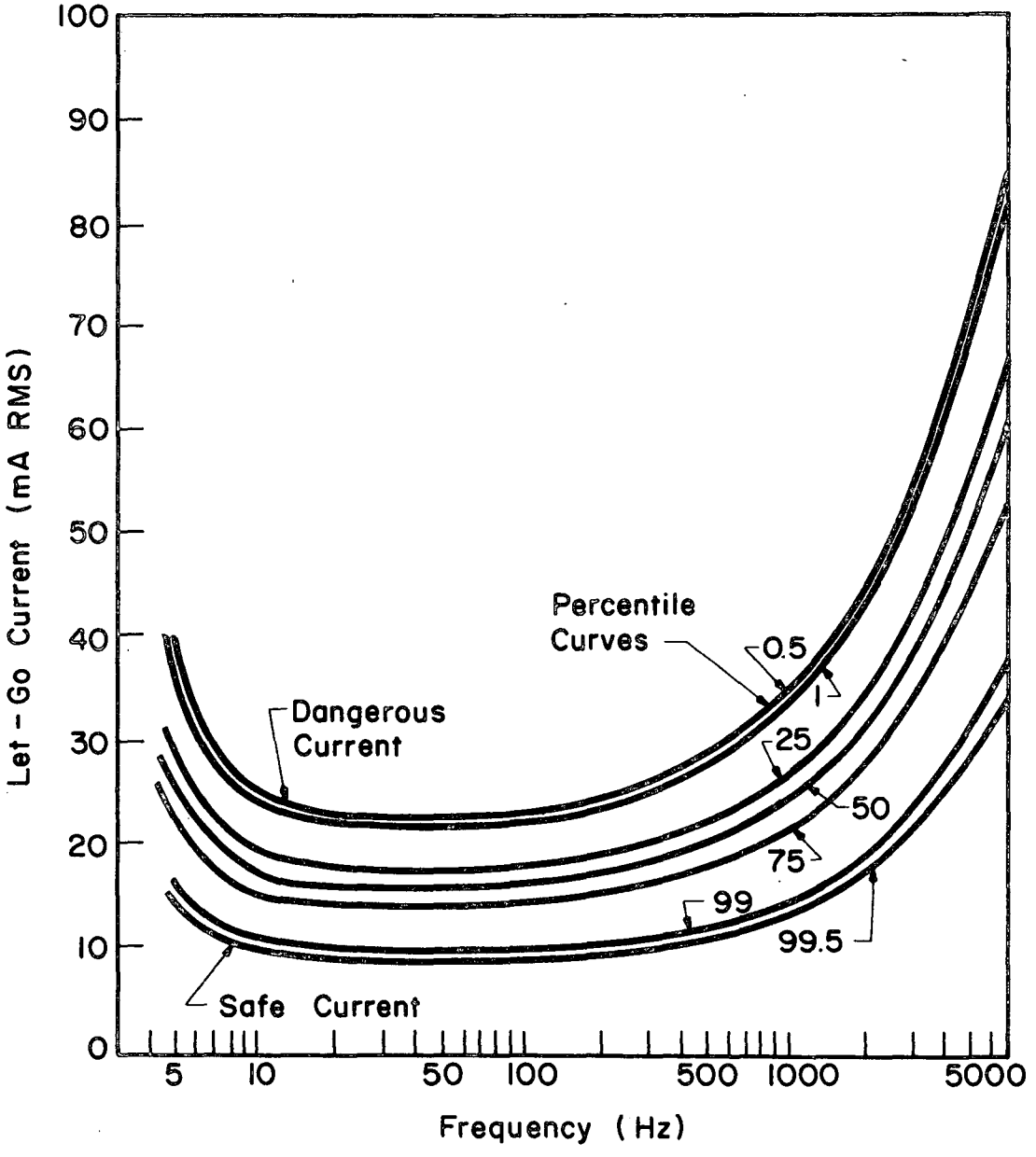
3. The corresponding data for direct current are 62 mA for men and 41 mA for women.

4. Let-go currents are affected by frequency. (See Figure 16.)

Dalziel's figures are compatible with those of Thompson's who, some years prior to Dalziel's work, reported let-go currents of 5.15 mA for women and 8.35 mA for men at 60 Hz AC[61].

Still further studies were made by Dalziel to evaluate the effect of wave form on let-go currents[12]. He observed that mean let-go current values obtained

Figure 16*

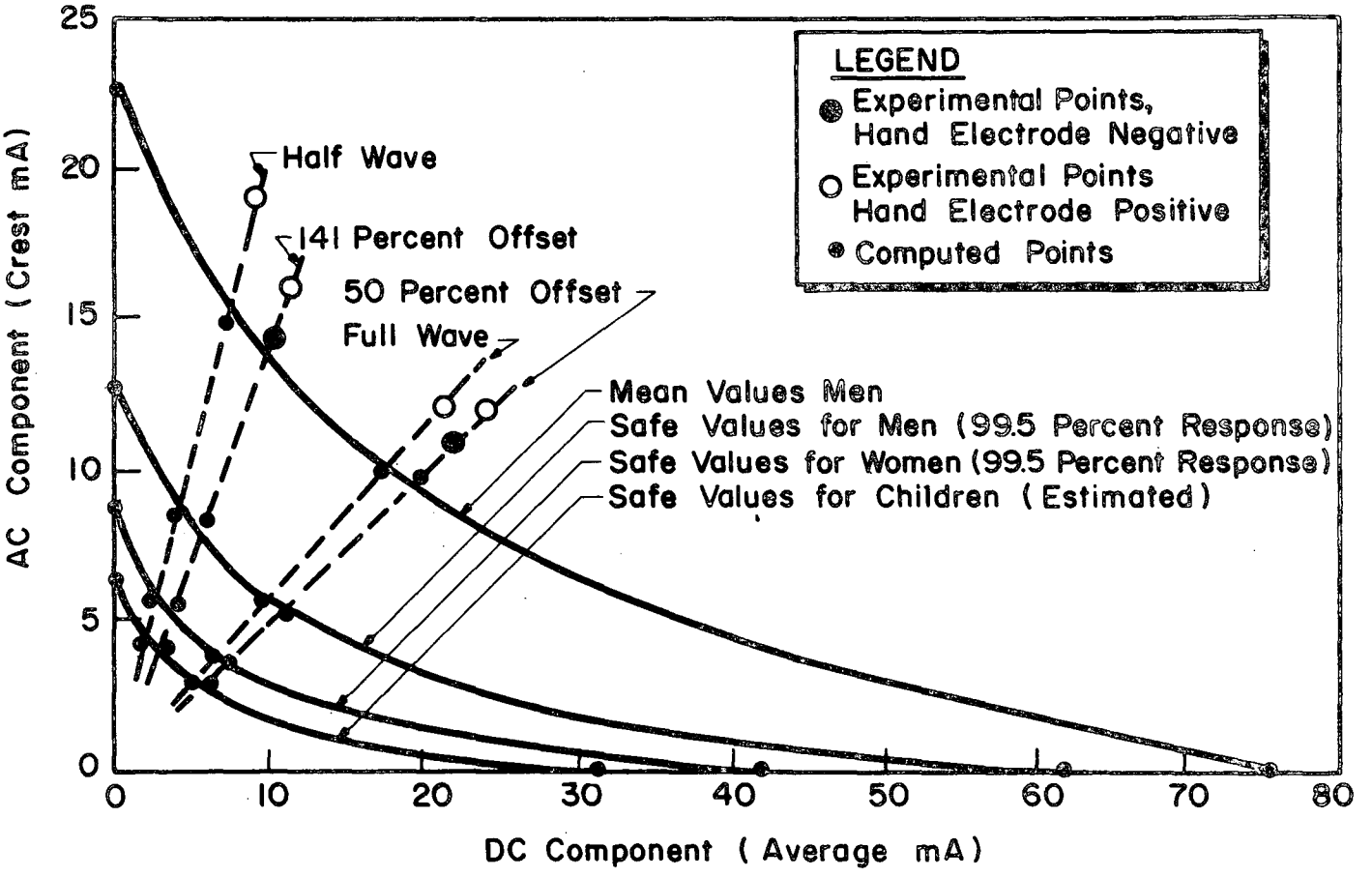


*Redrawn from Dalziel et al[21]

from tests made with various wave shapes follow the same curve if the crest value of the AC component is plotted on one axis versus the DC component on the other. Two conditions must be met in order to have the experimental data fall on the same curve. First, the reference axis for measurement of the alternating component must be the average value or the direct component and second, the peak or crest value of the alternating component must be measured in the direction of the maximum total current. Curves derived in this manner are illustrated in Figure 17. Figure 18 illustrates the reasonably safe current curves for sine wave currents. It is noted that human tolerance increases slowly at first and then quite rapidly for frequencies below 15 cycles or above 100 cycles. The relative discomfort curve on the same figure is arranged so that the discomfort is 100% for 60 cycles. It is noted that although a subject's let-go current increases considerably at the very low frequencies, his muscles follow the current variations and the sensations, presumably caused by the peaks of the current wave, are more painful than those experienced on the 60 cycle tests. At very high frequencies, sensations of heat rather than pain predominate. Thus, we again meet the problem of attempting to define "pain". As Dalziel suggests, the curve can only be taken to show in a general way the discomfort or the relative danger of a given current as a function of frequency.

Of considerable interest is the observation that after a current by which a man has been "frozen" to a conductor is interrupted, the man may be temporarily "paralyzed". This problem was studied by Dalziel[16]. Thirty-two men, ages 18-50 years, were "frozen" to a #8 copper wire by 60 Hz AC, 2 to 4 mA in excess of their let-go thresholds. It was found that 3 of the 32 men had a time delay of 0.4 sec in releasing the wire after the current had been stopped. Dalziel suggested that it is possible that the "let-go time delay" might be longer for higher 60 Hz currents and for short impulses of 100 or more mA.

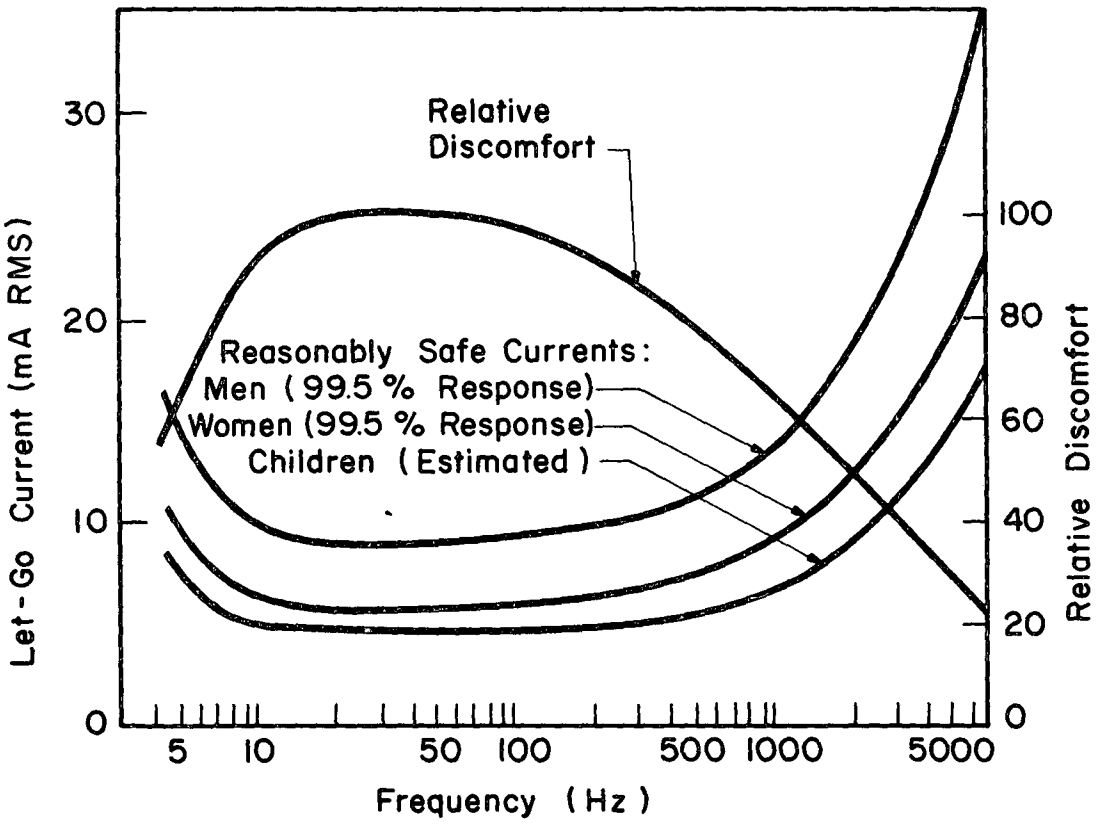
Figure 17*



Let-Go-Current Curves Plotted As A Function of A-C and D-C Components*

*From Dalziel[12]

Figure 18*



Sine-Wave Let-Go Currents and Relative
Discomfort Curves Versus Frequency*

*From Dalziel[12]

The Threshold for Ventricular Fibrillation

Ventricular fibrillation is a condition of completely asynchronous contraction and relaxation of the myocardial fibers of the ventricle. This random activity is not suitable for maintenance of cardiac output. Although there are many different etiologies for ventricular fibrillation, it is well known that an appropriate electrical stimulus may be such a causative agent.

The observation that electric current results in muscular contraction has been known since the time of Galvani. Animal studies performed at the end of the last century by Prevost and Battelli indicated that 200 Hz AC produced ventricular fibrillation with a tenth of the amplitude required at 2000 Hz[55]. Early in the thirties, Kouwenhoven and his associates began rather intensive studies on the effects of electricity on the heart. In studying the current flowing through the heart with an electric shock, Kouwenhoven, et al. observed in dogs that if the current pathway was parallel to the body axis, 9 to 10% of the total current flowed through the heart[39]. If, however, the current was transverse to the body axis, only 3% of the current flowed through the heart. The suggestion was made that in the human, the most dangerous path for electrical current was from the right hand to the foot.

Further studies were performed on dogs by Kouwenhoven, et al. to determine the effects of different electrical frequencies on the heart[40]. Studies were performed with both interrupted direct current and alternating current. The animals' chests were opened, electrodes placed directly on the heart and the minimum currents for a given frequency as well as the type of currents required to produce ventricular fibrillation were measured. Several observations were made. First, with interrupted direct current, the heart most readily fibrillated with currents

with the frequency of interruption near 60 times per second. As the frequency of interruption was increased from zero, the musculature of the heart became more responsive, responding most readily to shocks from 40 to 100 interruptions per second. At frequencies of interruption greater than 100 per second, the heart became less responsive and a greater current was required to produce ventricular fibrillation.

With alternating current, little difference in the reaction of the heart was seen to shocks from 25 to 60 Hz. The derived values for fibrillation currents for both AC and interrupted DC are shown in Table 12.

Table 12: Values for Fibrillating Currents (mA)*

Frequency (Hz)	Interrupted DC		Alternating Current	
	Mean	Max.	Effective	Max.
25	0.52	1.04	0.81	1.14
40	0.35	1.70	0.71	1.00
60	0.31	0.62	0.75	1.06

*From Kouwenhoven, et al.[40]

One of the most extensive early studies on the effects of electric shock on the heart was that performed by Ferris, et al.[26]. A number of species of animals were included in the tests to establish the trend of effects with variation in physiological and morphological factors; however, most of the experiments were upon animals comparable in body weight and heart rate and weight to man.

Seven different species of animals were studied for measurements of threshold currents for ventricular fibrillation[25]. Standard reference conditions included the use of a 60 Hz AC of three seconds duration with the electrodes on the right

foreleg and left hindleg, thus being somewhat analogous to many human accidental electrocutions.

Based upon these detailed investigations a number of observations were made:

1. Current rather than voltage is the proper criterion of shock instensity.

2. The stimulating effect of current through the heart can derange its actions causing ventricular fibrillation without damage to cardiac tissues but resulting in death unless fibrillation is arrested.

3. The current just below the threshold for ventricular fibrillation is the maximum to which man can safely be subjected. Based on animals comparable in size to man, this maximum current is about 0.1 A for a duration of one second or more if the current pathway is between an arm and a leg.

4. The threshold current for fibrillation is affected by a number of variables. The species and size of the animal is important. The threshold current increases roughly with both body weight and heart weight. (See Figure 19 from Geddes, et al.) Approximately similar threshold currents are found for currents from the arm to leg, across the chest, from the chest to the arm and from the head to the leg. Somewhat higher currents should be expected for pathways from arm to arm. (This is explained by Kouwenhoven's study, previously mentioned[39].) For current pathways from one leg to the other, the proportion of current reaching the heart is so small that fibrillation is not likely to occur even at currents as high as 15 A or more.

The threshold current alters with frequency. (This is shown well in graph form from a recent study by Geddes, et al., see Figure 20.) For shocks

of 1 sec or more in duration, the 25 Hz threshold current is about 25% higher than the 60 Hz value. For shock durations of less than 1 sec, this relation probably does not hold, all thresholds being expected to approach one another. For short shocks, the time of occurrence in relations to the heart cycle is important. The heart is the most sensitive for fibrillation to shocks occurring during the partial refractory phase of its cycle, which is about 20% of the whole and which occurs simultaneously with the T-wave of the electrocardiogram. With shocks of about 0.1 sec or less duration, it is practically impossible to produce ventricular fibrillation unless such shocks occur during this sensitive phase of the cardiac cycle. The middle of the refractory phase is more sensitive than its beginning or end.

The duration of the current is also important. The threshold current varies inversely with shock duration, but not uniformly, being most sensitive to change as the duration approaches the duration of one heart beat. (See Figure 21.) Within this sensitive phase of the heart cycle, the threshold fibrillating current for shock durations of 0.1 sec or less is ten times the threshold for durations of 1 sec or more. Shocks one-third of more of the heart cycle in duration may cause ventricular fibrillation even though they would not extend into the sensitive phase of the cycle if the heart continued its normal beat after the initiation of the shock. This is probably due to the induction of a premature heart beat which brings about a premature sensitive phase prior to the end of the shock.

5. Successive shocks have no cumulative effect on the susceptibility of the heart to fibrillation.

6. Susceptibility of the heart to fibrillation by short shocks increases with currents up to several times the threshold, then decreases, becoming very

small at currents of the order of 25 A through the body in the vicinity of the heart. However, other serious injury may be expected for such currents.

7. Fibrillation produced by electric shock will, in most cases, be arrested by a subsequent electric shock of high intensity and short duration through the heart.

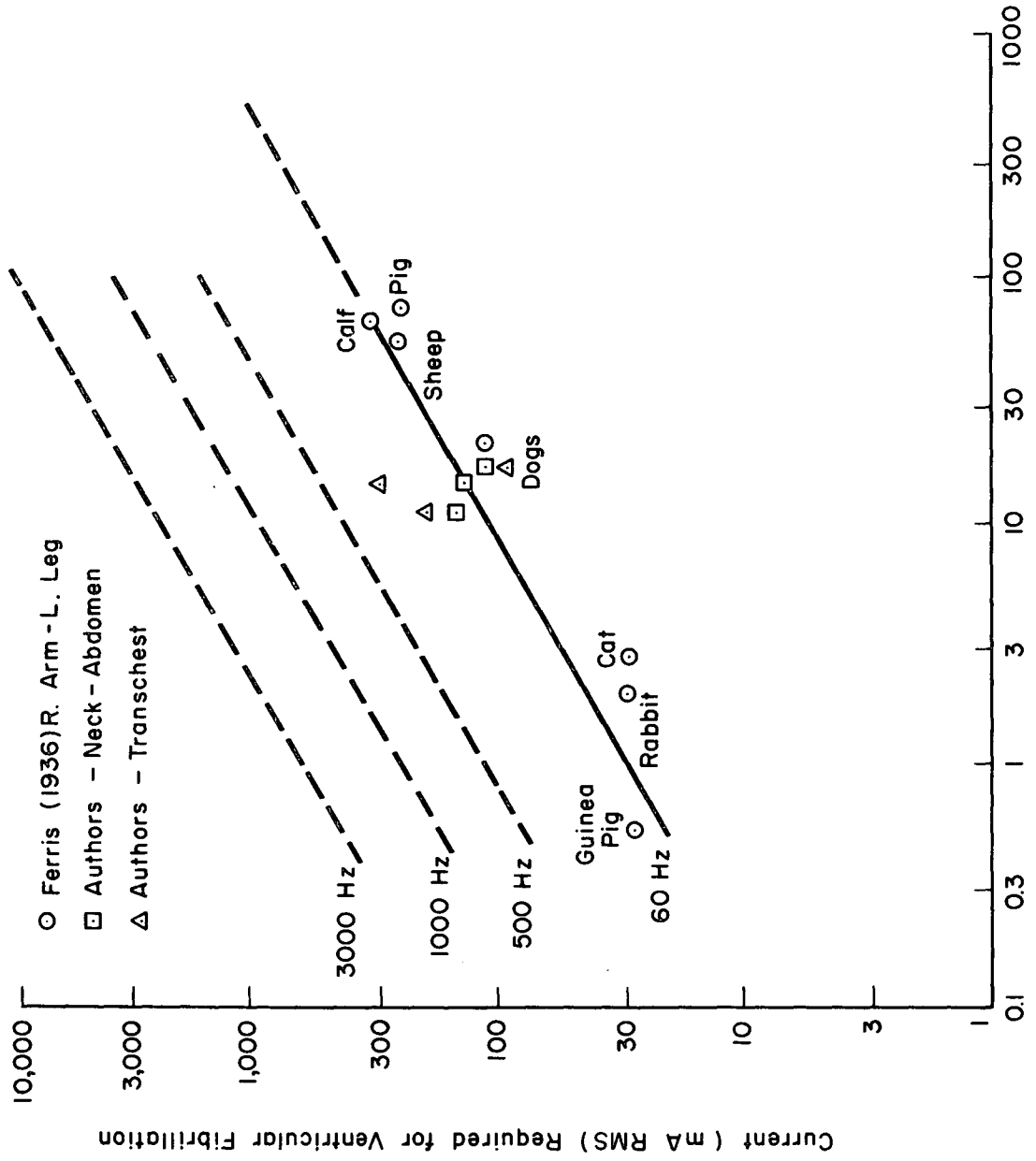
8. The results indicate on the whole, that sinusoidal currents in excess of 100 mA at 60 Hz from hand to foot will be dangerous for shock durations of three seconds or more for man.

Further studies evaluating the effects of electric shock during the vulnerable period of the heart cycle were done by Wiggers and Wegria[64]. Brief induction or condenser shocks were applied to normal hearts of old or young dogs by stigmatic electrodes. Fibrillation was produced only when the shocks fell during the vulnerable period. It was noted by these investigators that alternating current is more dangerous than direct current since effective variations of current strength fall during the vulnerable period (especially with 60 Hz) while these variations occur only during the closing and opening of the circuit with direct current.

Ten years after Ferris' et al., original paper was published, (previously mentioned in this paper) a further analysis of their data was performed by Dalziel[26,13]. In this analysis, Dalziel concerned himself with threshold currents likely to produce ventricular fibrillation in 1/2% of a large group of normal men. (Thus an analysis similar to that for "let-go" currents.) The formula derived was as follows:

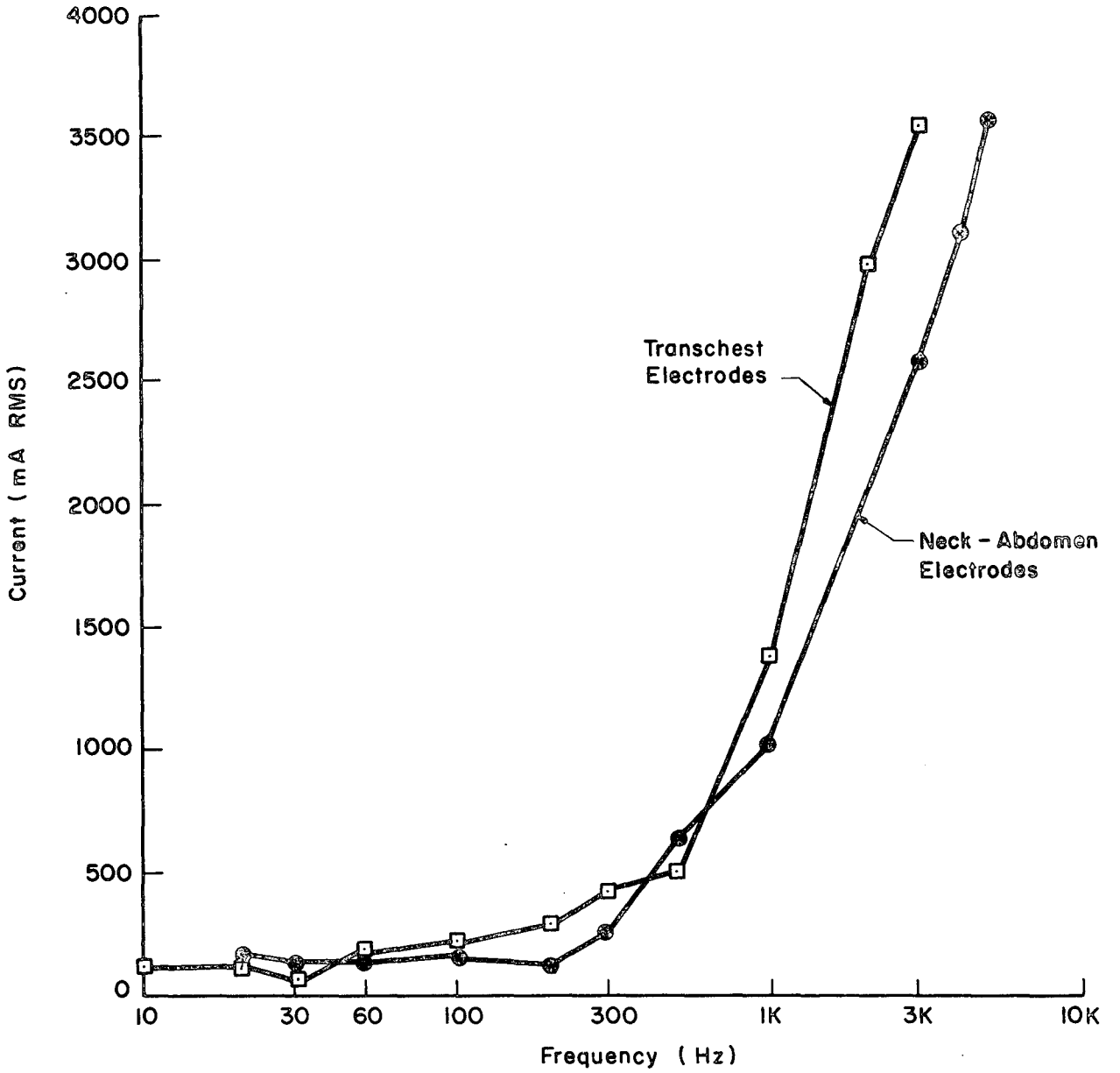
I (1/2%) = $165/\sqrt{T}$ mA, where T = time of current flow in seconds and assuming a "standard" 70 Kg man. (A defense with more complete statistical analysis of this formula is presented by Dalziel in a later paper.)[17]

Figure 19*



*From Geddes et al[31]

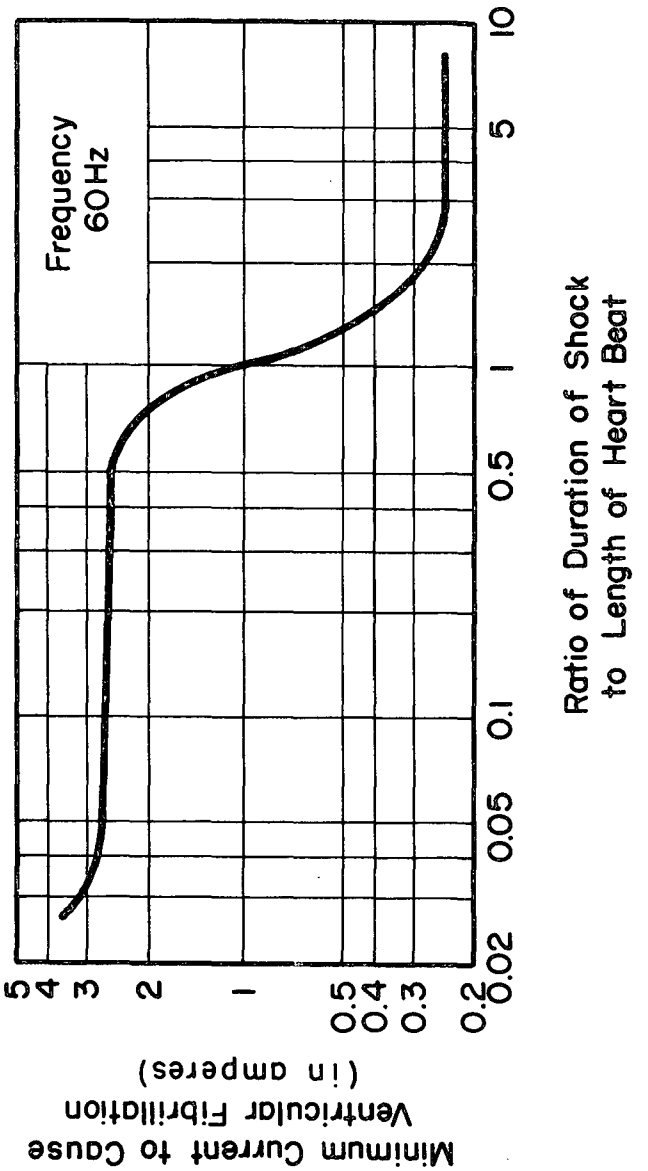
Figure 20*



Current For Ventricular Fibrillation In Dogs*

*Redrawn from Geddes et al[31]

Figure 21*



*Redrawn from Ferris[25]

Further analysis in the same paper suggested that the ratio of fibrillating current for direct current to alternating current is about 5 to 1. However, the author points out that this conclusion is drawn from limited data. Similarly, data derived from some of the author's own earlier studies, and analyzed in this paper, suggest that for capacitor discharges a reasonably safe value for man is 45 millicoulombs. Dalziel pointed out in a still later paper that the hazard from short shocks is believed to exist because of the energy contained in the discharge, while the crest of the initial current, the quantity in the pulse and the shock duration are related quantities of secondary importance[14].

Very recently, a still more comprehensive analysis using Dalziel's technique was performed by Dalziel and Lee[19]. In addition to the data included in the original analyses, data was included from the studies of Kouwenhoven, et al., Kiselev and Lee[41,19,46]. It was pointed out that shocks administered to hundreds of animals indicate that the minimum commercial frequency electric current causing ventricular fibrillation is proportional to body weight and inversely proportional to the square root of the shock duration. Thus, assuming a 50 Kg human, the equation, $I = 116/\sqrt{T}$ mA represents the 1/2% maximum non-fibrillating current line while the equation $I = 185/\sqrt{T}$ mA represents the 1/2% minimum fibrillating current line.

Using Dalziel and Lee's analysis, the actual figures for fibrillating currents for a 50 Kg human become 67 mA as the 1/2% maximum non-fibrillating current and 107 mA as the 1/2% minimum fibrillating current.

The authors point out that these equations are drawn from information about the effects of shocks of less than 5 sec duration. It is suggested that from 5 seconds to 20 or 30 seconds, the threshold may remain fairly steady, dropping

only slightly, while for longer periods, hypoxia may exert an influence and lower the threshold even further.

Confirmation of this idea may be furnished in part by the investigations of Sugimoto, et al., who noted that if an accelerating ventricular tachycardia that is produced by 60 Hz stimulation is of sufficient duration (e.g., 5 or 6 beats), the ventricular fibrillation threshold is reduced progressively after each premature ventricular response, thus making it possible to induce ventricular fibrillation with a very weak current[59].

To this point, we have discussed only the levels of electric current which will produce ventricular fibrillation when the current is applied to the body surface. There are, however, circumstances where electric current may reach the heart directly, as for example, through a dye-filled catheter passed through a vein into the right atrium. Thus, it is important to consider those currents which might be expected to produce ventricular fibrillation when the current is applied directly to the heart.

Weinberg, et al., performed such a study on dogs[62]. Catheters were passed into various heart chambers and measurements taken. It was found that with a catheter in each ventricle, currents as low as 35 μA and a voltage as low as 0.06 V could induce ventricular fibrillation. In those situations where a single intracardiac catheter was in place and a current flowed between the catheter and a metal plate (or electrode) on the chest, an average fibrillating current of 170 μA was measured with an average voltage of 0.2 V and an average resistance between electrodes of 920 ohms.

Similar studies were performed by Whalen, et al. on humans at the time of open heart surgery on cardio-pulmonary bypass, under moderate hypothermia (30-34°C)

and with light anesthesia[63]. Six patients were tested with electrodes 2.5 cm diameter and four patients with electrodes 0.25 cm diameter. In each case, the electrodes were placed on the apex of the left ventricle and the outflow tract of the right ventricle. Sixty Hz AC was used for the studies. The results are shown in Table 13.

Table 13: Variation in Threshold for Ventricular Fibrillation as Related to Electrode Size*

Electrode Diameter	#	Mean Current To Produce Fibrillation	Mean Voltage	Mean Resistance
2.5 cm	6	3366 μamp	0.85 V	252 Ω
0.25 cm	4	583 μamp	0.01 V	1732 Ω

*From Whalen, et al.[39]

The authors stated that the probable reason for the lower threshold with the small electrodes could be explained by the greater current density, while the greater impedance was due to the smaller cross-sectional area. The former point receives support in a study by Furman, et al.[29]. Although Furman and his associates' study was not to measure thresholds for ventricular fibrillation, but rather, to measure the threshold currents for stimulation of the heart by an implanted artificial pacemaker, he found also that as the electrode diameter increased, the current necessary for stimulation increased. This was felt to be explained by the lesser current density using larger electrodes. The summary of results of the study are shown in Table 14. Thus, Hopps has pointed out that these studies indicate that 60 Hz shocks are 500 to 5000 times more dangerous when delivered directly to the heart rather than to the body surface[36].

Table 14: Variation in Threshold for Cardiac Stimulation as Related to Electrode Size*

Catheter Number	1	2	3	4
Type	Cordis (2 mm.)	Cordis (4 mm.)	Cordis (6 mm.)	Medtronic
Number of measurements	10	21	18	10
Tip length (mm.)	1.68	3.56	6.73	6.22
Radius (mm.)	1.13	1.24	1.18	2.05
Exposed surface area ($cm.^2$)	0.119	0.277	0.499	0.87
Mean of threshold currents (mA)	0.39 ± 0.11	0.83 ± 0.33	1.57 ± 0.55	2.00 ± 0.54
Mean current density ($mA\ cm.^2$)	3.27	3.00	3.14	2.30
Mean pulse energy, microjoules	0.27 ± 0.12	0.71 ± 0.27	2.28 ± 1.45	3.65 ± 2.60

*From Furman, et al.[29]

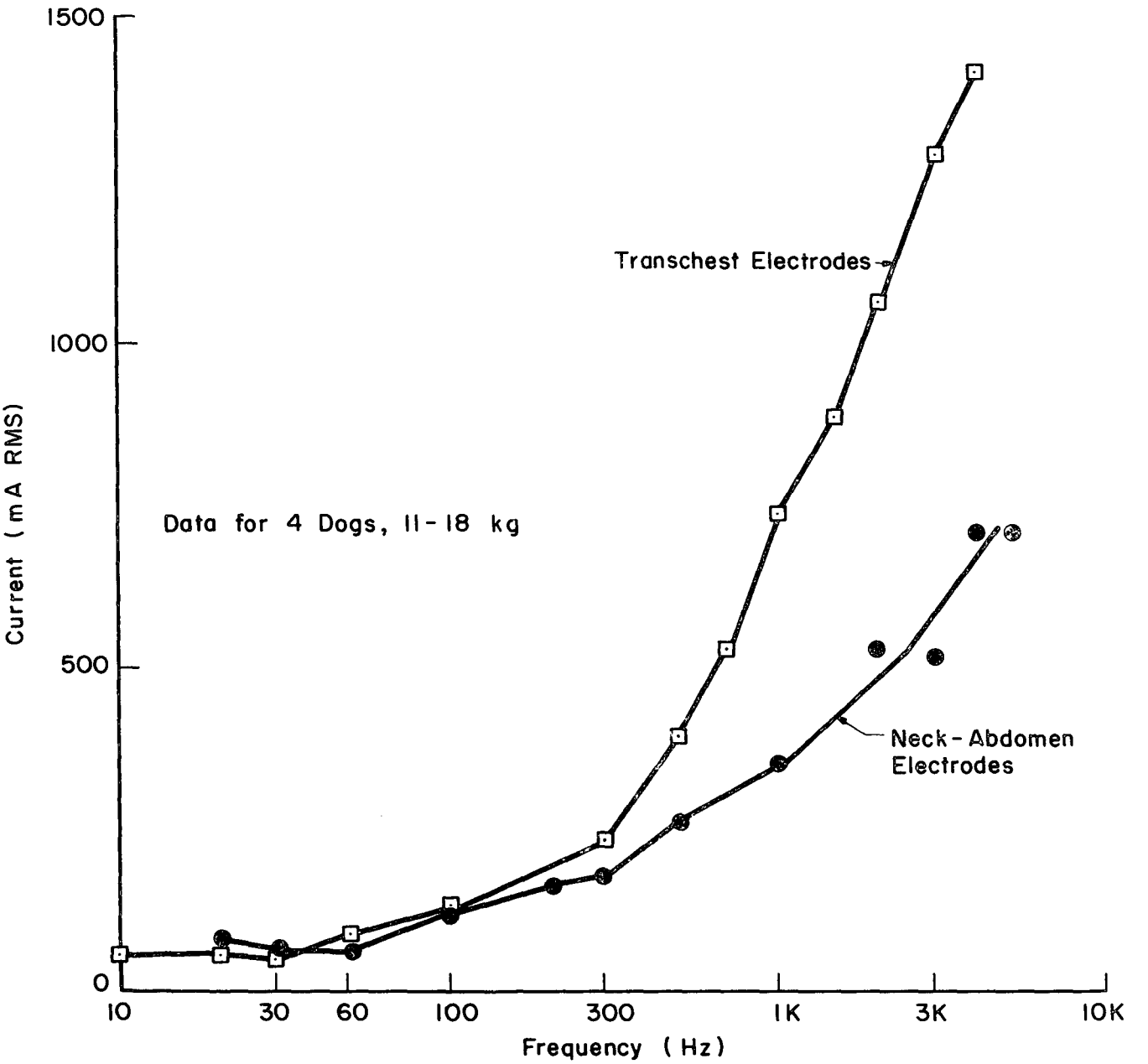
Finally, Geddes and his associates have pointed out yet another effect of electric current on the heart, albeit indirect[31]. When a current is passed through the thorax, stimulation of intrathoracic nerves may be expected. The most well-known example of this is with phrenic nerve stimulation, which produces tetanic contraction of the diaphragm and thus prevents respiration. However, stimulation of the vagus nerves was not reported until this study. Using metal band neck-abdomen electrodes and then transthoracic plate electrodes, current at several frequencies was increased until vagal slowing of the heart was observed. The results are shown in Figure 22. Proof that slowing of the heart was caused by stimulation of the vagus nerves was verified by the administration of atropine, which abolished the electrical effect.

Other Effects of Electricity on Humans

This section is not and cannot be all inclusive, since references abound which discuss the effect of electricity on virtually every human organ or function. An attempt has thus been made to include only a few of the most important or interesting studies - particularly the effect of electricity on the central nervous system. This latter emphasis is important since the placement of electrodes upon the head for purposes of biomedical monitoring opens the possibility of an electric current passing through the brain.

A study was performed by Kouwenhoven and Langworthy to investigate this problem[42]. Electrodes were placed on the skull and the base of the tail of the test animal (rats). Sixty Hz AC and DC at 110, 220, 500 and 1000 volts for varying time periods were used. Several conclusions were drawn. Injuries were not noted to be directly proportional to the amount of current; rather, the initial voltage, the duration of contact and the size of the animal were important. It was noted that when an electric current passes through the brain a temporary physiological

Figure 22*



Current for Slowing the Heart by Vagal Stimulation*

*Redrawn from Geddes et al [31]

block is produced in the respiratory center and spontaneous breathing ceases for a time. If no serious injury occurred to the heart, adequate artificial respiration gave time for recovery of the medullary center and normal breathing resumed spontaneously. Severe shocks produced central nervous system changes incompatible with life and immediate death in all cases was due to respiratory failure. Delayed death was due to hemorrhage within the brain.

A later study was designed by the same investigators to explore the problem of brain damage when the current did not pass through the brain[43]. If the main current path did not include the brain, spinal cord or nerves required for respiration, most experimental animals breathed at once and were active within a few minutes. It was observed that the chances for recovery of the animals were best when the brain did not lie directly in the current pathway.

The persistance of respiratory arrest when a current has passed through the brain has also been discussed by Lee[45]. He relates the account of W. Watson, who recorded an experiment by Benjamin Franklin, performed in 1751: "In this 'A pullet struck dead in like manner (viz., by "the electric shock" being directed through its head) being recovered by repeatedly blowing into its lungs, when set down on the floor, ran headlong against the wall.'" Lee notes, however, that recent experimental work indicates that permanent respiratory arrest is unlikely in accidental shocks which pass from one upper limb to another limb unless the currents are sufficiently great to cause gross burning, and, further, that in electro-convulsive therapy a current of several hundred mA is passed transversely through the brain and only very rarely causes respiratory arrest. Thus, it is implied that a longitudinal pathway of the current (i.e., through the brainstem) is required to produce respiratory arrest.

Alexander pointed out certain secondary effects of electric shock on the central nervous system[2]. These are effects which occur secondarily to circulatory dysfunction and include cerebral edema, perivascular hemorrhage, etc. It should be kept in mind, however, that these do not appear to be caused primarily by the electric current.

Aita has agreed with this interpretation in pointing out that the likely causes of permanent neurologic sequelae seen following accidental electroshock are, in general, due to hypoxia and heat damage and notes that most electrical neurologic injuries are expressed immediately[1].

However, Farrell and Starr have recently compiled a classification of the various neurological syndromes secondary to electrical injuries and have proposed a mechanism of delayed damage[24]. The classifications are as follows:

1. Cerebral Syndromes - delayed vascular occlusion due to intimal damage from the initial shock or primary basal ganglia damage.

2. Spinal Syndromes - intimal damage with delayed vascular occlusion or primary damage.

3. Radicular and Peripheral Nerve Syndromes - most typically secondary to burns but can be due to vascular occlusion or primary damage.

The authors point out that acute damage to various CNS structures may be expected because of the tissue heating effect. However, it is noted that such injury represents an acute problem and does not necessarily explain delayed injury. They thus postulate the following mechanism. Electric current may act like ionizing radiation, in that it alters biologically active proteins but does not kill the cell. These proteins then undergo conformational changes secondary to changes in weak chemical bonds. This interpretation is compatible with the fact that blood vessels are most prominently affected by ionizing radiation and

electrical injury since within the central nervous system, vascular endothelial cells are elements that most frequently divide. Thus, if secondary to either of the electromagnetic stimuli these cells die or become manifestly abnormal after mitosis a potential region for thrombosis occurs with a resultant alteration in blood flow.

The production of brain lesions with electric currents applied through implanted electrodes was studied by Rowland, et al.[56]. Using the cat as the experimental animal, pulsed and continuous unidirectional current was applied to the brain. It was observed that if the total quantitity of electricity (millicoulombs) was constant, wide variations in time of current flow, pulse form, amperage and voltage do not influence the volume of tissue alteration and such changes which do occur are found to be independent of heating. In studies with bidirectional flow (alternating current) the size of the lesions was dependent upon first, the number of microcoulombs per pulse in excess of a threshold value for damage (determined as 20 to 25 microcoulombs) and, secondly, the number of such pulses in the applied train. The lesions were found to be independent of time (pulse duration), frequency, amperage or voltage.

Lamb, et al. performed a study to investigate the problem of electrical thrombosis of blood vessels[44]. In vitro coagulation of dog whole blood and in vivo thrombosis of blood vessels by means of an electrical current were found to be voltage dependent phenomena. The critical potential difference below which they did not occur appeared to be 2.0 V. With in vitro studies, whole blood was found not to deposit as a coagulum on a positive electrode even when the amount of charge allowed to flow was greater than that which caused coagulation at higher voltages. In vivo electrical thrombosis was found to have similar voltage dependence in studies with femoral vein pairs of dogs. Those exposed to 2.5 V thrombosed,

whereas those at 2.0 V did not, even through the current and the total time it flowed were the same in each instance. The authors suggest that a transmural potential charge is not the initiating factor in the normal process of thrombosis, but that this does not preclude an involvement of the charge in the subsequent course of thrombus formation. Rather, it is believed that the accumulation of platelets or ions at an injury site may be affected by a charge.

Long has raised a number of interesting points in his review and experimental studies on the production of cataracts by electrical energy[48]. He noted that such cataracts typically developed only if one of the contacts was near the eye. Further, it was observed that the time of onset of the cataract was variable, from immediately to greater than one year after the shock, but generally occurring within two to six months. Long's own studies were performed with AC at 60 Hz and 50 V and DC with the same total power. A much greater local effect was noted for direct current with vascular corneal opacities common. Measurements of intraocular temperature revealed no increase during the electrical shocks. Cataracts produced by the electric current were believed to be due to changes in the capsular permeability of the lens. The author points out that the findings are exactly like those with X-irradiation except that X-ray produces changes on the posterior horizontal suture while electric energy produces changes on the anterior suture. This finding may lend support to the suggestions of Farrell and Starr, previously noted[24].

In the discussion of the effects of electricity on the brain, we have already mentioned the problem of primary respiratory arrest. Further comment is appropriate on the effects of electricity on respiration.

If a current is applied through the thorax and is of sufficient strength, tetanic contraction of the chest musculature may occur, thereby stopping respiratory exchange. Lee has suggested that this occurs when about 20 to 30 mA pass

through the chest[45]. Thus, asphyxial death with cyanosis may occur, respiration having been arrested while circulation continues. It is pointed out, however, that it may not be possible at autopsy to determine that this has happened, since the usual petechial hemorrhages occurring with obstructive asphyxia are not seen. These would not be expected, since the anoxic capillaries are not subjected to the strong subatmospheric intrapleural pressures developed with attempted inspiration during obstructive asphyxia. Many years prior to this study, an astute observation was made by Conrad and Haggard, who noted that, in general, shocks fatal in a short time were due to cardiac effects, while those requiring a longer time were secondary to respiratory failure[9].

In contrast to this purely muscular arrest of respiration, electricity may produce a true respiratory block, as previously mentioned. Angelis, et al. have studied the effects of direct current on respiration[3]. DC electric shocks were applied along the forelimb to forelimb pathway in rabbits. The effects on respiration were found to depend on the current value. With currents up to 50 mA, no respiratory effects were noted. From 50 mA to 180 mA there was arrest of respiration during the early part of the shock. With a current from 180 mA to 350 mA respiration was arrested throughout the shock with spontaneous resumption immediately afterwards. With a current from 350 mA and higher (to a maximum of 1.8 A) respiration was arrested throughout the shock with a delay before spontaneous resumption of respiration.

A similar study was performed by Lee, et al. to evaluate the effects of alternating current[47]. Fifty Hz AC of sufficient strength was passed through the forelimbs of rabbits such that there was a delay between the cessation of the shock and resumption of spontaneous respiration. The relation of this delay to the duration of shock and the current magnitude were examined independently and in terms of two physical concepts - the product of shock duration and current

magnitude ("charge equivalent") and a quantity proportional to the energy input. The influence of the shock duration apparently exceeded that of the current. Further, delay was strongly associated with both "charge equivalent" and energy input. When temporary circulatory arrest due to ventricular fibrillation occurred, an additional mechanism appeared to operate. Although protracted, the delay showed similar association with the shock duration and current magnitude. It was also observed that the interval between spontaneous defibrillation and the resumption of respiration showed a strong association with shock duration. The restarting of respiration appeared to depend upon circulation. It was suggested then when the circulation restarts, after a period of ventricular fibrillation, blood-borne inhibitory substances, which accumulated during the period of circulatory arrest, may affect the respiratory center.

THE PASSIVE ELECTRICAL PROPERTIES OF BIOLOGICAL MATERIAL: ELECTRICAL RESISTANCE AND IMPEDANCE

The mammalian body may be described electrically as a complex suspension of electrolytes and proteins in fluid, with many discontinuities created by various types of membranes, generating potentials and potential differences among different cells, tissues or organs as a normal function of maintaining what might appropriately be called the "spark of life". Thus, when one considers the action of extrinsic electric energy on the body, the final analysis must include integration of the body's intrinsic currents.

Nevertheless, in the presence of small currents various body structures may be analyzed in terms of their passive electrical phenomena, acting, in essence, as combinations of resistors and capacitors.

Electrical Resistance of Cells and Tissues

Electrical resistance may be defined as opposition by a conductor to the passage of an electrical current. Conversely, conductance may be defined as the capacity for conducting or the ability to convey. Electrical conductance can be represented as the reciprocal of resistance; i.e., Conductance = 1/Resistance.

When a steady direct current is passed through tissue, the tissue offers resistance to its passage. Perhaps the most electrically simple forms of "tissue" in the body are represented by the various electrolytic solutions - plasma, urine, bile, etc. - to which, in general, can be applied the principles of the conduction of electricity by electrolytic solutions. An excellent review of this area is given by Stacy, et al.; this can be summarized briefly as follows[58].

As the concentration of salts in a solution increases, the conductance increases since more of the ions in the solution become available for migration

to the electrodes at which the external voltage is applied. Conductance is defined on the basis of the number of charged particles per unit volume of the solution and can be expressed in several ways. Equivalent conductance is the conductance of a solution containing 1 gram equivalent of the electrolyte and separating the electrodes by a distance of 1 cm. Molecular conductance is the conductance of a solution containing 1 gram molecular weight of the electrolyte and separating the electrodes by a distance of 1 cm. The specific conductance, K, is the conductance of a solution without regard to the concentration of the electrolyte. Thus, stronger electrolytes may be expected to have a relatively higher specific conductance than a weak electrolyte.

The point may be illustrated by the following. If a potential difference (E) exists between two electrodes in an electrolytic solution all charges (q) in the solution will experience a force ($f = qE$) causing them to move along the field lines of force. The charged particles in the solution can be considered as being accelerated to a terminal velocity virtually immediately, following which they will drift at a terminal velocity proportional to the force. Specifically, the terminal velocity is equal to the product of the force (f) and the mobility (u), the latter defined as the velocity of the particle when unit force is acting upon it. (Terminal Velocity = fu). The total current (i) flowing through the electrolyte is then equal to the number of charges (N) times their velocity or $i = Nfu$. Ordinarily, the number of charges, positive and negative, will be equal to twice the number of dissociated atoms, and the anion and cation will have different mobilities, u_a and u_c. If the number of dissociated molecules in a solution of concentration (c) is indicated by δC, then the current flow can be represented by:

Equation 1: $$i = qE\delta C(u_a + u_c)$$

The conductivity of the solution is defined as the ratio of current to potential difference; potential difference (V) is related to the field by E = V/d where d is the distance between electrodes or, more specifically, the length of the line of force. If the electrodes are close together so that d is much smaller than the plate size, the lines of force are, on the average, just d in length. For such a case, the conductance of the cell is:

$$\text{Equation 2:} \quad \frac{1}{R} = \frac{q\delta C}{d} (u_a + u_c)$$

The conductivity, rho, of the solution in the cell would be the conductance per unit area normal to the direction of current flow, for unit distance of plate separation, or:

$$\text{Equation 3:} \quad \rho = q\delta C (u_a + u_c)$$

It is obvious, of course, that the body is composed of more than electrolyte solutions. Thus it is necessary to consider the problem of tissue electrical resistance. If the tissues are considered as suspensions of cells in extracellular fluid, then the theory of electrical resistivity of suspensions enables one to predict the resistivity of tissues with some accuracy. The behavior of a group of cells suspended in a conducting medium follows that of suspensions of conducting spheres in conducting media as described by Maxwell[8]. The Maxwell equation for this type of system may be expressed as:

$$\text{Equation 4:} \quad \frac{\frac{r_2}{r} - 1}{\frac{r_1}{r} + 2} = \phi \frac{\frac{r_1}{r_2} - 1}{\frac{r_1}{r_2} + 2}$$

when r is the resistivity of the solution, r_1 is the resistivity of the suspending medium, r_2 is the resistivity of the suspended material and ϕ is the relative volume occupied by the spheres.

This theory has been extended to describe the conductance of suspensions of non-conducting ellipsoids[58]. The extension is stated as:

$$\text{Equation 5:}\quad \phi = \frac{\frac{r}{r_1} - 1}{\frac{r}{r_1} - 1 + f}\ ;\ r = \frac{\phi r_1 - \phi f - r_1}{\phi - 1} = r_1 - \frac{\phi f}{\phi - 1}$$

The term f in this equation is a shape factor amounting to 1.5 for spheres and greater than 1.5 for structures of other shapes.

Thus, if living cells are non-conducting, Equation 5 is applicable, while if they are non-conducting, Equation 4 should be applied.

Finally, if conducting particles other than spheres suspended in a medium are considered, Equation 4 must be modified to introduce a shape factor similar to that used in Equation 5. Thus the statement for the resistive behavior of suspensions of ellipsoids which are conducting becomes:

$$\text{Equation 4a:}\quad \frac{1 - \frac{r_1}{r}}{f + \frac{r_1}{r}} = \phi \frac{1 - \frac{r_1}{r_2}}{f + \frac{r_1}{r_2}} \quad \text{or} \quad r_1 \frac{(1-\phi)r_1 + (f+\phi)r_2}{(1+f\phi)r_1 + f(1-\phi)r_2}$$

The complexity increases somewhat further when one recognizes that not only are living cells not all spherical, but that cells are not homogeneous objects. Rather they consist of relatively non-conducting membrane surrounding a volume of electrolyte solution which is of low resistivity. If the resistivity of cytoplasm is r_2^*, the resistance per unit area of the membrane is r_3 and the cell radius is a, then the r_2 in the preceding equation may be replaced as follows:

Equation 6: $r_2 = r_2^* + r_3/a$

Thus, the general expression for resistivity of cellular suspensions becomes:

Equation 7: $$r = r_1 \frac{(1-\phi)\, r_1 + (f+\phi)\, (r_2^* + r_3/a)}{(1+f\phi)\, r_1 + f\,(1-\phi)\,(r_2^* + r_3/2)}$$

An example of the use of these formulae is given by Cole and Curtis[8]. If a spherical cell has a cytoplasmic resistivity of 100 ohm cm., a membrane resistance of 1000 ohms per cm^2 and a radius of 10 μ or 10^{-3} cm, the equivalent homogeneous cell has a resistivity of 1.0001 ohm cm. (See Equation 4a). Under this condition, the current flow through the cell is determined almost entirely by membrane surface resistivity. If a suspension contains 50% by volume of these cells in an electrolyte of resistivity of 100 ohm cm, then the suspension has a resistivity of 249.93 ohm cm. If the cellular membranes are perfectly non-conducting, the suspension resistivity then becomes 250 ohm cm. (See Equation 7).

Another method for measurement and interpretation of cellular characteristics is by study of the flow of current through cell membranes when a potential difference exists between two points on the exterior of the cell membrane. Cells most easily studied in this manner are of a long, cylindrical configuration, such as nerve or muscle cells. The technique of analysis is based on the conventional cable theory.

If the assumption is made that the interior of a cell is conductive and if

V_e is the voltage at any point on the cell's exterior, x is the distance along the cell and R_e is the resistance of the layer of electrolyte on the outer surface of the cell per unit of length, then by Ohm's Law:

$$\text{Equation 8:} \quad \frac{\Delta V_e}{\Delta x} = -I_e R_e \text{ or } \frac{\Delta V_i}{\Delta x} = -I_i R_i$$

where V_i is the voltage on the inner surface of the membrane and R_i is the resistance of the cytoplasm per unit length. Variations of the currents flowing through both the "outside" and "inside" circuits are produced by current flowing through the membrane. Thus:

$$\text{Equation 9:} \quad \frac{\Delta I_e}{\Delta x} = \frac{\Delta I_i}{\Delta x} = I_m$$

where I_m is current per unit length through the membrane.

This relationship can be used to calculate the resistances of the internal cytoplasm, the external layer of electrolyte and the membrane. However, one must take into account the "characteristic length" of the fiber (λ), which is defined as:

$$\text{Equation 10:} \quad \lambda = \sqrt{\frac{r_m}{r_1 + r_2}}$$

where r_m is the membrane resistivity, r_1 is the resistivity of the solution in which the fiber is immersed and r_2 is the resistivity of the cytoplasm. The equation for the resistance (R) of the cell then becomes:

$$\text{Equation 11:} \quad R = \frac{r_1 r_2}{r_1 + r_2} s + \frac{2 r_1^2 \lambda}{(r_1 + r_2)(K + \coth s/2\lambda)}$$

where s is the distance between the electrodes and K is a constant which varies with the length of the electrode used. Cole has reported many measurements of resistivity of cell components[8]. The cytoplasmic resistivity of cells varies from 30-3000 ohm cm, with most mammalian cells having a resistivity of about 300 ohm cm. The membrane resistivity varies from 10^2 to 10^5 ohms/cm^2, with most cells falling in the 10^3 to 10^4 ohms/cm^2 range.

Electrical Impedance of Cells and Tissues

To this point, we have dealt only with the concept of cells and tissues as electrical resistances when a steady continuous current is applied to them. Further, if all the electrical energy applied to a biologic system is converted into heat, the system contains only resistances. However, electrical systems may, in general, store potential energy in capacities and kinetic energy in inductances. A thin, poorly conducting cell membrane may be expected to have "capacitance" (i.e., to act electrically as a capacitor). (It should be noted, however, that no recognized biologic mechanism exists in which cells or tissues act as inductances.) This property of biological capacitance becomes important when one considers the effects of other than steady current upon tissues, since in such a situation, we are no longer dealing with only an electrical resistance, but with an "impedance" as well. In this case, impedance may be defined as the opposition to the flow of an alternating current which is the vector sum of ohmic resistance plus additional resistance due to the capacitance effect of cell membranes, with the resistance afforded by the latter being called capacitative reactance. The equation for impedance may be expressed as follows:

Equation 12: $Z = \sqrt{R^2 + 1/\omega^2 C}$

Where Z is the impedance, R the ohmic resistance, ω the angular frequency of the applied electrical stimulus and C the capacitance. Thus, the impedance is equivalent to resistance with the application of a steady state current but includes the addition of the reactance term, $1/\omega C$. Readers not familiar with the derivation of this formula are referred to Stacy, et al. for an excellent explanation[58].

Tissue characteristics at low frequency are almost independent of membrane reactance and internal resistivity since at low frequencies cells function practically as non-conductors. At high frequencies, the membrane reactance and resistance become nearly negligible. Tissue behavior at intermediate frequencies is primarily a function of the membrane capacitance. Although the exact reason for the capacitive behavior of cell membranes at intermediate frequencies is not known, Cole has suggested that the Debye concept of dipoles may offer an explanation[8]. This concept states that any material having a dipole moment of its molecules can exhibit dielectric behavior which might vary with frequency because of the time required for rotation of the dipoles in an electrostatic field. At low frequencies, there is time for rotation of the dipoles and an equilibrium state between the orienting effect of the applied voltage and the disorienting effect of thermal agitation can be achieved. At intermediate frequencies, this state can be only partially achieved and at high frequencies, there is not time for any rotation or orientation of the dipoles.

Stacy, et al. note that measurements of the capacitance of membranes of different cells have shown that in most cells the value is quite constant with the characteristic value being about 1.0 microfarad per cm^2 of membrane surface[58].

Impedance Measurements of Various Organs of the Body

Although we have not yet begun the discussion of the physiological or psychological effects of electricity when it is applied to some part of the human body, it is obvious that when such electricity enters the body it may pass through many different types of tissues and organs. Thus, the current delivered to the body from some source is expressed by Ohm's Law, $I = V/Z$, if Z represents the overall impedance of the body. The value of the impedance is identical with the sum of the individual impedances of each tissue or organ the current traverses. Thus, $Z_{total} = Z\ (skin) + Z\ (subcutaneous\ tissue) + Z\ (muscle) + ...Z_x$.

If one is to have an understanding of the response of the human to the passage of electric current, it is thus necessary to have some knowledge of impedance measurements for many different biological materials since impedance to any particular current passing through the body will vary, not only with the nature of the current, but with the pathway taken by the current as it traverses the body. An excellent review of the studies making such measurements has been made by Geddes and Baker and a discussion of their review follows[30].

In the mammalian species, approximately 70% of the body weight is water, with 50% being intracellular fluid and about 20% being extracellular. The latter includes such fluids as blood, urine, the bile, cerebrospinal fluid, etc.. Inasmuch as all the body fluids are electrolyte solutions, they typically have rather low resistivities and, in the absence of cellular elements, can be expected to act electrically as resistors or, conversely, conductors. Table 15 gives resistivity figures measured in various studies for biological fluids which are relatively cell-free. It should be noted that, in general, the conductivity of these fluids increases as the temperature rises thus exhibiting a negative temperature coefficient of resistivity.

Table 15: The Resistivity of Body Fluids*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
C.S.F						
Human	64.6(64.0-65.2)	1 kc/s-30 kc/s	24.5	Not given	Radvan-Ziemnowicz, 1964	
Cat	65.7(65.5-66.1)	1 kc/s-30 kc/s	24.5	Not given	Radvan-Ziemnowicz, 1964	
Rabbit	55.9 aver.(51-62)	1 kc/s	39	2	Crile, 1922	
Bile						
Cow-pig	60	Audio	37	2	Osswald, 1937	
	78	Audio	20	2	Osswald, 1937	
	59	50 Mc/s	37	2	Osswald, 1937	
	76	50 Mc/s	20	2	Osswald, 1937	
Rabbit	66.2 aver.(61-72)	1 kc/s	39	2	Crile, 1922	
Amniotic fluid						
Sheep	65	1 kc/s	25	2	Unpublished	Measured after 2 days of refrigerated storage
	49	1 kc/s	37.5	2	Unpublished	
Urine						
Cow-pig	30	Audio	37	2	Osswald, 1937	
	39	Audio	20	2	Osswald, 1937	
Physiological solutions						
Saline	72	d.c.	18	4	Burger, 1943	
Saline 0.9%	57 aver.(56-58)	200-900 Mc/s	27	2	Schwan, 1953	
Tyrode	52	Not given	37	?	Freygang, 1955	
Saline 0.9%	70	1 kc/s	20	2	Unpublished by authors	
	50.5	1 kc/s	37.5	2	Unpublished by authors	
3 M KCL	4.28	1 kc/s	20	2	Unpublished by authors	
	3.26	1 kc/s	37.5	2	Unpublished by authors	
	3.85	—	23.5	—	Frank, 1959	
	3.70	—	38	—	Frank, 1959	

*From Geddes and Baker[30]

Continued next page

Table 15: The Resistivity of Body Fluids-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Saline 1%	55.5	—	23.5	—	Frank, 1959	
	50.0	—	38	—	Frank, 1959	
Saline 2M	7.14	—	23.5	—	Frank, 1959	
	5.88	—	38	—	Frank, 1959	

Table 16 presents resistivity figures for blood. Figure 23 demonstrates the negative temperature coefficient noted for human blood. From the previous discussion in this paper, it might be expected that resistivity of blood would vary with its cellular content. That such a variance does exist is shown by Figure 24 which illustrates the fact that as the cellular content of blood increases (i.e., as the hematocrit increases) its conductivity decreases. Figure 24 also illustrates that a difference in conductivity exists for flowing and stationary blood, with the later exhibiting a higher resistance. This difference becomes more marked as the cellular content of the blood is increased.

The resistivity values for cardiac muscles are listed in Table 17. It is obvious that considerable differences exist among the various measurements. The data derived by Rush may explain this variability[30]. In his study, resistivity was measured parallel and transverse to the direction of the muscle fibers. Transverse measurements were found to be about 2.2 times as great as measurements taken parallel with the fibers. The recorded measurements for human cardiac tissue are noted to be lower than that recorded for cardiac muscle of other mammalian species. Since the human studies were performed on post-mortem specimens, the lower resistivities found may fit with the view that after death, cell membranes lose their ability to maintain their insulating properties and ionic gradients.

Multiple measurements for resistivity of skeletal muscles are tabulated in Table 18. As is the case with measurements of cardiac muscle, the resistivity values are found to vary with the direction of current flow; i.e., whether the current is directed parallel with or transverse to the muscle fibers. Thus the ratio of transverse to longitudinal resistivities as based on the data in Table 18 is approximately 5 to 1.

Table 16: The Resistivity of Blood*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human blood	150	d.c.	40	4	Burger, 1960-61	
	155	20 c/s-5 kc/s	40	4	Burger, 1960-61	
	165 aver. (148-176)	1 kc/s	37	2	Rosenthal, 1948	Normal subjects
	137.8	1 kc/s	37	2	Rosenthal, 1948	34.4% hematocrit
	170.3	1 kc/s	37	2	Rosenthal, 1948	37.2% hematocrit
	169.1	1 kc/s	37	2	Rosenthal, 1948	40.2% hematocrit
	176.0	1 kc/s	37	2	Rosenthal, 1948	42.5% hematocrit
	131.2	1 kc/s	37	2	Rosenthal, 1948	43.9% hematocrit
	230.9	1 kc/s	37	2	Rosenthal, 1948	50.9% hematocrit
	199.8	1 kc/s	37	2	Rosenthal, 1948	55.6% hematocrit
	180.0	1 kc/s	37	2	Rosenthal, 1948	56.4% hematocrit (all calculated values)
	160	d.c.	37	4	Burger, 1943	
	154 aver. (of two methods)	120 kc/s	36.3 aver.	2 and 4	Molnar, 1953	Flowing venous blood
	200	d.c.	20	4	Burger, 1960-61	
	195	20 c/s-5 kc/s	20	4	Burger, 1960-61	
	230	d.c.	18	4	Burger, 1943	
	363	120 kc/s	1.3	2 and 4	Molnar, 1953	Flowing blood
Human plasma	63 aver. (61-67)	1 kc/s	37	2	Rósenthal, 1948	Normal subjects
	100	d.c.	18	4	Burger, 1943	
	70	d.c.	Body	4	Burger, 1943	
Dog blood	108	100 kc/s	Body	2	Kinnen, 1964	29% hematocrit
	118	100 kc/s	Body	2	Kinnen, 1964	33% hematocrit
	120	100 kc/s	Body	2	Kinnen, 1964	36% hematocrit
	129 and 158	100 kc/s	Body	2	Kinnen, 1964	40% hematocrit
	155	100 kc/s	Body	2	Kinnen, 1964	41% hematocrit
	153	100 kc/s	Body	2	Kinnen, 1964	47% hematocrit
	156-243	Inductorium	38	2	Galeotti, 1902	Measured within 1 min.
	207 aver. (185-230)	1 kc/s	Body	2	Kaufman, 1943	Approx. 50% hematocrit

*From Geddes and Baker[30]

Continued next page

Table 16: The Resistivity of Blood-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Dog serum	138 aver. (98-178)	1 kc/s	Body	2	Kaufman, 1943	
Cow blood	145	20 c/s-5 kc/s	38	4	Burger, 1960-61	
	131	d.c.	37	4	Burger, 1960-61	
Cow-pig blood	137 aver. (119-152)	Audio	37	2	Osswald, 1937	
	192 aver.	Audio	20	2	Osswald, 1937	
Cow blood	190	d.c.	20	4	Burger, 1960-61	
	180	20 c/s-5 kc/s	20	4	Burger, 1960-61	
	169.6 aver. (164.5-174)	1 kc/s	Room	2	Sigman, 1937	Stationary 70% cells
	164 aver. (159-168)	1 kc/s	Room	2	Sigman, 1937	Flowing at 15 cm/sec-70% cells
	271.75	1 kc/s	Room	2	Sigman, 1937	100% cells stationary
	249.75	1 kc/s	Room	2	Sigman, 1937	100% cells flowing-15 cm/sec
	116.15	1 kc/s	Room	2	Sigman, 1937	40% cells stationary
	114.65	1 kc/s	Room	2	Sigman, 1937	40% cells flowing-15 cm/sec
	80.75	1 kc/s	Room	2	Sigman, 1937	5% cells stationary
	80.75	1 kc/s	Room	2	Sigman, 1937	5% cells flowing-15 cm/sec
	196.5 aver.	1 kc/s	Room	2	Sigman, 1937	80% hematocrit-stationary
	189.25 aver.	1 kc/s	Room	2	Sigman, 1937	80% hematocrit flowing-15 cm/sec
	145.4 aver.	1 kc/s	Room	2	Sigman, 1937	60% hematocrit-stationary
	145.25 aver.	1 kc/s	Room	2	Sigman, 1937	60% hematocrit flowing-15 cm/sec
	91.5 aver.	1 kc/s	Room	2	Sigman, 1937	20% hematocrit-stationary
	91.35 aver.	1 kc/s	Room	2	Sigman, 1937	20% hematocrit flowing-15 cm/sec
Cow-pig blood	91 aver.	25-100 Mc/s	37	2	Osswald, 1937	
	133 aver.	25-100 Mc/s	20	2	Osswald, 1937	
	99 aver.	25-100 Mc/s	37	2	Osswald, 1937	

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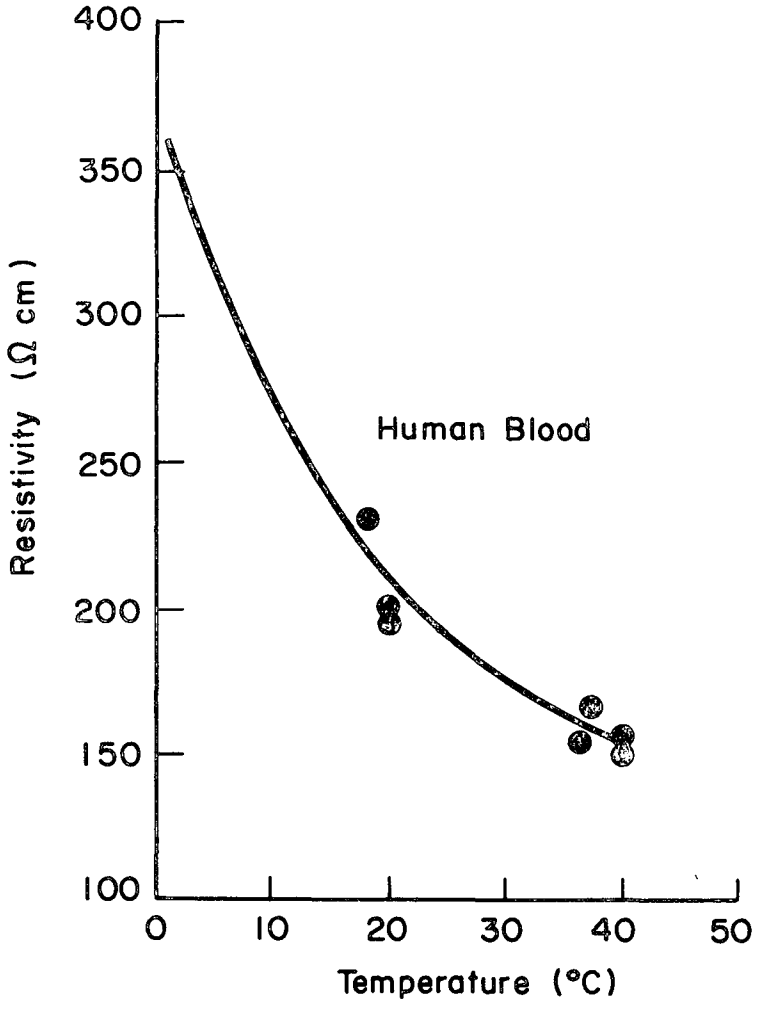
Table 16: The Resistivity of Blood-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Cow blood	89 aver. (80-96)	200-900 Mc/s	27	2	Schwan, 1953	
Cow plasma	65	20 c/s-5 kc/s	40	4	Burger, 1960-61	
Cow-pig serum	62.5	Audio	37	2	Osswald, 1937	
	83	Audio	20	2	Osswald, 1937	
Cow plasma	90	20 c/s-5 kc/s	20	4	Burger, 1960-61	
Calf serum	89.4	87 kc/s-4.52 Mc/s	21.6	2	Fricke, 1926	
Cow-pig serum	62.5	25-100 Mc/s	37	2	Osswald, 1937	
	83	25-100 Mc/s	20	2	Osswald, 1937	
Horse red cells	3890	1 kc/s	25	2	Philipson, 1920	Centrifuged and packed
	840	400 kc/s	25	2	Philipson, 1920	Centrifuged and packed
	410	1 Mc/s	25	2	Philipson, 1920	Centrifuged and packed
	285	2 Mc/s	25	2	Philipson, 1920	Centrifuged and packed
	232	3.5 Mc/s	25	2	Philipson, 1920	Centrifuged and packed
Rabbit blood	128 (117-136)	1 kc/s	39	2	Crile, 1922	
	129-176	Inductorium	39	2	Galeotti, 1902	

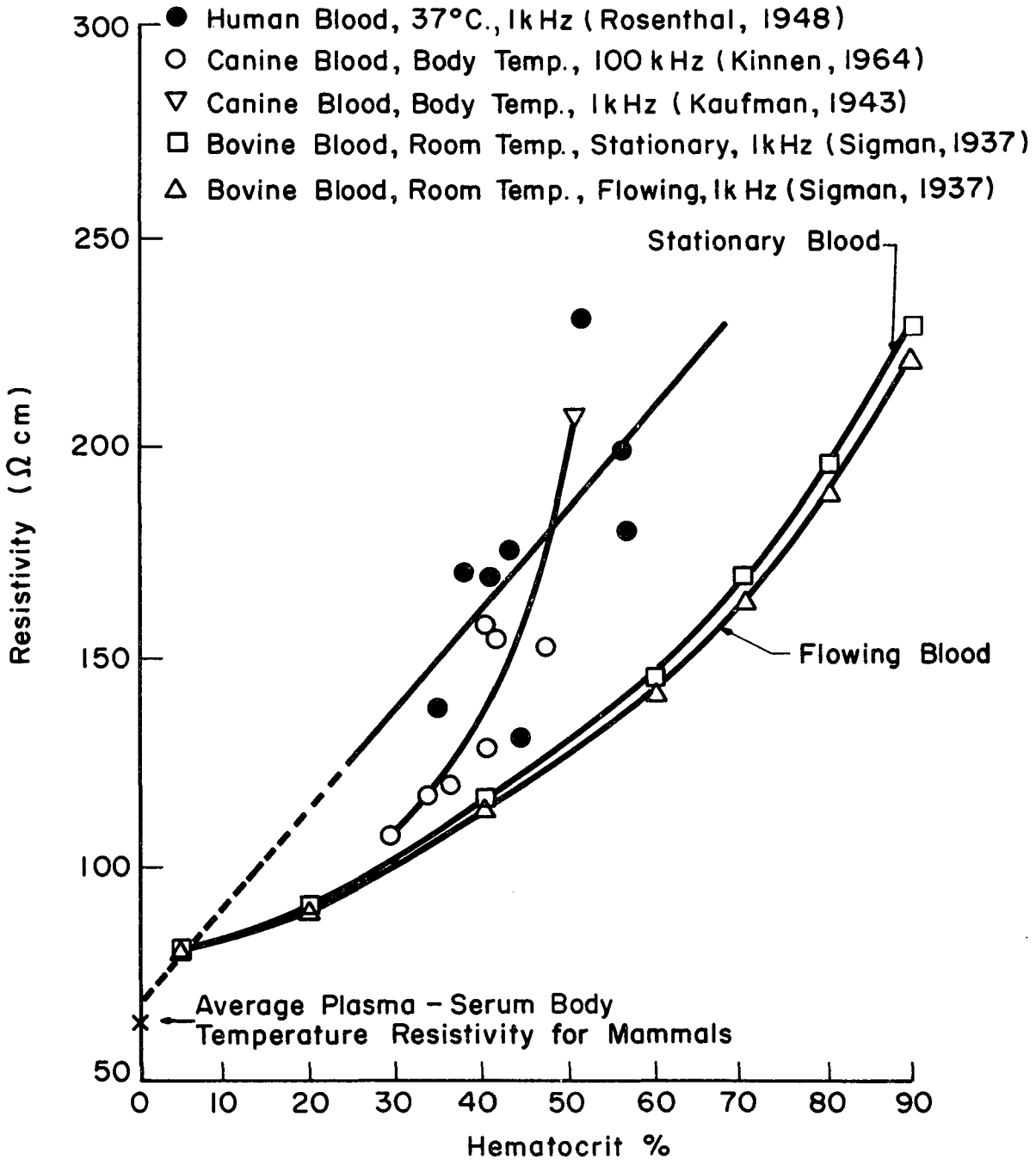
Figure 23*



Resistivity vs. temperature for human blood*

*From Geddes & Baker[30]

Figure 24*



Resistivity vs. hematocrit*

*From Geddes & Baker[30]

Table 17: The Resistivity of Cardiac Muscle*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	106 aver. (83-130)	200-900 Mc/s	27	2	Schwan, 1953	Autopsy material (aver. values)
	132	1 Mc/s	Near room temp.	2	Hemingway, 1932	2-3 hr. after death
Dog	563	d.c. pulse 0.1 sec	Body	4	Rush, 1963	Transverse to fibers
	252	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Parallel to fibers
	965 aver.	10 c/s	Body	2	Schwan, 1956-57	Anesthetized animal
	1250	10 c/s	Body	2	Schwan, 1955	Anesthetized animal
	925	100 c/s	Body	2	Schwan, 1956-57	Anesthetized animal
	1150	100 c/s	Body	2	Schwan, 1955	Anesthetized animal
	215 aver. (207-224)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized animal
	875 aver. (750-1000)	1 kc/s	Body	2	Schwan, 1956	Anesthetized animal
	825 aver. (700-950)	1 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	845	1 kc/s	Body	2	Schwan, 1956-57	Anesthetized animal
	600	10 kc/s	Body	2	Schwan, 1956-57	Anesthetized animal
	825 aver. (700-950)	10 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	456	100 kc/s	Approx. Body	2	Kinnen, 1964	Left ventricle
	1235	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
Dog-adult	1346	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	1170 aver.	Inductorium	18	2	Galeotti, 1902	Freshly extirpated
Dog	1368	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	1380	Inductorium	12	2	Galeotti, 1902	Freshly extirpated
Dog pericardium	419 aver. (405 and 434)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized animal

*From Geddes and Baker[30]

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Table 17: The Resistivity of Cardiac Muscle-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Rabbit	900 aver. (855-952)	1 kc/s	39	2	Crile, 1922	Author reports variability
	1252 aver.	Inductorium	18	2	Galeotti, 1902	Author reports variability

Table 18: The Resistivity of Skeletal Muscle*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	245	d.c.	37	4	Burger, 1960-61	Longitudinal
	240	100-1000 c/s	37	4	Burger, 1960-61	Longitudinal
	675	100-1000 c/s	37	4	Burger, 1960-61	Transverse
	110	1 Mc/s	Freshly excised	2	Hemingway, 1932	Between body and room temp.
	100 aver. (81-120)	200-900 Mc/s	27	2	Schwan, 1953	Autopsy material
Dog	965	10 c/s	Body	2	Schwan, 1956-57	Anesthetized
	1150 aver. (800-1500)	10 c/s	Body	2	Schwan, 1955	Anesthetized
	1075 aver. (850-1400)	100 c/s	Body	2	Schwan, 1955	Anesthetized
	800	100 c/s	Body	2	Schwan, 1956-57	Anesthetized
	1000 aver. (700-1300)	1 kc/s	Body	2	Schwan, 1955	Anesthetized
	643 aver. (575-711)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized
	830 aver.	1 kc/s	Body	2	Schwan, 1956-57	Anesthetized
	875 aver. (750-1000)	1 kc/s	Body	2	Schwan, 1956	Anesthetized
	760	10 kc/s	Body	2	Schwan, 1956-57	Anesthetized
	900 aver. (600-1200)	10 kc/s	Body	2	Schwan, 1955	Anesthetized
	1885	d.c. pulses-0.1 sec	Body	4	Rush, 1963	Anesth. spinal transverse
	2300	d.c. pulses-0.1 sec	Body	4	Rush, 1963	Anesth. spinal transverse
	205	d.c. pulses-0.1 sec	Body	4	Rush, 1963	Anesth. spinal longitudinal
	150	d.c. pulses-0.1	Body	4	Rush, 1963	Anesth. spinal longitudinal
	1040	Inductorium	38	2	Galeotti, 1902	Tongue longitudinal cut
	490	Inductorium	38	2	Galeotti, 1902	Tongue freshly extirpated

*From Geddes and Baker[30]

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Table 18: The Resistivity of Skeletal Muscle-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Dog-adult	472	Inductorium	24	2	Galeotti, 1902	Tongue
Dog-newborn	834	Inductorium	24	2	Galeotti, 1902	Tongue
Dog	1280	Inductorium	24	2	Galeotti, 1902	Transverse current
	408	Inductorium	24	2	Galeotti, 1902	Longitudinal current
	395	100 kc/s	Room?	2	Kinnen, 1964	Excised semitendinous
Dog-adult	485 aver.	Inductorium	18	2	Galeotti, 1902	Tongue
	984	Inductorium	18	2	Galeotti, 1902	Transverse current
	470	Inductorium	12	2	Galeotti, 1902	Tongue freshly extirpated
Dog	408	Inductorium	12	2	Galeotti, 1902	Longitudinal current
Dog-adult	1072	Inductorium	12	2	Galeotti, 1902	Transverse current
Cow and Horse	1000	2- c/s-10 kc/s	33	2	Burger, 1960-61	Random orientation
	300	20 c/s-5 kc/s	33	4	Burger, 1960-61	Longitudinal
	700	20 c/s-5 kc/s	33	4	Burger, 1960-61	Transverse
	550	20 c/s-5 kc/s	33	4	Burger, 1960-61	Random orientation
Cow-pig	1000	Audio	37	2	Osswald, 1937	Average values
	1110	Audio	20	2	Osswald, 1937	Average values
	124	50 Mc/s	37	2	Osswald, 1937	
	170	50 Mc/s	20	2	Osswald, 1937	
Rabbit	1800	20 c/s-1 kc/s	37	4	Burger, 1960-61	Transverse
	1750	20 c/s-1 kc/s	37	4	Burger, 1960-61	Random orientation
	125	20 c/s-1 kc/s	37	4	Burger, 1960-61	Longitudinal
	169 aver. (134-290)	1 kc/s	39	2	Crile, 1922	
	1243	Inductorium	18	2	Galeotti, 1902	Transverse current
	548	Inductorium	12	2	Galeotti, 1902	Longitudinal current
	1720	Inductorium	12	2	Galeotti, 1902	Transverse current

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Table 18: The Resistivity of Skeletal Muscle-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Guinea pig	1840	1 kc/s	25	2	Philipson, 1920	
	1130	10 kc/s	25	2	Philipson, 1920	
	725	20 kc/s	25	2	Philipson, 1920	
	595	50 kc/s	25	2	Philipson, 1920	
	435	100 kc/s	25	2	Philipson, 1920	
	310	200 kc/s	25	2	Philipson, 1920	
	183	600 kc/s	25	2	Philipson, 1920	
	158	1 Mc/s	25	2	Philipson, 1920	
	145	2.5 Mc/s	25	2	Philipson, 1920	
	1280	Inductorium	24	2	Galeotti, 1902	Transverse current

Since lung tissue contains varying amounts of air, it might be expected that resistivity values would vary considerably. In vivo studies suggest that this is, in fact, the case, with resistivity measured during maximum inspiration being two or three times that during maximum expiration. These data are shown in Table 19. Post-mortem studies, however, show fairly good agreement for mammalian species at body temperature and in the low frequency region.

Table 20 shows resistivity values for the kidneys of various mammalian species. The data suggest the possibility of a negative temperature coefficient of resistivity.

Resistivity figures are shown for liver, spleen and pancreas in Tables 21, 22 and 23 respectively. Data for spleen resistivity indicate a slightly negative temperature coefficient. Liver and spleen data are rather sparse and few conclusions can be drawn.

Data for the resistivity of nervous tissue are shown in Table 24. As in muscle tissue, where there are long well-defined fibers, the longitudinal and transverse resistivities vary considerably. In different nerve tissues, ratios of transverse to longitudinal resistivities are found to vary between 5.7 and 9.41. In addition, one would expect differences in the resistivities of white and gray matter of the brain when the histological structural differences are considered. Such is the case where comparisons have been made with the white matter having a resistivity about twice that of the gray matter.

Data for fat resistivity are shown in Table 25. It should be noted that there are no human data for the low frequency region.

Table 19: The Resistivity of Lung Tissue*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	161 aver. (137-190)	200-900 Mc/s	27	2	Schwan, 1953	Autopsy material
Dog	2390	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Peak inflation-anesth. animal
	1950	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Max. deflation-anesth. animal
	2170	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Average-anesth. animal
	1120	10 c/s	Body	2	Schwan, 1956-57	Anesthetized animal
	900-1600	10 c/s	Body	2	Schwan, 1955	Anesthetized animal
	1090	100 c/s	Body	2	Schwan, 1956-57	Anesthetized animal
	800-1500	100 c/s	Body	2	Schwan, 1955	Anesthetized animal
	1100	10 c/s-100 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	744-766	1 kc/s	Body	2	Kaufman, 1943	End inspiration anesth. animal
	1227-1367	1 kc/s	Body	2	Kaufamn, 1943	Super inflation-anesth.
	401	1 kc/s	Body	2	Kaufman, 1943	Deflation-anesthetized
	800-1300	1 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	1040	1 kc/s	Body	2	Schwan, 1956-57	Anesthetized animal
	750-1000	1 kc/s	Body	2	Schwan, 1956	Anesthetized animal
	950	10 kc/s	Body	2	Schwan, 1956-57	Anesthetized animal
	800-1200	100 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	1530	100 kc/s	Body	2	Kinnen, 1964	Full inspiration
	1345-2100	100 kc/s	Body	2	Kinnen, 1964	Mid inspiration
	1200	100 kc/s	Body	2	Kinnen, 1964	Complete expiration
	1720	Inductorium	24	2	Galeotti, 1902	Five min. after extirpation
Dog-adult	1636 aver.	Inductorium	18	2	Galeotti, 1902	
Dog	1840	Inductorium	12	2	Galeotti, 1902	
Dog-adult	1739	Inductorium	12	2	Galeotti, 1902	

*From Geddes and Baker[30]

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Table 19: The Resistivity of Lung Tissue-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Cow-pig	1250 aver.	Audio	37	2	Osswald, 1937	
	345 aver.	50 Mc/s	37	2	Osswald, 1937	
	500 aver.	50 Mc/s	20	2	Osswald, 1937	
Rabbit	1770 aver. (1410-1970)	1 kc/s	39	2	Crile, 1922	
	1864 aver.	Inductorium	18	2	Galeotti, 1902	
	2180 aver.	Inductorium	12	2	Galeotti, 1902	

Table 20: The Resistivity of Kidney Tissue*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	126	1 Mc/s	Near room	2	Hemingway, 1932	2-3 hours after death
	94 aver. (81-104)	200-900 Mc/s	27	2	Schwan, 1953	Autopsy material
Cow-pig	111	Audio	37	2	Osswald, 1937	
	119	50-100 Mc/s	37	2	Osswald, 1937	
	143	Audio	20	2	Osswald, 1937	
	147	50-100 Mc/s	20	2	Osswald, 1937	
	204	25 Mc/s	20	2	Osswald, 1937	
Dog	272	Inductorium	38	2	Galeotti, 1902	3 min. after extirpation
	600	100 kc/s	Body	2	Kinnen, 1964	
Dog-newborn	380	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
Dog-adult	241	Inductorium	18	2	Galeotti, 1902	
Dog-adult	252	Inductorium	12	2	Galeotti, 1902	
Dog-newborn	410	Inductorium	12	2	Galeotti, 1902	
Dog-newborn	376	Inductorium	12	2	Galeotti, 1902	Freshly extirpated
Guinea pig	449	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
	424	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
	396 aver.	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	702	Inductorium	18	2	Galeotti, 1902	
Rabbit	391	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	454 aver.	Inductorium	18	2	Galeotti, 1902	
	685 aver.	Inductorium	12	2	Galeotti, 1902	

*From Geddes and Baker[30]

Table 21: The Resistivity of Liver*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	298	1 Mc/s	Near room	2	Hemingway, 1932	2-3 hr. after death
	128 aver. (92-170)	200-900 Mc/s	27	2	Schwan, 1953	Autopsy material
Cow-pig	833 aver.	Audio	37	2	Osswald, 1937	
	192 aver.	25 Mc/s	37	2	Osswald, 1937	
	182 aver.	50 Mc/s	37	2	Osswald, 1937	
	164 aver.	100 Mc/s	37	2	Osswald, 1937	
	667 aver.	Audio	20	2	Osswald, 1937	
	250 aver.	25 Mc/s	20	2	Osswald, 1937	
	213 aver.	50 Mc/s	20	2	Osswald, 1937	
	200	100 Mc/s	20	2	Osswald, 1937	
Dog	700	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Anesthetized
	1100 aver. (1000-1200)	10 c/s	Body	2	Schwan, 1955	Anesthetized
	840	10 c/s	Body	2	Schwan, 1956-57	Anesthetized
	800	100 c/s	Body	2	Schwan, 1956-57	Anesthetized
	925 aver. (850-1000)	100 c/s	Body	2	Schwan, 1955	Anesthetized
	900	10 c/s-100 kc/s	Body	2	Schwan, 1965	
	900 aver. (800-1000)	1 kc/s	Body	2	Schwan, 1955	Anesthetized
	765	1 kc/s	Body	2	Schwan, 1956-57	Anesthetized
	875 aver. (750-1000)	1 kc/s	Body	2	Schwan, 1956	Anesthetized
	589 aver. (506-672)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized
	685	10 kc/s	Body	2	Schwan, 1956-57	Anesthetized
	775 aver. (700-850)	10 kc/s	Body	2	Schwan, 1955	Anesthetized
	600 aver. (300-900)	100 kc/s	Body	2	Kinnen, 1964	Anesthetized
	1070	Inductorium	38	2	Galeotti, 1902	3 min. after extirpation

*From Geddes and Baker[30]

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Table 21: The Resistivity of Liver-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Dog-newborn	3220	Inductorium	24	2	Galeotti, 1902	
Dog-adult	1010 aver.	Inductorium	18	2	Galeotti, 1902	
Dog	1460 aver.	Inductorium	12	2	Galeotti, 1902	
Dog-newborn	2530 aver.	Inductorium	12	2	Galeotti, 1902	
Dog-newborn	1447	Inductorium	12	2	Galeotti, 1902	
	1235 aver. (990-1639)	1 kc/s	39	2	Crile, 1922	Freshly extirpated
Rabbit	1100 aver. 1885, 3730 aver.	Inductorium	18	2	Galeotti, 1902	
Guinea pig	3700	Inductorium	38	2	Galeotti, 1902	
	3710	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
	2380	1 kc/s	25	2	Philipson, 1920	
	464	200 kc/s	25	2	Philipson, 1920	
	317	800 kc/s	25	2	Philipson, 1920	
	260	2 Mc/s	25	2	Philipson, 1920	
	225	3.5 Mc/s	25	2	Philipson, 1920	
	3860	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	1335	Inductorium	18	2	Galeotti, 1902	

Table 22: The Resistivity of Splenic Tissue*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	256	1 Mc/s	Near room	2	Hemingway, 1932	2-3 hrs. after death
Dog	885	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
	1053	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
Dog-adult	1010 aver.	Inductorium	24	2	Galeotti, 1902	
	1040 aver.	Inductorium	18	2	Galeotti, 1902	
	1196 aver.	Inductorium	12	2	Galeotti, 1902	
Dog	1178	Inductorium	12	2	Galeotti, 1902	Freshly extirpated
Cow-pig	715 aver.	Audio	37	2	Osswald, 1937	
	137 aver.	50 Mc/s	37	2	Osswald, 1937	
	120 aver.	100 Mc/s	37	2	Osswald, 1937	
	833	Audio	20	2	Osswald, 1937	
	175	25 Mc/s	20	2	Osswald, 1937	
	156	50 Mc/s	20	2	Osswald, 1937	
	147	100 Mc/s	20	2	Osswald, 1937	

*From Geddes and Baker[30]

Table 23: The Resistivity of Pancreatic Tissue*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Cow-pig	770 aver.	Audio	37	2	Osswald, 1937	
	185 aver.	25-100 Mc/s	37	2	Osswald, 1937	
	625 aver.	Audio	20	2	Osswald, 1937	
	250 aver.	25-100 Mc/s	20	2	Osswald, 1937	

*From Geddes and Baker[30]

Table 24: The Resistivity of Nerve Tissue*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Brain						
Cow-pig	588 aver.	Audio	37	2	Osswald, 1937	
	222	25 Mc/s	37	2	Osswald, 1937	
	196 aver.	50 Mc/s	37	2	Osswald, 1937	
	185 aver.	100 Mc/s	37	2	Osswald, 1937	
	910 aver.	Audio	20	2	Osswald, 1937	
	322 aver.	25 Mc/s	20	2	Osswald, 1937	
	244 aver.	50 Mc/s	20	2	Osswald, 1937	
	232 aver.	100 Mc/s	20	2	Osswald, 1937	
Rabbit cerebrum	570 aver. (521-725)	1 kc/s	39	2	Crile, 1922	
Rabbit cerebellum	730 aver. (610-855)	1 kc/s	39	2	Crile, 1922	
Cat-internal capsule	800 aver.	20 c/s-20 kc/s	Body	3	Nicholson, 1965	Transverse to fibers-anesth.
	85 aver.	20 c/s-20 kc/s	Body	3	Nicholson, 1965	Along fibers-anesth.
Rabbit cortex	321	5 c/s	Body	4	Ranck, 1963	Anesthetized
	230	5 kc/s	Body	4	Ranck, 1963	Anesthetized
	208 ± 6	1 kc/s	Body	3	Van Harreveld, 1963	Anesthetized animal
Rabbit white matter	957 (approx.)	1 kc/s	Body	3	Van Harreveld, 1963	Anesthetized animal
Rabbit cerebellum	662-794	1 kc/s	39	2	Crile, 1922	
Rabbit cerebrum	505-621	1 kc/s	39	2	Crile, 1922	
Rabbit spinal cord	576 aver. (386-863)	1 kc/s	39	2	Crile, 1922	
Rabbit cerebral (gray)	438 aver.	1 kc/s	39	2	Crile, 1922	
Rabbit cerebral (white)	746 aver.	1 kc/s	39	2	Crile, 1922	

*From Geddes and Baker[30]

Continued on next page

Table 24: The Resistivity of Nerve Tissue-Continued

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Cat cortex	222 ± 9	Square pulses 0.3-0.7 m sec.	37	4	Freygang, 1955	Anesthetized animal
Cat white matter	344 (approx.)	0.3-0.7 m sec	37	4	Freygang, 1955	
Cat-spinal cord	138-212	5-10 c/s	Body	4	Ranck, 1965	Longitudinal
	1211	5-10 c/s	Body	4	Ranck, 1965	Transverse

*From Geddes and Baker[30]

Table 25: The Resistivity of Fat*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	2180	1 Mc/s	Freshly excised	2	Hemingway, 1932	Between body and room temperature
	1500-5000	200 Mc/s	27	2	Schwan, 1953	Autopsy material
	1300-4000	400 Mc/s	27	2	Schwan, 1953	Autopsy material
	1100-3500	900 Mc/s	27	2	Schwan, 1953	Autopsy material
Dog	1500-3000	10 c/s-100 kc/s	Body	2	Schwan, 1965	
	2500	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Anesthetized animals
	2006 aver. (1808-2205)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized animals
	1000-3000	100 kc/s	Body	2	Kinnen, 1964	
	1500-5000	1 kc/s	Body	2	Schwan, 1956-57	Anesthetized
	3000 aver. (1500-5000)	1 kc/s	Body	2	Schwan, 1956	Anesthetized
Cow-pig	2500 aver.	Audio	37	2	Osswald, 1937	
	2000 aver.	25-100 Mc/s	37	2	Osswald, 1937	
	3850 aver.	Audio	20	2	Osswald, 1937	
	2780 aver.	25-100 Mc/s	20	2	Osswald, 1937	

*From Geddes and Baker[30]

Table 26: The Resistivity of Bone*

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human (thorax)	16,000	Low	Not given	Not given	Lepeschkin, 1951	(ECG spectrum)
Human	1800	1 Mc/s	Freshly excised	2	Hemingway, 1932	Between body and room temperature
Cow-pig	4550 aver.	Audio	37	2	Osswald, 1937	
	3700 aver.	25-100 Mc/s	37	2	Osswald, 1937	
	6250 aver.	Audio	20	2	Osswald, 1937	
	5000 aver.	25-100 Mc/s	20	2	Osswald, 1937	

Although figures for bone resistivity are given in Table 26, Geddes and Baker point out that such data should be viewed with reservation[30]. This is so if it is recognized that of all the tissues in the body, the resistivity values for bone are the most variable, since bone at different locations in the body is of such varied composition. Two examples can be given. The skull consists of two dense poorly conducting bony tables separated by a spongy region containing blood which is, as previously noted, a good conductor. Likewise, the long bones are poorly conducting tubes filled with highly conducting vascularized marrow.

From the general tabulation of data on resistivities, certain reasonable estimates can be made for the resistivities of specific human organs. These figures are shown in Table 27. In those cases where human data are not available, animal data are presented, and the appropriate cautions involving the extrapolation of animal data to man should be considered.

When considering the action of electricity applied to the body it is also of some importance to attempt to determine the resistivity of certain body segments since this is, in fact, the manner in which the current may pass through the body. However, caution must be used in this approach. Implied in the determination of resistivity is the existence of a known current-density distribution between the electrodes which are being used to measure the potential. In non-uniform conductors such as a body segment, current density distribution will likely not be uniform. Thus, slight alterations in electrode positions may result in large changes in measured resistivity. Nonetheless, attempts to estimate these figures do have some importance and such values are shown in Table 28.

2

Table 27: Estimates of Resistivity for Specific Organs*

Substance	Resistivity	Frequency	Temp.	Comments
Blood	148-176 ohm-cm.	"low"	Body	Normal Hct.
Plasma & Serum	66 ohm-cm.	"low"	Body	
Cardiac Muscle (Canine)	750 ohm-cm.	"low"	Body	Randomly oriented fibers
Skeletal Muscle (Canine)	950 ohm-cm.	"low"	Body	Randomly oriented fibers
Lung (Canine)	1275 ohm-cm.	"low"	Body	Average without regard to respiratory phase.
Kidney (Various Mammals)	370 ohm-cm.	"low"	Body	Sparse data
Liver (Canine)	817 ohm-cm.	"low"	Body	Mammalian results scattered
Spleen (Canine)	885 ohm-cm.	"low"	Body	Exhibits negative temperature coefficient
Brain (Cow, Pig and Rabbit)	580 ohm-cm.	"low"	Body	Average without regard to fiberorientation or gray or white matter.
Fat (Cow, Pig and Dog)	2720 ohm-cm.	"low"	Body	Averaged data

*Adapted from Geddes and Baker[30]

Table 28: The Resistivity of Body Segments*

Substance	Resistivity (-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human						
Arm	160	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Corrected for bone and Fat
	470	d.c.	Body	4	Burger, 1943	Transverse
Forearm	230	d.c.	Body	4	Burger, 1943	Longitudinal
	330	d.c.	Body	4	Burger, 1943	Geometric mean
Fingers and hand	280	d.c.	Body	4	Burger, 1943	
Finger	235	d.c.	Body	4	Burger, 1943	Current along finger
Neck	280	d.c.	Body	4	Burger, 1943	
Trunk	415	d.c.	Body	4	Burger, 1943	Along axis of body
Head	840	d.c.	Body	4	Burger, 1943	Trans-temporal
Head (Scalp)	230	d.c.	Body	4	Burger, 1943	Closely spaced electrodes
	455	d.c.	Body	4	Burger, 1943	Maximum inspiration
	375	d.c.	Body	4	Burger, 1943	Maximum expiration
Thorax	463	d.c. pulses 0.1 sec	Body	4	Rush, 1963	
Dog						
	445	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Intact thorax
	281	d.c. pulses 0.1 sec	Body	4	Rush, 1963	Shell-less heart and lungs

*From Geddes and Baker[30]

Kouwenhoven has suggested that the minimum value of body resistance (for the hand to foot pathway) is about 500 ohms[28]. Most of this resistance is in the extremities, where a large portion of the total cross-section is taken up by the bones. Thus, in estimating the total resistance offered to electrical current flow in the body, the resistance of the trunk is considered to be small compared to that of the limbs.

Only minimal information is available on the resistivity of the teeth. Mumford, using Ag-$AgCl_2$ electrodes, has measured the <u>in vitro</u> resistivity of enamel in 13 specimens and has found a mean value of 45 ohm cm[51]. Similar measurements for dentine, measured along the lines of the dentinal tables revealed a value of 330 ohm cm.

In the discussion of their review paper, Geddes and Baker make several comments which are of such importance that they should be carefully considered[30]. First, most biological structures are composed of cells and hence exhibit different properties in different directions because of cellular orientation. Secondly, variations in biological material related to altered physiology of the mammal - due to environmental changes or disease - may be expected to exist. The size of the sample of tissue or organ being examined may be important and, in general, data from small samples of tissue should be avoided, since the nature of cellular structure will become an important factor in the resistivity measurement. Further, when physiologically active structures are being measured, significant resistance changes may be observed during depolarization and repolarization of the structure.

Conspicuously absent to this point has been any mention of the electrical resistance of the skin. The skin is unique as an organ in its role as an interface

with the external environment. Because of this role, it is most typically through the skin that electric energy enters the body. Certain exceptions do exist to this situation, as with the case of implanted electrodes or in situations where mechanical devices, such as venous catheters, have been passed through the skin and thus potentially offer a direct pathway for the transmission of an electric current into the body.

The resistance or impendance of the skin lies primarily in the epidermis, where the normally dry, horny layer of stratum corneum acts as a poor conductor. Thus, any factor affecting the epidermis may be expected to alter skin resistance. An example of this is the variation in skin resistance noted on different parts of one body. Resistance is normally lowest in those areas of the body where the skin is "thin" - e.g., the axillae, the popliteal fossae, etc. - and may be only 1K to 2K ohms. It is highest in thick calloused skin areas and may be 70K to 100K ohms or more[38].

Skin resistance is lowered by moisture, sweat gland activity or by the application of a conducting paste between the skin and an electrode. Kouwenhoven has pointed out that if the skin is wet, its resistance may drop to 1/100th of its usual value[38]. Thomas and Korr examined the quantitative relationship between the number of active sweat glands and electrical resistance of the skin[60]. They noted that conductance varies approximately linearly with increasing or decreasing numbers of active sweat glands. The conclusion was reached that each active gland contributed a conduction pathway electrically analogous to adding a small resistance in parallel to other sweat gland resistances. Further, small variations in slope and intercept on rising and falling curves noted during measurements involving increasing and decreasing sweat gland activity were felt to be related to hydration of nonsudorific conduction pathways.

If the structural integrity of the epidermis is altered, as by cuts, abrasions or by burning, the skin resistivity will fall. This fact is used to advantage when the skin is abraded prior to the application of an electrode. (See Figure 25.)

With the use of skin electrodes, both the pressure with which the electrode is applied (see Figure 26) and the area of electrode contact with the skin affect measurements of skin resistivity.

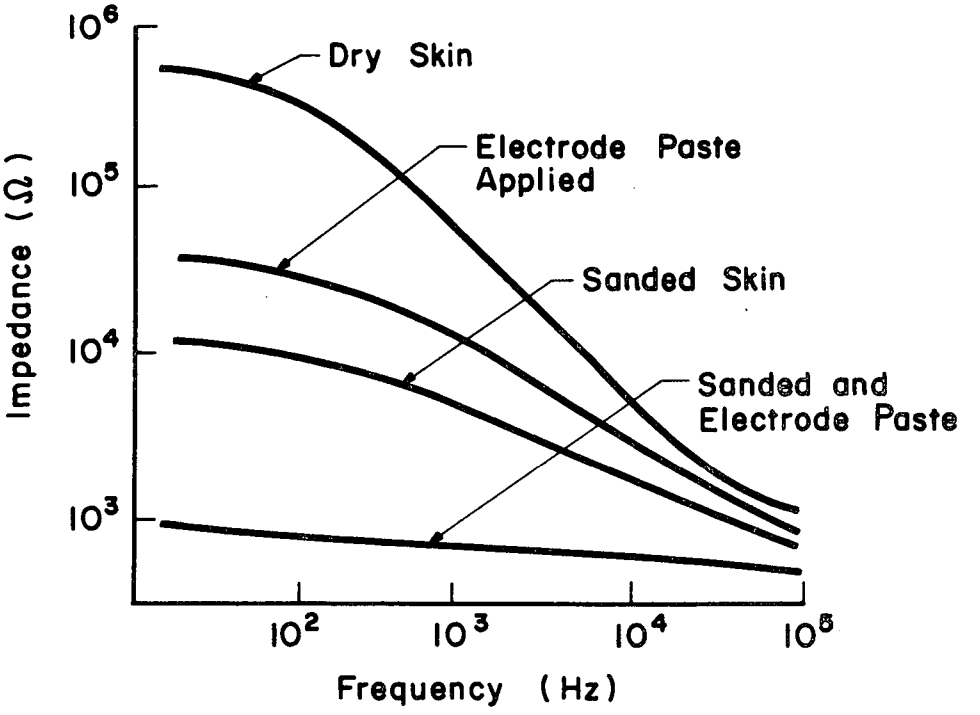
An example of the effect of electrode sizes on measurements of skin resistivity is given in the study reported by Thompson[61]. The study was performed on 70 subjects - 28 women and 42 men. The subject's left hand was immersed to the wrist in a weak saline solution. Four types of electrode contacts were made with the right hand. First, tapping a metallic surface with the tip of the forefinger; second, pinching a metallic conductor with the thumb and forefinger; third, gripping a long metal rod 1 inch in diameter; fourth, immersing the hand in salt water to the wrist. Table 29 gives the results of the study. It should be noted that the resistance is reported as average "body" resistance. Since under the conditions of the experiment the internal body resistance would not be expected to change, the variations reported reflect the changes in resistance at the entrance point of the current through the skin.

Table 29: Effects of Surface of Skin-Electrode Contact on Measurements of Skin Resistance*

Type of Contact	Avg. Body Resistance (Kohms)			Avg. Voltage Drop (Volts)		
	Women	Men	All	Women	Men	All
Tap	43.7	33.4	37.5	11.5	13.2	12.5
Pinch	14.1	13.9	14.0	7.0	10.6	9.2
Grip	7.4	7.4	7.4	6.0	7.6	6.9
Immersed	1.7	1.4	1.5	1.5	3.0	2.3

*From Thompson[61]

Figure 25*

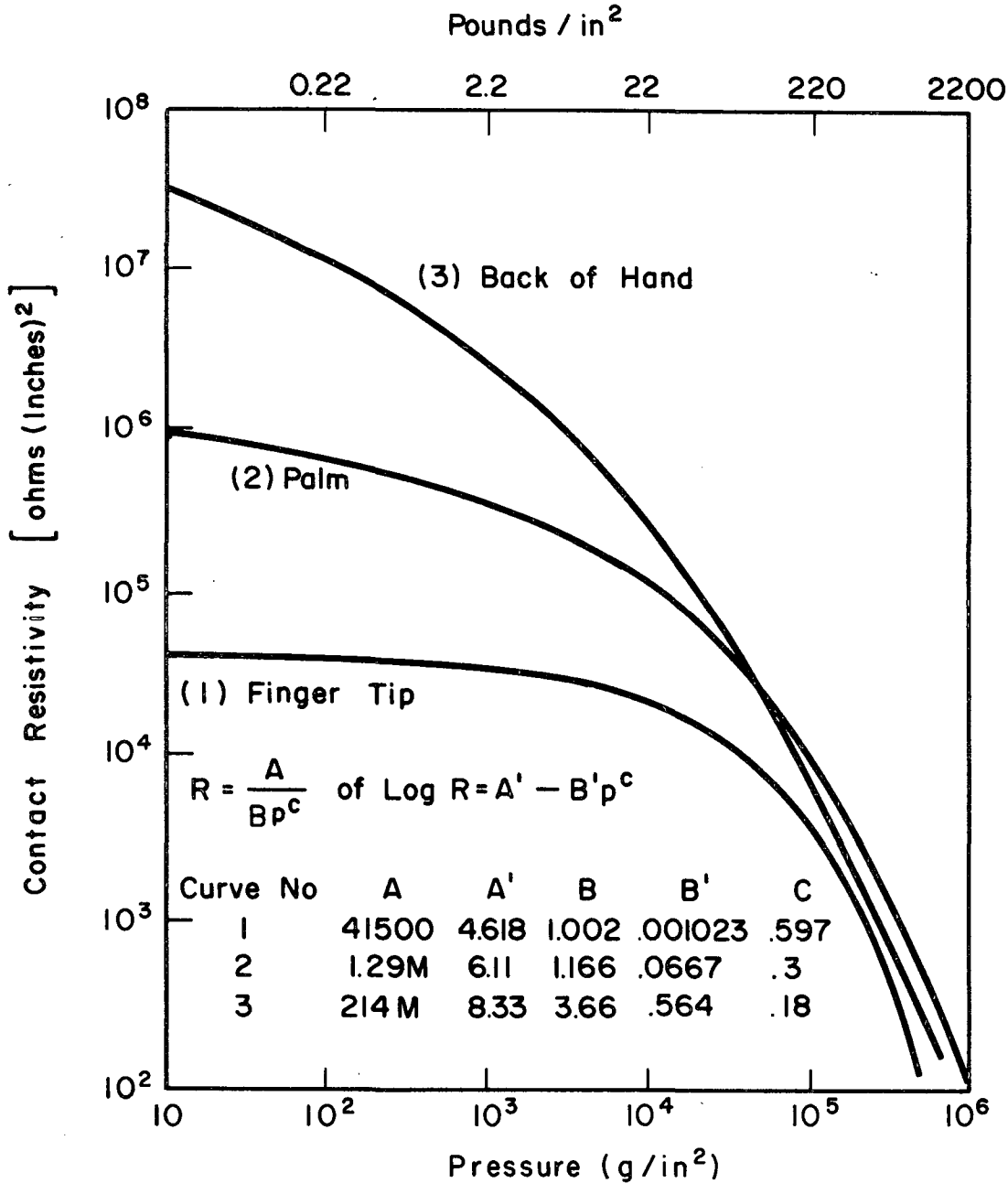


An Example of the Variation of Skin Impedance with Frequency and Condition of Electrode-Skin Contact.*

*From Burns[6]

Figure 26*

Variables Controlling Skin to Electrode Contact



Relation Between Pressure and Resistivity for the Contact of Dry Human Skin to Metal.*

*From Morse [49]

Further, it should be kept in mind that the resistance of the skin varies with the type of current being applied. Thus, responses may vary not only between direct current and alternating current, but with different frequencies of alternating current as well. (Figure 25.)

It has been suggested that racial differences in skin resistance may exist. Johnson and Corah reported findings from two separate laboratories using different measurement techniques, different electrodes and different aged subjects[37]. In both studies, skin resistance was found to be greater for Negroes than for Caucasians. The results of these studies are shown in Table 30.

Table 30: Racial Variations in Skin Resistance*
(All Resistances in Kohms)

	St. Louis Study				San Diego Study			
	Caucasian		Negro		Caucasian		Negro	
		Mean R		Mean R		Mean R		Mean R
Male	#65	170.75	#22	210.09	Male #16	171.	#16	373.
Female	#55	168.94	#32	309.93	Female #5	171.	#5	373.

*From Johnson and Corah[37]

The authors concluded that skin color itself was not the important variable, since the melanin is located in the basal layers. They suggested that the differences were either because of a thicker stratum corneum in Negroes or possibly because of differences in active eccrinesweat glands between the two races. Another study, however, has pointed out that racial difference in skin resistance exist which are not correlated with the amount of sweating[54].

Slyn'ko performed an investigation of the electrical conductance of the skin during brief hypoxia[57]. Experiments conducted on rabbits using low frequency,

low voltage alternating current showed that brief general or localized hypoxia does not produce noticeable changes in the electrical conductance of skin which has no sweat glands or malfunctioning ones. It was also observed that changes in skin temperature and electrode temperature caused changes in skin conductivity of about 2.6% per degree Centigrade.

SUMMARY

When an electric current enters and passes through the body, the electrical characteristics of the entrance site and of the tissues in the pathway taken by the current must be considered. Thus, different responses are to be expected to direct current and alternating current as well as to different frequencies of alternating current. Further, variations of individual responses, be these physiological or psychological, must be expected. Within these limitations then, general statements can be made regarding certain human responses to electrical stimuli.

The first physiological response to an electric current can usually be regarded as the perception of the current. For perception through the hand, Dalziel and Mansfield suggested that with direct current, about 5 mA is perceptible, while a current of less than 1 mA is perceptible with 60 Hz alternating current[20]. Lower figures were reported by Carter and Coulter, suggesting that for direct current, 0.2 - 0.3 mA is perceptible and that nearly similar levels of alternating current at 100 Hz are perceptible[7]. Using trans-chest electrode and neck-abdomen electrode arrangements, Geddes el al. found responses to alternating current in fair agreement with those levels reported by Dalziel[31].

Somewhat lower figures for direct current perception were suggested by Green[34]. (See Figure 2). Conrad et al. have pointed out the time dependency of a response to direct current[11].

There is general agreement that for alternating current as the frequency increases the threshold for perception increases. There is, however, little

difference in responses between 60 Hz and 400 Hz. It also is generally agreed that as the area of contact with the source of current increases, the threshold increases.

Minimal evidence suggests that hypoxia does not significantly alter sensation thresholds. Further, the threshold does not appear to be altered significantly by changes in skin temperature, unless rather drastic temperature changes occur.

The problem of defining pain has previously been discussed. Thus, it is to be expected that studies to evaluate "pain" can only suggest some range of responses.

Using a "pain prick" sensation as the subjective response to be called painful, Notermans reported levels for alternating current quite close to those levels previously discussed as sensation thresholds[52]. He also observed that as an impulse duration increased, the pain threshold fell. Measurement of pain thresholds by Plutchik and Bender suggested slightly higher current levels than those reported by Notermans (approximately 1.0 mA as opposed to 0.5 mA) but still within the ranges previously mentioned as "sensation" thresholds[54].

More generally accepted levels for the pain threshold are those suggested by Lee, based upon data from Kouwenhoven and Milnor, Dalziel and Morse[28]. He suggested a range of 3 to 10 mA as annoying or painful. This range is in agreement with the data of Farmer[27] at one end and with the data of Davidson and McDougall[22] at the other.

The threshold for the induction of muscular contraction by electric current has been studied extensively by Dalziel who has defined the "let-go" current as that current above which a man cannot voluntarily release his contact. Defining a "reasonably safe current" as the let-go current which 99½% of a large group of subjects can release by using muscles directly affected by that current, Dalziel established 62 mA DC for men and 41 mA DC for women as reasonably safe currents[21]. Corresponding values for 60 Hz AC are 9 mA for men and 6 mA for women. The values for alternating current are frequency dependent, tending to increase as the frequency increases from 60 Hz. However, the rate of increase with increasing frequency is slow between 60 and 500 Hz.

The nature of the study demands that most investigations of the production of ventricular fibrillation by electric current be performed on animals. Ferris et al. performed extensive studies on different animal species and observed that the threshold current to produce ventricular fibrillation was related to the body and heart weight[26]. Based on animals comparable in size to man, it was suggested that (with 60 Hz AC, for a duration of 1 or more seconds with a current path between an arm and a leg) a current of 100 mA would produce ventricular fibrillation. The threshold for ventricular fibrillation also alters with frequency. (See Figure 20). Further, the duration of the shock is important, since for short shocks (e.g., less than 1 sec), the shock must occur during the sensitive phase of the heart cycle.

An extensive analysis of the problem was performed by Dalziel who derived a formula to predict the production of ventricular fibrillation in ½% of a large group of normal men; i.e., $I\ (\tfrac{1}{2}\%) = 165/\sqrt{T}$ mA, where T is the time of

current flow in seconds and assuming a "standard" 70 Kg man[13]. Further, Dalziel has suggested that the ratio of fibrillating current for DC to AC is about 5 to 1. Further discussion of the derivation of Dalziel's formula is presented in the text of this paper. Numerous studies on the production of ventricular fibrillation by the application of an electric current either directly to the heart or reaching the heart through a catheter indicate that in such cases only very small amounts of current produce fibrillation. Thus, it has been suggested that 60 Hz shocks are 500 to 5000 times more dangerous when delivered directly to the heart, rather than to the body surface[36].

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