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Thermal Reflex Sweating
in Normal and Paraplegic Man

By

Russell C. Seckendorf

A Dissertation Submitted to the
Faculty of the Graduate School of
Loyola University in Partial
Fulfillment of the Requirements for
the Degree of Doctor of Philosophy

February

1959

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BIOGRAPHY

Russell Charles Seckendorf was born in Brooklyn, New York, on October 23, 1926. He received his elementary education in the public school system of Albany, New York and graduated from the Christian Brother's Academy of Albany in 1944.

The same year he entered the United States Army in which he served for 27 months.

In 1946 he enrolled at Siena College in Loudonville, New York. He pursued a course of study with a major in biology and a minor in chemistry. He was awarded a Bachelor of Science degree in June 1949.

In September of the same year he entered a program of graduate study toward a degree of Master of Science in Physiology at St. Louis University in St. Louis, Missouri. He was awarded said degree in July 1951. He remained at this University until 1952.

In August of 1952 he moved to Philadelphia, Pennsylvania where he accepted a position as Instructor in Physiology at Temple University Dental School. Concurrently, he entered a part-time program of graduate study in Physiology at Jefferson Medical College in Philadelphia. He continued in this dual capacity until March 1957. At that time, he moved to Chicago to begin a program of study towards the degree of Doctor of Philosophy in Physiology at Loyola University. To date he has been fulfilling the requirements for this degree.

INTRODUCTION

A study of sweating responses from regional skin areas in man has been made by several investigators (1, 2, 3, 4 & 5). These studies established the existence of regional differences in the sweating rates. However, Randall (6, 7) was the first to elucidate the pattern of these regional differences. In his first investigation of the problem (6) Randall observed, during thermal equilibrium studies with an ambient temperature just above the sweating threshold, that sweating was confined to the most inferior portions of the body. At higher ambient temperatures, sweating responses spread rostrally in an orderly sequence until all areas exhibited sudomotor activity. In a detailed analysis of this phenomenon Randall et al. (7, 8) established that when the entire body of normal man is exposed to a progressive elevation of environmental temperature, thermal sweating is consistently recruited first on the lowermost portions of the body (dorsum of the foot, calf) with progressive recruitment cephalad to ultimately include all regional areas. Randall et al. (9) found that the same general pattern of recruitment obtained if only the upper portion of the body was heated. These studies refuted the opinion that human sweating always appears universally over the entire body (10, 11).

Although heating only half of the body surface brings about recruitment of sweating of all regional areas, it seemed reasonable to assume that heating a

very small fraction of the body surface would not elicit recruitment of all areas. Between these two fractions there probably exists a critical quantity of skin surface that must be heated, to a given level over a particular time, before recruitment is complete. If such an hypothesis were valid, heating a subminimal area for any given set of conditions would recruit no sweating or sweating on limited areas of the body.

It is an important function of these investigations to test the validity of this hypothesis and to study the relationship between the area heated and the areas on which sweating is recruited.

Examination of Randall's work (7) reveals that recruitment frequently started before a rise in body temperature occurred and in many instances when body temperature was falling. Randall was inclined to the opinion that the recruitment of these sudomotor responses was related to sensory stimulation by heat. It seemed unlikely that initiation of the response by a rise in hypothalamic temperature could occur concurrently with a fall in body temperature.

According to present concepts, thermoregulatory sweating is effected in two ways: (1) blood at elevated temperatures perfuses the hypothalamus and stimulates thermoregulatory centers, and (2) afferent nerve impulses, arriving from peripheral receptors, activate the same centers. The operation of the first mechanism has been proved beyond doubt. Ranson and his associates (12, 13 & 14) demonstrated this function of the hypothalamus and showed the thermolytic areas to be situated in the anterior portion (15). With the hypothalamus intact, thermoregulatory sweating is well maintained in spite of experimental destruction of higher centers. Clinical studies in which specific

lesions have been anatomically demonstrated offer further conclusive evidence (16, 17, 18 & 19). The efferent pathways through the lower brain stem and spinal cord to the sympathetic outflow are not clearly understood, although several authors (20, 21 & 22) have contributed to an anatomical description.

Afferent pathways for reflex thermal sweating are not known. Neither have the peripheral sensory receptors been satisfactorily defined. Until recently the afferent receptor was considered to be the end organ of Ruffini (23) but this was primarily an assumption unsupported by facts. Weddell et al. (24, 25 & 26) have shown that encapsulated endings are probably not those associated with thermal reception and that the true sensory ending is probably unencapsulated. Also, it has been demonstrated that for any given area the sensation of warmth and the onset of sweating are not related (9).

Although the anatomical nature and spatial position of the peripheral receptor is unknown, it is clear that afferent nerve impulses impinge upon the central nervous system and cause reflex sweating. Randall et al. (27, 28) observed that if one limb is heated with its circulation occluded, reflex sweating occurs. This has been thoroughly confirmed by Isekutz et al. (29). Also, Kuno (30) found that cooling an extremity with its circulation occluded causes inhibition of sweat outbreak on other areas. Although these studies clearly demonstrate that reflex sweating occurs, they do not demonstrate the extent, or for that matter, the actual participation of the hypothalamus in reflex sweating.

The recruitment patterns of Randall (7, 9) reveal cyclic activity of the sweat glands within a regional area as well as a cyclic response among the

various sweating areas. The cycles on different areas may be in or out of phase. The process of recruitment is regular, and if it is controlled by the hypothalamus, one must imagine a system in which the hypothalamus discharges differentially to each of the separate cutaneous areas. On the other hand, mediation of thermoregulatory sweating could occur at spinal levels through facilitation by sensory impulses impinging upon them from peripheral receptors. Variations in threshold of spinal centers would account for the successive recruitment.

Classical teaching has held, however, that hypothalamic influence is necessary for thermal sweating to occur (31, 32 & 33), and several workers (34, 35, 36, 37 & 38) have reported that in paraplegia thermal reflex sweating does not occur below the level of spinal transection. This level is not that of the structural injury to the cord, but rather that lowermost postganglionic sympathetic connection with uninjured proximal portion of the central nervous system. The early and outstanding contributions of Head and Riddoch (34) are often quoted in support of the concept that thermoregulatory sweating does not occur on those areas served by the isolated spinal cord. However, this work did not involve critical observations on the thermoregulatory responses. Moreover, all of the patients studied were in a debilitated state and none had recovered from the post-shock state of hyper-reflexia.

Relatively recent workers (35, 36, 37 & 38) have reinforced the concept that thermoregulatory sweating does not occur below the level of transection. All of these later investigators studied paraplegics who had completely recovered from the generalized mass reflex response as well as chronic hyper-

reflexia. They all used either the quinazarin test of Guttman (39) or the starch-iodine technique of Minor (40).

It is well recognized that reflex sweating may occur below the level of the lesion in paraplegia during the mass reflex and under conditions of visceral stimulation such as bladder or rectal distention (34, 41 & 42). Since such visceral reflex sweating does occur, it is obvious that the spinal cord is capable of mediating a sweating reflex and that the efferent limb of the reflex arc, as well as the sweat glands, are capable of functioning. Also, it seems reasonable that the afferent limb of the thermal sweating reflex is intact. It appears then, that all of the necessary components for thermal spinal reflex sweating are present. It was felt that the inability of previous investigators to demonstrate such sweating was due to an inadequate stimulus or improper recording techniques.

A careful and thorough study of thermal sweating in paraplegic patients comprises an important portion of the current study.

MATERIALS AND METHODS

1. Climate Chamber

In all studies a climate chamber was employed that permitted control of environmental temperature between 18° and 70°C. The chamber was approximately 8 feet long, 6 feet wide, and 7 feet high. The door, walls and ceiling were constructed of a double layer of $\frac{1}{2}$ inch wall board separated by a 1 inch air space. To obviate the necessity of opening the door during an experiment, two 6 inch square rubber dam "portholes" with slits in their centers enabled material to be passed into or out of the chamber.

A General Electric Thinline air conditioner was mounted in one wall of the chamber enabling a decrease in temperature to 18°C. This was an advantage on days when the ambient temperature was above the threshold level for sweating. On such days, the cooling procedure was applied only to the subject completely enclosed in the chamber in order to establish a zero base line for sweating.

The temperature within the chamber was elevated by means of a thermostatically controlled heating unit mounted in one wall. Adequate circulation of the warm air without excessive convection currents was accomplished by a built in fan. Temperatures as high as 70°C were usually reached within approximately $2\frac{1}{2}$ hours. Experimental time periods greatly in excess of this were a source of increasing discomfort for the subject who was obliged to re-

main relatively quiet during the entire procedure.

In all studies, except those involving only one arm in the chamber, the subject reclined comfortably on a 28 inch x 76 inch copper screen mesh bed. The chamber was modified to permit exposure of limited areas of the body to the ambient temperature within the chamber. In one wall of the chamber were two insulated doors, one above the other. A framed rubber diaphragm was fitted about the body of the subject at a level which demarcated that portion of the body to be placed in the chamber. The bed was constructed to permit the subject to lie in relative comfort with the frame about his body. It was then wheeled through the opening until the frame of the diaphragm came flush with the frame in the upper door. The two frames were then bolted together to make a tight seal. The lower compartment door was then closed, making a seal with the lower portions of the bed frame and the diaphragm. Thus, the inside of the chamber was completely sealed from the outside even though only a portion of the subject lay within the chamber (Figure 1). The rubber diaphragms were individually fitted for each subject and for each portion of the body to which they were applied.

The bed was not used in experiments involving only one arm in the chamber because of difficulty in application. In these studies the subject sat on a chair with one arm protruding through the diaphragm.

2. Methods of Recording Cardiac Responses

In the initial experiments, recording responses were recorded by the method of Russell (1931). This method employed a highly sensitive bond paper (e.g., Fox River bond) which was applied to a skin area previously painted with a 1 per cent solution of iodine in 95 per cent ethyl alcohol.

Figure 1

The gallium chloride used was as pure as is commercially available. A 1 per cent solution was used but due to insoluble impurities, only the decanted supernatant obtained after centrifugation could be used. The solution was applied to the bond paper by means of large cotton applicators.

The area of skin from which records were to be obtained was painted with

2. Methods of Recording Sweating Responses

In the initial experiments, sweating responses were recorded by the technique of Randall (43). This method employed a high starch content bond paper (e.g., Fox River Bond) which was applied to a skin area previously painted with a 3 per cent solution of iodine in 95 per cent ethyl alcohol. In the presence of sweat, reddish blue spots characteristic of the starch-iodine reaction appeared on the paper. This technique, although extremely sensitive, presented two technical problems neither of which, however, affected the validity of the results. First, the starch-iodine spots were sensitive to light and in time faded and disappeared. In order to make the spots permanent it was necessary to undertake the tedious task of retouching them with ink. Second, the unretouched spots did not reproduce well on photographic paper. Thus, a new technique was developed in an effort to obviate these problems, particularly the former, and yet retain the high sensitivity of this well proven technique.

The new procedure consisted of applying paper, coated with palladium chloride, to a skin surface previously painted with potassium iodide. In the presence of sweat, a precipitate of palladium iodide formed distinct dark brown spots on the paper.

The palladium chloride used was as pure as is commercially available. A 1 per cent solution was used but, due to insoluble impurities, only the decanted supernatant obtained after centrifugation could be used. The solution was applied to the bond paper by means of large cotton applicators.

The area of skin from which records were to be obtained was painted with

a 40 per cent solution of potassium iodide in 50 per cent ethyl alcohol and water. Potassium iodide is rather highly soluble in water but only slightly soluble in ethyl alcohol. The alcohol was added to make the solution more volatile and give it a lower surface tension. This resulted in a rapidly drying liquid film that left a thin evenly dispersed coating of potassium iodide crystals on the skin surface.

The spots of palladium iodide which are formed in the presence of sweat are permanent. However, during the application of the paper to the skin, a few small crystals of potassium iodide invariably adhere to the paper. Since the formation of the precipitate of palladium iodide requires the presence of water, a spot will not appear if sweat is not present at the point of contact of such a crystal. However, potassium iodide is somewhat hygroscopic and if the recording papers remain in contact with a warm humid environment, these crystals will in time pick up enough moisture to allow the formation of the palladium iodide precipitate. Spots may then appear on the papers which were not caused by sweat. In a summer environment of 90°F, and 90 per cent relative humidity, these "false" spots sometimes appeared in one hour. In the cooler months of the year, when the room temperature was lower and the absolute water content of the air was considerably less, the hygroscopic ability of the potassium iodide was apparently not great enough to bring about hydration of the crystals and the "false" spots did not appear. Recording slips have been stored in the latter environment for several months without the appearance of the "false" spots.

This fault in technique was detected during the latter part of the investi-

gation. It was observed that recording slips which showed no spots at the time of experimentation did show some spots when the papers were graded a day or two later. It was then deemed necessary to cover all the slips with a protective coating that would seal, after experimentation, the recording surface of the paper from the environmental moisture. An effective seal was made by the application of a strip of Du Pont Mylar tape to the recording surface. This is a transparent pressure sensitive polyester tape similar in appearance to Scotch cellophane tape but with decided additional advantages. Over long periods of time, it will not dry out, discolor, become brittle, or lose its tack. Its moisture resistant properties prevented the formation of "false" spots even when the tape coated recording papers were exposed to steam.

In a series of mock experiments in which a rubber membrane was substituted for the skin surface, spots did not appear on the recording papers.

Considerable trial and error was necessary before this simple method of protecting the recording papers was devised. During the interim, the studies were conducted with the aid of the starch-iodine technique. A comparison study of the two methods showed no essential difference in the sweat patterns recorded simultaneously from two adjacent skin areas.

3. Methods of Temperature Measurement

Skin temperatures in all studies were measured by means of a Brown Instrument Company continuous thermocouple recorder. This apparatus consists of 16 copper-constantan thermocouples connected to a potentiometric circuit. An automatic selector switch operating at 2 second intervals permitted the recording of all 16 thermocouples in 32 seconds. A permanent record was obtained on moving graph paper calibrated in 0.2° intervals from 0°C. to 50°C. Specially designed oral and rectal thermocouples were also attached to this circuit. Ambient temperatures within the limits of the recorder were likewise measured in this manner. Ambient temperatures above 50°C. were obtained with a mercury thermometer.

In several studies, concomitant with thermocouple recordings, the skin temperatures were measured with a Stoll-Hardy Radiometer (14). The heat sensitive elements of this instrument are 4 very small thermistors suitably connected in a Wheatstone Bridge. Temperature readings in $^{\circ}\text{C.}$ above or below ambient were read directly from a meter scale on the instrument. Ambient temperature was recorded from an aluminum reference block against which the radiometer head was balanced before each temperature reading.

4. Experimental Procedure

This study consisted of 63 experiments conducted on 10 normal and 4 paraplegic subjects. The paraplegic subjects studied had surgically verified anatomically complete spinal transections between the levels of T₃ and T₈. Subjects with transections below this level were not studied because it has been reported (45) that postganglionic sympathetic fibers to the legs may have some preganglionic connections as high as T₉.

All subjects reclined on the screen mesh bed for at least 45 minutes prior to experimentation. All paraplegic subjects were protected from the screen mesh by a foam rubber mattress 4 inches thick. This was necessary to avoid any excessive pressure on skin areas below the level of the lesion. During this pre-experimentation period, the bed and subject were placed in the appropriate position. The "hot" junctions of the thermocouples, mounted in plastic holders, were fastened to the regional skin areas with Scotch tape (Figure 2).

In most of the studies the same 8 representative regional skin areas were used for recordings. They were the following: the dorsum of the foot, calf, thigh, abdomen, chest, forearm, upper arm¹ and forehead. The calculations of DuBois et al. (46) (Table I) were used to determine the percentage of body surface area heated in the "minimal area" studies.

Sweat papers were placed on the painted areas for a period of 15 or 30 seconds at intervals of 2, 3 or 4 minutes (Figure 2). In studies in which the radiometer was used, a reading from each area was usually obtained at intervals

¹In these studies the upper arm refers to the area between the forearm and the shoulder.

TABLE I

Percentage of total
body surface area

Head (not including neck)

Upper extremities (including hands)

Figure 2

TABLE I

	Percentage of total body surface area
Head (not including neck)	7
Upper extremities (excluding hands)	14
Hands	5
Feet	7
Legs	13
Thighs	19
Trunk (including neck)	35
	<hr/>
	100

of 8 to 10 minutes. The relative comfort of the normal subject was periodically checked to avoid any psychic influence from extreme discomfort. In the case of the paraplegic subject, the rectal or oral temperature was closely observed as well as his subjective sensations of comfort. It was desirable to avoid an elevation in body temperature appreciably in excess of 1.5°C .

Before the conclusion of many experiments the chamber door was opened and the interior rapidly cooled. A fan was sometimes used to accelerate this cooling.

EXPERIMENTAL RESULTS

1. Patterns of Sweat Recruitment in Normal Man

Figure 4 represents a "typical" pattern of successive cranial recruitment of regional areas when the entire body of normal man was exposed to a rising environmental temperature. As in all studies, the magnitude of the sweating responses was expressed in arbitrary units from a plus 1 to a plus 10 (Figure 3a). Although there were variations in the timing of recruitment from area to area in different experiments, the general patterns remained remarkably consistent. The lowermost portions of the body always exhibited sweating before the uppermost areas. A time lapse of 20-50 minutes commonly occurred between the appearance of sweat on the dorsum of the foot and its appearance on the forehead. The more rapid the rise in environmental temperature, the shorter the time interval required for recruitment of all areas. The earliest sweating rates could not be detected by visual observations of the skin but were marked and unmistakable when recorded by the palladium iodide or starch paper techniques. At ambient temperatures illustrated in Figure 4, a relatively profuse response was eventually seen on all areas. The sudden and dramatic decline in sweating was effected by opening the chamber door and cooling the interior as rapidly as possible.

A similar pattern of recruitment also obtained in normal man when only the lower (Figure 5) or upper (Figure 6) portion of the body was heated in the

(a)

(b)

Figure 3 (a) Sweat intensity grading chart

(b) Plus 3 sweating response from dorsum of the foot of paraplegic patient

Figure 4

NORMAL SUBJECT LOWER HALF OF BODY IN CHAMBER

Figure 5

NORMAL SUBJECT UPPER HALF OF BODY IN CHAMBER

Figure 6

chamber. The level of the umbilicus was the dividing line between "in" and "out". In these studies it was necessary to heat the portion of the body in the chamber for a longer period of time and to a higher temperature in order to recruit sweating on all areas. The magnitude of response was usually less on areas outside the chamber than on those inside the chamber. This was particularly true when only the lower portion of the body was heated (Figure 5). However, exceptions occurred and are illustrated by the forehead responses in Figures 5 and 6.

Figure 7 represents a study with the normal subject seated outside the chamber with one upper extremity inserted into the chamber through the rubber diaphragm. Under these conditions an essentially normal pattern of recruitment was invariably obtained on all subjects. The magnitude of the sweating responses for all areas outside the chamber was less than in the studies with all or half of the body inside the chamber. In the experiment illustrated in Figure 7 records of sweating were not made on the parts inside the chamber.

When both feet of the normal subject were exposed in the heated chamber, a successive recruitment of all areas again obtained (Figure 8). Very high chamber temperatures were necessary to elicit such a response (over 60°C.), but in no instance was failure to recruit all areas encountered. Time intervals of an hour and a half or more were usually observed between the appearance of sweating on the dorsum of the foot and its appearance on the uppermost areas. Responses on all areas outside the chamber were of relatively low magnitude as compared to the studies that involved heating of larger surface areas (Figures 5 and 6). This was not true for the areas being heated. Note

NORMAL SUBJECT ENTIRE ARM IN CHAMBER

Figure 7

NORMAL SUBJECT BOTH FEET IN CHAMBER

Figure 8

the relatively high level of response on the dorsum of the foot in Figure 8. Recordings from this area were not made for the duration of the experiment because prolonged exposure to such very high temperatures became unbearable for the individual taking the recordings.

In a few experiments, occasional bursts of sweating appeared on the forehead before they were observed on the other upper areas.

Figure 9 exhibits data obtained in an experiment in which only the head and a large portion of the subject's neck were in the chamber. The head itself represents approximately 7 per cent of the body area and the entire neck another 2 or 3 per cent. Consequently, close to 9 per cent of the body surface area was exposed to heat. In this series of studies recruitment of all areas consistently required less time and less heat than when both feet were exposed to the high temperatures. The "head in" studies exhibited results remarkably similar to the "arm in" studies.

It is especially interesting that sweating first appeared on the forehead 42 minutes after it had been recorded on the dorsum of the foot even though only the head was exposed to the high ambient temperature. This is in significant contrast to the data illustrated in Figure 8 in which sweating first appeared on the area warmed.

A study of the normal subject with one foot in the chamber is illustrated in Figure 10. In this series, failure to recruit sweating on all areas occurred for the first time. Exposing the foot to a progressive elevation in temperature up to 70°C. over a period of 2 1/2 hours failed to produce sweating above abdomen. In each of seven such experiments all areas up to and including the abdomen were recruited but in no instance was sweating observed on any

NORMAL SUBJECT HEAD IN CHAMBER

Figure 9

NORMAL SUBJECT ONE FOOT IN CHAMBER

Figure 10

area above the abdomen. Figure 10 represents the practical limits of the experimental procedure with regard to time and temperature. Exposure of an area to such high ambient temperatures for an appreciably longer period caused pain in the heated area and emotional sweating supervened.

A comparison of the sweating responses of the dorsum of the foot placed inside the chamber and the dorsum of the foot outside the chamber showed that both of these areas recruited before any others. However, the dorsum of the foot receiving the heat recruited first and attained higher levels of sweating than did the other foot. This is in contrast to experiments (not illustrated in this paper) in which recordings were taken simultaneously from both feet when they were the only areas being heated. Both feet began sweating at the same time and the patterns of their responses were almost identical.

Figure 11 represents the pattern of response when only one hand was heated. In this figure, the plotted scale of response has been doubled. In no instance did recruitment ascend above the level of the thigh and in one subject it did not appear above the calf. Any sweating responses observed, although very definite, were of a low magnitude and were not sustained above the zero level for long periods. The experimental conditions of this study were almost identical to those of Figure 10 and both studies were conducted on the same subject.

All of the illustrated studies involving only a portion of the body in the chamber were selected because the ambient temperatures outside the chamber were similar. This choice was made so that the total thermal stimulus required to effect the various recruitment patterns could be compared. Similar studies

NORMAL SUBJECT ONE HAND IN CHAMBER

Figure 11

were conducted when lower ambient temperatures existed outside the chamber; the lowest being 19°C. In none of these was there a change in the number of areas recruited. However, an increase was usually observed in the time and/or the heat required to bring about recruitment.

2. Observations on Oral and Rectal Temperatures of Normal Man during Sweat Recruitment

When the entire body of normal man was heated in the chamber, recruitment of sweating generally started before any change in oral or rectal temperature occurred and in many instances (illustrated in Figure 4) all areas commenced sweating before these temperatures rose. An elevation in these temperatures was commonly seen after the chamber door was opened and sweating declined or stopped.

When half of the body was exposed to heat, recruitment of sweating usually started before rectal temperature rose and sometimes was complete before any rise occurred (Figure 5). More frequently, however, body temperature showed some elevation before all areas started to sweat (Figure 6). These differences were not correlated with heating a particular half of the body.

When lesser amounts of body surface were exposed to heat (Figures 7, 8, 9, 10 and 11) rectal temperature generally remained constant or fell progressively during the experiment. In the experiments illustrated in Figures 7 and 11, the downward trend in deep temperatures was reversed after recruitment was well started. Even in these studies, however, deep temperatures failed to rise above control levels. In all of the studies in which small areas were heated, a rise in deep temperature above the control level was observed on only one occasion.

3. Patterns of Sweat Recruitment in Paraplegic Man

All of the following observations were made on patients with surgically verified, anatomically complete spinal cord transections. When the entire body of the paraplegic subject was placed in the chamber and the temperature progressively elevated, sweating appeared on those areas completely removed from high center control (Figure 12). Indeed, it occurred first on the lower extremities and proceeded cephalad in the identical recruitment pattern described for the normal subject. Thus, we may draw the significant conclusion that a thermal sweating reflex was mediated by segments of the spinal cord below the level of transection. Sweating on the lower areas was of relatively low intensity when compared with the normal subject (Figure 4). Nevertheless, the thermal spinal reflex was clear cut and sometimes reached the magnitude of a plus 4 response (Figure 3a). Figure 3b is an un-retouched photograph of a plus 3 response from the dorsum of the foot of a patient with a complete lesion at T₅. A comparison of Figures 4 and 12 reveals that the time and heat required to effect recruitment of sweating was essentially the same for the normal and paraplegic subjects. Sweating usually started before a rise in body temperature occurred but a rise invariably occurred before all areas were recruited.

In order to further examine the factors responsible for the initiation of spinal reflex sweating, the paraplegic subject was studied with only the upper or lower portion of his body exposed to heat. The level of structural injury to the spinal cord was the dividing line between "in" and "out". Figure 13 represents a study in which only that portion of the body below the level of

PARAPLEGIC SUBJECT T5 ENTIRE BODY IN CHAMBER

Figure 12

PARAPLEGIC SUBJECT T5
LOWER HALF OF BODY IN CHAMBER

Figure 13

the lesion was heated in the chamber. As in the normal subject (Figure 5), heating only the lower portion of the body was sufficient to bring about recruitment of sweating on the entire body. Note that the dorsum of the foot began to sweat before a body temperature rise occurred, but a rise of 0.4°C . was observed before all of the areas below the lesion exhibited a response. A rise of over a degree in oral temperature occurred in the latter stage of the study due undoubtedly to the low sweating responses on most areas. It is interesting that even with prolonged heating at very high temperatures and with an elevation in body temperature of over a degree centigrade, the sweating responses on the lower extremities still did not rise a great amount above the relatively low initial rates. The normal subject with the lower portion of the body in the chamber exhibited considerably higher rates on these lower areas. However, the temperature and time relationship for recruitment of all areas was again the same as that of the normal subject.

When the paraplegic subject was reversed so that only portion of the body above the lesion was heated, the normal recruitment pattern was broken (Figure 14). Sweating occurred first on the upper portion of the body and last on the lower extremities. These lower areas exhibited a response only after prolonged heating at high environmental temperatures and only after body temperature had risen from 0.6° to 1.0°C . When sweating did appear on the lower extremities it was in a characteristic recruitment pattern, that is, with the dorsum of the foot sweating first.

PARAPLEGIC SUBJECT T7
LOWER HALF OF BODY OUT OF CHAMBER

Figure 14

4. Skin Temperatures of Normal Man

In all experiments skin temperatures were recorded by means of thermocouples. In some experiments radiometer measurements were also taken. A comparison of data derived simultaneously from the two methods is illustrated in Figure 15 in which a subject was studied with the lower extremities in the chamber. Thermocouple and radiometer measurements usually agreed within 0.5°C . until ambient temperatures exceeded 40°C – 42°C . At higher ambient temperatures a deviation of 2.0°C . or more was commonly observed between the readings of the two methods. The thermocouple readings were always consistently higher and undoubtedly did not correctly represent the skin temperatures, since the thermocouples were unshielded and were influenced by the radiant sources in the chamber in the same way as the skin to which they were applied. The thermocouple data were plotted for all experiments illustrated in this report because they were more complete. At high ambient temperatures where this data was questionable, it was employed only to interpret general directional changes in skin temperature.

When the entire body of normal man was heated in the chamber a rather rapid early rise in skin temperature occurred on all areas (Figure 4). The areas with the lowest initial temperatures exhibited the greatest percentage change (e.g. dorsum of the foot). When sweating commenced on an area, the temperature usually continued to rise but at a slower rate. It is interesting that even though the forehead exhibited the highest temperatures it was one of the last areas to sweat (Figure 4). On the other hand, the dorsum of the foot had the lowest temperatures and it was the first area to sweat. When

COMPARISON OF RADIOMETER AND THERMOCOUPLE RECORDINGS

AREAS OUTSIDE CHAMBER							
AMBIENT °C		25 ————— 27					
FOREHEAD	Ra	34.1	34.4	34.2	34.1	34.1	34.0
	Th	34.4	34.5	34.4	34.1	34.2	34.6
UPPER ARM	Ra	32.8	32.8	32.3	32.1	32.1	31.9
	Th	33.0	32.7	32.2	32.2	32.0	32.0
FOREARM	Ra	33.5	34.1	34.0	33.7	33.8	33.2
	Th	33.5	33.9	33.7	33.9	34.1	33.1
CHEST	Ra	34.2	33.5	33.2	33.3	33.2	32.6
	Th	33.8	33.6	33.2	33.3	33.1	32.2
ABDOMEN	Ra	33.5	33.9	33.7	32.5	32.6	32.4
	Th	33.5	34.0	33.4	32.6	32.2	32.2

AREAS INSIDE CHAMBER							
AMBIENT °C		25-30	35-40	40-42	42-45	46-48	51-53
THIGH	Ra	34.0	35.3	36.6	36.6	36.2	36.7
	Th	33.8	35.5	37.0	37.6	38.3	38.6
CALF	Ra	33.3	35.0	35.8	36.1	36.1	36.3
	Th	33.6	35.0	36.2	36.8	37.5	38.3
DORSUM FOOT	Ra	31.7	34.1	34.3	35.1	35.1	37.8
	Th	32.0	34.2	34.6	36.5	37.2	40.0

Ra - RADIOMETER READING

Th - THERMOCOUPLE READING

Figure 15

the chamber was rapidly cooled, a precipitous drop in temperature occurred on all areas.

When only a portion of the body was heated, skin temperatures on that portion consistently rose in a manner similar to that described above. The rise was greater, however, when the elevation of temperature was greater and the duration of application longer (e.g. dorsum of the foot, Figures 8 and 10).

A different temperature pattern was characteristic of the areas outside the chamber. These areas usually showed an initial rise in temperature and if sweating occurred, leveled off or even declined. These points are well illustrated on the upper areas in Figure 5. Exception to this sometimes occurred. For example, the dorsum of the foot and the calf in Figure 6 show a progressive decline in temperature throughout the entire pre-sweating and sweating periods.

Frequently, when the chamber was suddenly cooled, a rise in skin temperature was observed on areas outside the chamber after they had ceased sweating. This rise often continued at a gradual rate until the termination of the experiment (Figure 7).

Superimposed upon the long range progressive increases or decreases in the temperatures of various areas were short term periodic fluctuations. Such changes did not appear to follow a set pattern, and were observed most frequently and clearly on areas outside the chamber. The upper areas in Figure 11 illustrate this point. A minute to minute analysis of these temperatures (not illustrated) revealed very gradual increases and decreases in the temperatures of these areas.

5. Skin Temperatures of Paraplegic Man

When the entire body of the paraplegic subject was heated in the chamber, the skin temperature pattern was essentially the same as in the normal individual. However, the peak temperatures attained on most areas were usually higher than those exhibited by the normal individual (Figures 4 and 12).

In studies in which the lower portion of the paraplegic subject was in the chamber, all areas exposed to heat showed a progressive rise in temperature as did those of the normal subject (Figure 13). Most upper areas outside the chamber exhibited a gradual rise which on occasion tended to "level off" during the sweating phase (e.g. forearm and chest, Figure 13). The magnitude of temperature change of areas outside the chamber was not as great as in the normal subject. Also, the outside areas did not show as large a drop in temperature during the sweating phase as did comparable areas in the normal subject. A rise in temperature of outside areas was sometimes observed several minutes after cooling the chamber. This rise usually continued until the termination of the study (e.g. chest and forearm, Figure 13).

When only the upper portion of the paraplegic subject was heated, the upper areas exhibited responses essentially the same as the normal subject except that the peak temperatures were higher (Figure 14). A progressive fall in the temperatures of the lower areas outside the chamber was observed.

DISCUSSION AND CONCLUSIONS

The studies on paraplegic patients were initially planned in an effort to more completely understand the phenomenon of sweat recruitment in normal man. Because several informative conclusions may be drawn from these studies it seems practical to discuss them first.

The sweating responses below the level of surgically verified anatomically complete spinal cord transections demonstrate beyond question the existence of thermal spinal reflex sweating in man. This fact has not been demonstrated previously and is in direct contrast to classical concepts. Although the response is clear and unmistakable (Figure 3a) its relatively low intensity, as compared with normal, indicates that the thermal spinal reflex can elicit a sweating response of only a limited magnitude. For profuse sweating rates to occur, continuity between the spinal cord and the hypothalamus appears necessary. The sequential recruitment of sweat glands on the lower extremities and the cyclic nature of the responses demonstrate that the isolated spinal cord is capable of eliciting the same qualitative response as in the normal subject. The essential difference observed in this investigation was quantitative.

It is probable that one or more of the following factors were primarily responsible for eliciting the thermal reflex pattern below the lesion. First, the environmental temperature acting directly on cutaneous receptors and/or effector organs. Second, an elevated blood temperature warming cutaneous re-

ceptors and/or effector organs. Third, an elevated blood temperature affecting spinal centers. An attempt was made to resolve this problem by studying the paraplegic subject placed half in and half out of the chamber. Application of heat to areas below the lesion induced a normal pattern of recruitment of sweating on all areas. However, when the heat was applied to areas above the lesion the normal recruitment pattern was broken. This conclusively demonstrated that thermal stimulation of cutaneous receptors and/or effector organs was required for recruitment to occur in a normal sequential pattern. However, sweating on the lower extremities, although late, did occur. This sweating commenced only after a very significant elevation in blood temperature. In Figure 14 the lower extremities exhibited a continuous decline in skin temperature throughout the study. Although the location of the sensory receptors to heat is unknown, it is difficult to imagine that their temperatures increased as skin temperatures fell. This would tend to rule out the affect of blood temperature on peripheral receptors and end organs. Thus, the stimulus for response was most probably the direct action of an elevated blood temperature on spinal centers.

The fact that the lower extremities eventually sweat in a sequential pattern when only the areas above the lesion are heated is important to the whole problem of recruitment. There appears to be within the spinal cord a gradient of excitability decreasing in a caudal to cephalad direction. Some evidence of quantitative differences at various spinal levels of facilitation in the sudomotor pathways has been reported (47). In the "upper half in" studies on paraplegic patients the external facilitating influence (blood

temperature) was probably the same at all levels of the isolated spinal cord. The apparent gradient of facilitation could therefore be explained on the basis of an inherent difference in the neuron pools within the spinal cord. Whatever the cause of this inherent difference, it appears to be reflected in a lower threshold for response. The lower threshold areas would be more easily facilitated by a given stimulus regardless of whether it was afferent drive from the periphery or an elevation in cord temperature.

The sequential recruitment of sweating in the normal subject could also be explained on the basis of such a postulation. Even though in many of these studies the hypothalamus was undoubtedly exerting an influence, it is difficult to imagine sequential recruitment facilitated by differential hypothalamic discharges or preferential pathways to various cord levels. It seems more reasonable that hypothalamic influence is exerted by a similar and simultaneous discharge to all spinal areas. If the latter were true, what appears to be a gradient of facilitation of various spinal levels would actually be a gradient in excitability of the neuron pools within the cord.

The studies on normal subjects that comprised heating of 9 per cent or less of the total body surface all demonstrated complete or fractional sequential recruitment of the body. The sudomotor responses were directly related to sensory stimulation by heat. As the percentage of heated area increased, the completeness of recruitment and/or the intensity of response increased. Also, the responses were directly related to the duration and intensity of heat application to an area. It is obvious from these studies that the afferent drive from the periphery was exerting a facilitating in-

fluence upon the cord. This influence could have been directly on the cord or indirect through a long reflex mechanism via the hypothalamus. As for direct influence, when only the arm is heated, it is difficult to imagine that the lower portion of the cord responded first because there was a greater impingement of impulses on it from the periphery. It is more logical to presume that the lower cord area is more easily facilitated by a given level of afferent drive due to an inherently lower threshold for response. If the influence of afferent drive is exerted via the hypothalamus, then it is again improbable that a differential discharge to various cord levels occurs. Although no direct physiological evidence exists demonstrating the existence of a long reflex via the hypothalamus, the anatomical pathways, although unknown, probably do exist. The profuse projection of ascending fiber tracts into the hypothalamus make it easy to postulate the existence of such a pathway. Probably there is both a direct and an indirect influence of afferent drive on the cord. The hypothalamus undoubtedly contributes to the magnitude of the sweating response. This is demonstrated by the fact that the responses obtained on the lower extremities of the normal subject when only the arm was heated were greater than those of the lower extremities of the paraplegic patient when his entire body was heated.

In these "minimal area" studies the recruitment responses during periods of falling rectal temperature minimized the possibility of their origin in rising hypothalamic temperature. Although rectal temperature may not necessarily reflect hypothalamic temperature, it is unlikely that the two temperatures would proceed in opposite directions. The "head in" studies may

be an exception to this.

There are several experimental demonstrations that give further indication that the recruitment patterns in normal man are reflexly mediated at spinal levels. First, the lower extremities started sweating first regardless of which area of the body was heated. Second, when both feet were heated sweating began simultaneously on both feet. When only one foot was heated sweating occurred on both feet but it appeared earlier and reached a higher intensity on the heated side. Third, when only the upper extremity or head was heated, and the chamber suddenly cooled, sweating subsided quite abruptly on most areas. Fourth, all of these phenomena occurred when the deep temperature was at or below control levels. Also, when the entire body was heated and then cooled, rectal temperature usually rose as sweating subsided. It is difficult to reconcile these facts without postulating spinal mediation of thermal reflex sweating.

When 7 per cent or more of the total body surface of the normal subject was heated a sequential recruitment of sweating was observed on all regional areas. When 3.5 per cent or less of the body surface was heated a fractional recruitment of the body obtained. Thus, for the experimental conditions presented, the minimal amount of the body surface area that must be heated to bring about recruitment of the entire body lies between 3.5 and 7 per cent of the total surface area.

The "head in" and "arm in" studies each involved heating about 9 per cent of the body surface area. The ease of recruitment as well as the magnitude of response was consistently greater than when 7 per cent of the body area was

heated. Also, recruitment of more areas consistently occurred when one foot (3.5 per cent) was heated than when one hand (2.5 per cent) was heated. Thus, a 1 or 2 per cent reduction in total surface area heated caused a definite difference in response. An alternative explanation for these differences could involve a significantly different concentration of afferent receptors in the hand and foot. Since these studies were made on heated surface areas near or below the minimal necessary to effect complete recruitment, it is not particularly surprising to see this. Even though 1 per cent of the total body surface is a very small fraction of the whole, a reduction of this amount from the "one foot in" to the "one hand in" studies represented approximately a 30 per cent reduction in the area being heated. A comparison of the "head in" and "arm in" studies with the "both feet in" studies represented a decrease of only 2 per cent of the total body surface area being placed in the chamber. However, it represented a reduction of over 20 per cent in the area actually heated.

The sudden decline in sweating, observed in many of the studies when the chamber was rapidly cooled, occurred before any significant change in deep temperature was recorded. It was most probably due to two factors. First, the withdrawal of sensory stimulation by heat and the consequent decrease in afferent drive. Second, reflex central inhibition brought about through stimulation of inhibitory afferents by the cool air. The central inhibition could be caused by direct action on the cord or by indirect influence through a long reflex via the hypothalamus. The supposition of central inhibition is supported by studies (not illustrated) in which the upper half of the body was

heated and the chest then cooled by the application of an ice pack. Even though heat was continuously applied to the remaining upper areas, and deep temperature was not immediately altered, a dramatic cessation of sweating occurred on all areas. When this same study was repeated with the entire body in the chamber, a sudden decrease in sweating rates occurred on all areas. However, the lowermost areas continued to sweat at a reduced rate. Apparently in the latter studies, the central inhibition was subminimal for complete depression of the afferent drive effect of heat on the lower threshold areas of the cord.

When the entire body of normal man was heated in the chamber, the initial rise in skin temperature of all areas reflected primarily two phenomena: (1) the direct heating of the skin, and (2) peripheral vasodilatation. The latter point is demonstrated by the fact that areas of normally high vasomotor activity (e.g. the foot) showed a greater change in skin temperature than areas of normally less intense vasomotor activity (e.g. forehead). In these studies, the tendency for skin temperature to level off when high sweating rates occurred demonstrated the direct effect of evaporative heat loss on skin temperature.

When only a portion of the body was heated, the common occurrence of an initial rise in skin temperature of the non-heated areas most probably reflected reflex peripheral vasodilatation. The "leveling off" or decline in temperature of these areas when sweating commenced, and the subsequent rise when sweating ceased, offers further demonstration of a correlation between evaporative heat loss and skin temperature. The periodic fluctuations in temperature of non-sweating areas (e.g. upper areas of the "hand in" study, Figure 11) also are

probably indicative of reflex vasomotor activity.

It is particularly interesting that the areas with the highest initial temperatures are not the first to sweat. Also, note that the dorsum of the foot in the "one hand in" study (Figure 11) started sweating after very little change in its temperature. A comparison of this evidence to the skin temperature of the heated foot in the "one foot in" study (Figure 10) demonstrates an important point. That is, the initiation of a sweating response on a particular area is not necessarily correlated with the temperature of that area.

In the studies on paraplegic subjects an essential difference from normal was noted in the skin temperature of areas below the lesion. This difference was well demonstrated when only the areas above the lesion were heated. The lower areas showed only a decline in temperature with no periodic fluctuations.

SUMMARY

When the entire body of normal man is exposed to a progressive elevation of environmental temperature, sweating responses are characterized by a consistent pattern of recruitment in which sweating first occurs on the lowermost portion of the body and then proceeds cephalad to ultimately include all regional areas. This same general pattern of recruitment also obtains when lesser amounts of the body surface area are heated. The minimal amount of the total body surface that must be heated to effect recruitment of all regional areas is between 3.5 and 7 per cent. Recruitment of only the lower areas of the body occurs when 3.5 per cent or less is heated. All of the sweating responses observed when 9 per cent or less of the body area is heated occur when rectal temperature is the same as or below control levels. It is postulated that these responses are reflexly mediated at spinal levels. The probability of facilitation of spinal levels through a long reflex via the hypothalamus is discussed.

When the entire body of the paraplegic patient (surgically verified complete spinal cord transection) is exposed to an elevated ambient temperature, sweating does occur on those areas completely removed from high center control. It occurs first on the lower extremities and proceeds cephalad in the normal recruitment pattern. Thus, in contrast to classical concepts, a thermal sweating reflex is mediated by segments of the spinal cord below the level of

transection. The two primary causes of these spinal thermal sweating responses are most probably cutaneous sensory stimulation by heat, and increased excitability of spinal centers due to elevated blood temperature.

In normal subjects a correlation is seen between the skin temperatures and cutaneous evaporative heat losses. Skin temperature changes indicative of peripheral vasomotor activity are also observed.

BIBLIOGRAPHY

1. Ikeuchi, K., and Kuno, Y. On the regional differences of the perspiration on the surface of the human body. *J. Orient. Med.*, 7: 67-89 and 106-7, 1927.
2. Burch, G. E., and Sodeman, W. A. Regional relationships of rate of water loss in normal adults in a sub-tropical climate. *Am. J. Physiol.*, 138: 603, 1943.
3. Weiner, J. S. The regional distribution of sweating. *J. Physiol.*, 104: 32-40, 1945.
4. Hertzman, A. B., Randall, W. C., Peiss, C. N., and Seckendorf, R. Regional rates of evaporation from the skin at various environmental temperatures. *J. Appl. Physiol.*, 5: 153-61, 1952.
5. Hermann, F., Prose, P. H., and Sulzberger, W. B. Studies on sweating. V. Studies of quantity and distribution of thermogenic sweat delivery to the skin. *J. Invest. Dermat.*, 18: 71-86, 1952.
6. Randall, W. C., Hertzman, A. B., and Ederstrom, H. E. Dermatoma recruitment of sweating in response to heat. *Fed. Proc.*, 10: 103-104, 1951 (No. 1).
7. Randall, W. C., and Hertzman, A. B. Studies on cutaneous heat losses. III. The dermatoma recruitment of sweating in response to generalized radiant heating. A. F. Technical Report No. 6680, 13 pp., December, 1951.
8. Randall, W. C., and Hertzman, A. B. The dermatoma recruitment of sweating in response to generalized radiant heating. *J. Appl. Physiol.*, 5: 399-409, 1953.
9. Randall, W. C., Peiss, C. N., and Rawson, R. O. Simultaneous recruitment of sweating and perception of warmth in man. *J. Appl. Physiol.*, 12: 385-89, 1958.
10. Kuno, Y. The Physiology of Human Perspiration. London: J. and A. Churchill Ltd., 1934.
11. Adolph, E. F. The initiation of sweating in response to heat. *Am. J. Physiol.*, 145: 710-15, 1946.

12. Ranson, S. W., Fisher, C., and Ingram, W. R. Hypothalamic regulation of temperature in the monkey. *Arch. Neurol. and Psychiat.*, 38: 445-66, 1937.
13. Ranson, S. W. The hypothalamus as a thermostat regulating body temperature. *Psychosom. Med.*, 1: 486-95, 1939.
14. Clark, G., Magoun, H. W., and Ranson, S. W. Hypothalamic regulation of body temperature. *J. Neurophysiol.*, 2: 61-80, 1939.
15. Magoun, H. W., Harrison, F., Brobeck, J. R., and Ranson, S. W. Activation of heat loss mechanisms by local heating of the brain. *J. Neurophysiol.* 1: 101-114, 1938.
16. Davison, C., and Selby, N. E. Hypothermia in cases of hypothalamic lesions. *Arch. Neurol. and Psychiat.*, 33: 570-91, 1935.
17. Davison, C. Disturbances of temperature regulation in man. *Assoc. for Research Nerv. and Ment. Dis.* 20: 774-823, 1940.
18. Erickson, T. C. Neurogenic hyperthermia. *Brain*, 62: 172-90, 1939.
19. Zimmerman, H. M. Temperature disturbances and the hypothalamus. *Assoc. for Research Nerv. and Ment. Dis.* 20: 824-40, 1940.
20. List, C. F. and Peet, M. M. Sweat secretion of man. V. Disturbances of sweat secretion with lesions of the pons, medulla and cervical portion of the cord. *Arch. Neurol. and Psychiat.*, 42: 1098-1127, 1939.
21. Beaton, L. E., and Leninger, C. R. Spinal distribution of the thermoregulatory pathways in the monkey. *J. Neurophysiol.*, 6: 37-38, 1943.
22. Roth, G. M., Johnson, D. A., and Craig, W. McK. Physiologic effect of anterolateral chordotomy in man. *J. Appl. Physiol.*, 5: 261-66, 1952.
23. Bazett, H. C. Theory of reflex controls to explain regulation of body temperature at rest and during exercise. *J. Appl. Physiol.* 4: 254-62, 1951.
24. Sinclair, D. C., Weddell, G., and Zander, E. The relationship of cutaneous and sensibility to neurohistology in the human pinna. *J. Anat.*, 86: 402-11, 1952.

25. Hagen, E., Knoche, H., Sinclair, D. C., and Weddell, G. The role of specialized nerve terminals in cutaneous sensibility. Proc. Roy. Soc., London, s. B111: 279-87, 1953.
26. Lale, P. P., Weddell, G., and Williams, C. M. The relationship between heat transfer, skin temperature and cutaneous sensibility. J. physiol., 126: 206-33, 1954.
27. Randall, W. C. Reflex sweating responses and the influence of arterial occlusion upon sweat gland activity. Fed. Proc. 6: 183-84, 1947.
28. Randall, W. C., Deering, R., and Dougherty, J. Reflex sweating and the inhibition of sweating by prolonged arterial occlusion. J. Appl. Physiol., 1: 53-59, 1948.
29. Isekutz, B., Hetenyi, G., and Doisy, A. The physiology of sweat secretion. Arch. Intern. Pharmacodynamie, 83: 133-42, 1950.
30. Kuno, Y. Human Perspiration. Springfield, Ill.: C. C. Thomas Co., 1956.
31. Evans, C. L. Principles of Human Physiology. Philadelphia: Lea and Febiger, 1952.
32. Rothman, S. Physiology and Biochemistry of the Skin. Chicago: Univ. of Chicago Press, 1954.
33. Fulton, J. F. Textbook of Physiology. Philadelphia: W. B. Saunders and Co., 1954.
34. Head, H., and Riddoch, G. The automatic bladder, excessive sweating and some other reflex conditions, in gross injuries of the spinal cord. Brain, 40: 188-263, 1917.
35. List, C. F., and Piments, A. D. Sweat secretion in man: Spinal reflex sweating. Arch. Neurol. and Psychiat., 51: 501-507, 1944.
36. Gilliat, R. W., Guttman, L., and Whitteridge, J. Inspiratory vasoconstriction in patients after spinal injuries. J. Physiol., 197: 67-88, 1948.
37. Pyzik, S. W. Defects in the regulatory mechanisms of autonomic function in injuries to the spinal cord. Proc. Clin. Paraplegia Conf. 5: 78-80, 1956.

38. Pollock, L. J., Boshes, B., Chor, H., Finkelman, J., Arieff, A. J., and Brown, M. Defects in regulatory mechanisms of autonomic functions in injuries to the spinal cord. *J. Neurophysiol.*, 14: 85-93, 1951.
39. Guttman, L. Ein neues einfaches Colorimetrisches Verfahren zur Untersuchung der Schweissdrusenfunktion. *Klin. Wschr.* 16: 212-13, 1937.
40. Minor, V.: Eines neues Verfahren zu der klinischen Untersuchung der Schweissabsonderung, *Deutsche Ztschr. f. Nervenhe.* 101: 302-08, 1927.
41. Riddoch, G. The reflex functions of the completely divided spinal cord in man, compared with those associated with less severe lesions. *Brain*, 40: 264-402, 1917.
42. Guttman, L., and Whitteridge, D. W. Effects of bladder distension on autonomic mechanisms after spinal cord injuries. *Brain*, 70: 361-404, 1947.
43. Randall, W. C. Sweat gland activity and changing patterns of sweat secretion on the skin surface. *Am. J. Physiol.* 147: 391-98, 1946.
44. Hardy, J. D. and Stoll, A. M. Radiometric measurement of skin temperatures. Methods in Medical Research, Vol. 6, Chicago: Year Book Publishers, 1954.
45. Foerster, O. Die Symptomatologie der Schussverletzungen der peripheren Nerven, *Handb. f. Neurol.*, 1485, 1929.
46. DuBois, D., and DuBois, E. F. Clinical Calorimetry. The measurement of surface area of man. *Arch. Int. Med.*, 15: 868, 1915.
47. Thomas, P. E., and Korr, I. M. Significance of areas of low electrical skin resistance. *Fed. Proc.* 11: 162, 1952.

APPROVAL SHEET

The dissertation submitted by Russell C. Seckendorf has been read and approved by five members of the faculty of the Graduate School.

The final copies have been examined by the director of the dissertation and the signature which appears below verifies the fact that any necessary changes have been incorporated, and that the dissertation is now given final approval with reference to content, form, and mechanical accuracy.

The dissertation is therefore accepted in partial fulfillment of the requirement for the Degree of Doctor of Philosophy.

4-23-59
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