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THE EFFECT OF MICROWAVE DIATHERMY ON THE PERIPHERAL CIRCULATION AND ON TISSUE TEMPERATURE IN MAN *

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Microwaves are electromagnetic radiations with wavelengths between 1 meter and 1 millimeter.[1] This corresponds to a frequency range of 300 to 300,000 megacycles per second. Their optical properties, which enable them to be reflected, refracted, diffracted and polarized, may make these radiations convenient for therapeutic use, for they can be focused and directed. Microwaves could be used therapeutically to produce heat, when an oscillator with sufficient power output could be manufactured. The magnetron, an oscillator which could generate microwaves, was described by A. W. Hull[2] in 1921, but its output was too low. During the two decades from 1921 to 1940, a few types of magnetrons were developed, with progressive increases in the power output and frequency. By 1940 the British had developed the magnetron to the point at which there was a high power output even at the highest frequencies of the microwave range.[3] This multicavity magnetron was brought to the United States, and the first American experiment was performed on Oct. 6, 1940.[4] Although the energy output was sufficiently high, the use of the magnetron for military purposes prevented investigation of its therapeutic potentialities at that time.

The first reports concerning the biologic effects of microwaves appeared during World War II and were concerned with very short bursts of energy, such as were used in connection with radar work. Follis[5] showed that radiations of this type had no ill effects on guinea pigs. Leden and associates[6] studied the effects of microwaves on trained and anesthetized dogs and found that there was an increase of cutaneous, subcutaneous and muscle temperatures in the exposed extremity, accompanied with an increase of blood flow. Worden[7] and his co-workers found increases in the temperature of normal and ischemic tissue in the dog after exposure to microwaves. Kemp and his associates[8] reported an increase of blood flow in the anesthetized dog after microwave diathermy. After having obtained definite heating of

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1. Brownell, A. B., and Beam, R. E.: Theory and Application of Microwaves, ed. 1, New York, McGraw-Hill, 1947.
2. Hull, A. W.: Physical Rev. 18:31, 1921.
3. Hagstrum, H. D.: Proc. Institute Radio Engineers 35:548, 1947.
4. Fisk, J. B.; Hagstrum, H. D., and Hartman, P. L.: Bell System Tech. J. 25:167, 1946.
5. Follis, R. H., Jr.: Am. J. Physiol. 147:281, 1946.
6. Leden, Ursula M.; Herrick, J. F.; Wakim, K. G., and Krusen, F. H.: Brit. J. Phys. Med. 10:177, 1947.
7. Worden, R.: Unpublished data.
8. Kemp, C. R.; Paul, W. D., and Hines, H. M.: Arch. Phys. Med. 29:12, 1948.

tissues in animals in our laboratories on exposure of various regions of the body to microwaves, we decided to study the effects of microwaves on normal human beings. The purpose of this study was to determine the effect of various outputs of microwaves and of different periods of exposure to microwave diathermy on the peripheral circulation and on the tissue temperature in the exposed limb of man. Special attention was directed toward the determination of the optimal effects on tissue temperature and on the peripheral circulation.

Method

This study was made on 50 normal human subjects, 37 men and 13 women. The total number of observations made was 254. These were divided into two groups, one of which consisted of temperature studies and the other of blood flow studies. In the group in which attention was directed primarily toward tissue temperature, the temperatures were recorded by means of copper-constantan thermocouples. The muscle thermocouple was inserted to a depth of 1.5 cm. The subcutaneous thermocouple was 1.9 cm. long and was inserted so that the entire shaft was underneath the skin, with the recording tip near the shaft of the muscle thermocouple. The cutaneous thermocouple was placed on the skin close to the other two but not in contact with either. It was weighted so that it would exert identical pressure on the skin in all observations. The three thermocouples were placed in the zone of maximal energy according to antenna pattern, which in this case is 3 mm. outside the outer margin of the director of the microwave generator, in an area where there were no visible blood vessels. The galvanometer deflection which resulted from the difference of temperature between the reference and the recording thermocouples was recorded visually. The studies on blood flow were done on the exposed and on the contralateral extremity with the venous occlusion plethysmograph and the compensating spirometer recorder.[9] In the group in which observations on blood flow were made, the cutaneous temperature was taken both on the exposed and on the unexposed extremity by means of a thermistor.

The source of the microwaves to which the forearm was exposed was the air-cooled multicavity magnetron. The frequency of these electromagnetic radiations was 2,450 megacycles per second (corresponding to a wavelength of approximately 12 cm.). The energy was transported from the oscillator to the director by means of a coaxial cable. The hemispherical director, with a diameter of approximately 9 cm., was used in this study. The distance from director to skin was 5 cm. in all the observations.

Control readings of peripheral blood flow or temperature of the tissues or both were determined after the subject had been lying quietly for at least half an hour in a room the temperature of which did not vary during the observations. Exposure to the microwaves was not begun until the blood flow and the temperature were fairly constant. The microwaves were applied to the volar surface of the forearm, with the proximal margin of the director approximately 8 cm. from the elbow. In all but 26 observations blood flow readings were taken five minutes after the end of the period of exposure to the microwaves. In these 26 observations, which will be referred to later, the first blood flow readings were taken on an average of 6.8 minutes after the microwaves had been turned off. In some experiments additional blood flow determinations were made ten minutes after exposure to microwaves. In those subjects on whom blood flow studies were made, the cutaneous temperature was taken on the exposed extremity immediately after exposure to microwaves and again one minute after. The temperature of the unexposed extremity was taken one minute after exposure to microwaves. In those subjects whose temperatures were taken by means of thermocouples the first readings were taken one minute after the end of heating. Since the thermocouples could not be left in place during the period of exposure because of the heating which occurs in metals in the radiation field, marks were made on the skin so that they would be inserted at the same place. Additional readings were often taken every minute for five minutes, while in a few subjects the temperature study was continued for forty minutes, with readings taken at five-minute intervals.

In 133 observations the oral temperature was taken, and in 73 observations the pulse rate also was taken before and after exposure to microwaves.

9. Berry, M. R.; Baldes, E. J.; Essex, H. E., and Wakim, K. G.: J. Lab. & Clin. Med. 33:101, 1948.

Results

Temperature Studies (Table 1; Charts 1, 2, and 3). — One Minute of Exposure at 80 Watts (10 Observations): The average rise of cutaneous temperature was 1.6 degrees C., with a range from 0.8 to 2.2 degrees; the average rise of subcutaneous temperature was 1.8 degrees C., with a range from 1.3 to 2.6 degrees; the average rise of muscle temperature was 1.4 degrees, with a range from 1.0 to 1.7 degrees. The maximal temperature reached in the skin was 35.8 C.; in the subcutaneous tissue and in the muscle the maximal temperature was 36.7 C. In 3 observations the greatest rise of temperature took place in the skin; in 4 the greatest rise occurred in the subcutaneous tissue; in 2 the rise of temperature was the same in skin and subcutaneous tissue, and in 1 the rise of temperature of subcutaneous tissue

TABLE 1. — *Effect of Microwaves on Temperature of Skin, Subcutaneous Tissue and Muscle.*

Dosage, Watts	Duration of Heating, Min.	Observations	Cutaneous Temperature, °C. Before Exposure Mean	S.D.	After Exposure Mean	S.D.	Increase Mean	S.D.	Subcutaneous Temperature, °C. Before Exposure Mean	S.D.	After Exposure Mean	S.D.	Increase Mean	S.D.	Muscle Temperature, °C. Before Exposure Mean	S.D.	After Exposure Mean	S.D.	Increase Mean	S.D.
80	1	10	33.8	0.30	35.4	0.26	1.6	0.47	34.3	0.28	36.1	0.31	1.8	0.45	34.8	0.20	36.2	0.20	1.4	0.23
80	5	26	32.8	0.96	37.3	1.14	4.5	1.02	33.6	1.07	38.8	1.25	5.2	1.31	34.0	1.28	39.5	1.34	5.5	1.19
80	10	25	33.5	0.97	38.3	1.07	4.8	1.38	33.9	1.20	39.6	1.42	5.7	1.86	34.7	1.10	40.8	1.93	6.1	1.43
80	15	10	32.7	1.47	37.5	0.61	4.8	1.72	33.8	1.84	39.3	0.64	5.5	2.38	34.4	1.66	41.1	0.56	6.7	1.32
80	20	25	33.5	0.97	38.2	1.43	4.7	1.64	33.9	1.20	39.7	1.51	5.8	1.81	34.7	1.10	41.4	1.40	6.7	1.74
80	25	10	33.7	0.46	38.0	0.46	4.3	0.77	34.0	0.42	39.0	0.53	5.0	0.65	34.7	0.24	40.0	0.82	5.3	0.84
80	30	10	33.0	0.45	35.9	0.57	2.9	1.01	34.2	0.64	37.6	0.78	3.4	1.28	34.7	0.46	39.0	1.02	4.3	1.29
60	15	10	33.5	0.74	37.6	0.49	4.1	0.80	34.5	0.63	39.3	0.63	4.8	1.00	34.7	0.60	40.9	0.28	6.2	0.62
60	20	10	32.4	0.75	37.4	0.85	5.0	0.75	33.4	0.70	38.8	1.05	5.4	1.11	34.3	0.64	40.9	0.72	6.6	0.63
60	30	10	33.0	0.31	36.7	0.56	3.7	0.60	34.2	0.40	38.2	0.79	4.0	0.84	34.8	0.32	40.2	0.84	5.4	0.83

and muscle was the same. The preheating temperature was highest in the muscle in all 10 observations. After the completion of the exposure to microwaves, the temperature was highest in the muscle in 8 observations and highest in the subcutaneous tissue in 2.

Five Minutes of Exposure at 80 Watts (26 Observations): The average rise of cutaneous temperature was 4.5 degrees C., with a range from 3.0 to 7.3 degrees; the average rise of subcutaneous temperature was 5.2 degrees, with a range from 2.3 to 7.5 degrees; the average rise of muscle temperature was 5.5 degrees, with a range from 3.9 to 8.6 degrees. The maximal temperature reached was 39.4 C. in the skin, 41.2 C. in the subcutaneous tissue and 41.7 C. in the muscle. In 10 observations the greatest rise of temperature took place in the subcutaneous tissue; in 14 the greatest increase occurred in the muscle; in 1 observation the rise of cutaneous and subcutaneous temperature was the same, while in 1 instance the rise of subcutaneous and muscle temperature was identical. The preheating temperature was highest in the subcutaneous tissue in 4 observations and highest in the muscle in 22. After exposure to microwaves the temperature was highest in the subcutaneous tissue in 4 and highest in the muscle in 22 observations.

Ten Minutes of Exposure at 80 Watts (25 Observations): The average rise of cutaneous temperature was 4.8 degrees C., with a range from 1.9 to 8.8 degrees; the average rise of subcutaneous temperature was 5.7 degrees, with a range from 2.7 to 10.6 degrees; the average rise of muscle temperature was 6.1 degrees, with a range from 2.8 to 9.1 degrees. The maximal temperature reached was 40.9 C. in the skin, 43.0 C. in the subcutaneous tissue and 44.2 C. in the muscle. The greatest rise of temperature occurred in the muscle in 13 observations, in the subcutaneous tissue in 10 observations and in the skin in only 2 observations. The preheating temperature was highest in the subcutaneous tissues in 3 observations, highest in the muscle in 21 and identical in subcutaneous tissue and muscle in 1. The temperature after heating was highest in the skin in 1 instance, highest in the subcutaneous tissue in 4 and highest in the muscle in 20.

Fifteen Minutes of Exposure at 80 Watts (10 Observations): The average rise of cutaneous temperature was 4.8 degrees C., with a range from 2.6 to 7.8 degrees; the average rise of subcutaneous temperature was 5.5 degrees, with a range from 1.8 to 8.9 degrees; the average rise of muscle temperature was 6.7 degrees, with a range from 5.2 to 9.3 degrees. The maximal temperature reached was 38.6 C. in the skin, 40.2 C. in the subcutaneous tissue and 42.0 C. in the muscle. The greatest rise of temperature took place in the subcutaneous tissue in 2 observations and in the muscle in 8. The preheating temperature was highest in the subcutaneous tissue in 1 observation, highest in the muscle in 7 and identical in subcutaneous tissue and muscle in 2. The temperature after exposure to microwaves was highest in the muscle in all 10 observations.

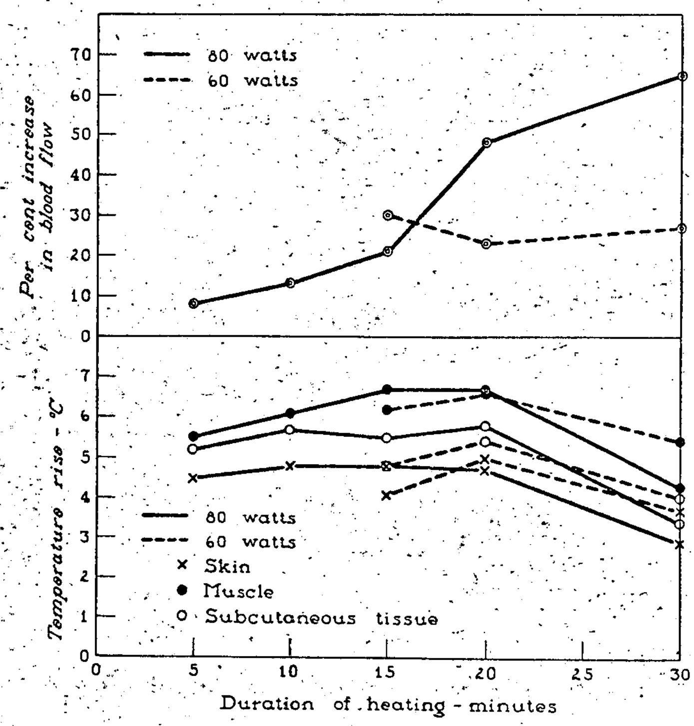


Chart 1. — Effects of exposure to microwaves (60 and 80 watts) on blood flow and on tissue temperature in the treated extremity. Blood flow readings were taken five minutes after microwaves had been turned off. Temperature readings were taken one minute after microwaves had been turned off. Each point is the average of 9 to 26 observations, as indicated in tables 1 and 3.

Twenty Minutes of Exposure at 80 Watts (25 Observations): The average rise of cutaneous temperature was 4.7 degrees C., with a range from 1.1 to 9.3 degrees; the average rise of subcutaneous temperature was 5.8 degrees, with a range from 3.1 to 9.9 degrees; the average rise of muscle temperature was 6.7 degrees, with a range from 2.8 to 11.1 degrees. The maximal temperature reached was 42.8 C. in the skin, 44.2 C. in the subcutaneous tissue and 45.0 C. in the muscle. The greatest rise of temperature occurred in the skin in 1 observation, in the subcutaneous tissue in 5 and in the muscle in 18, while in 1 observation the rise of temperature of subcutaneous tissue and muscle was the same. The temperature before exposure to microwaves was highest in the subcutaneous tissue in 3 observations and highest in the muscle in 21, while in 1 these two tissues were at the same temperature. After heating, the temperature was highest in the

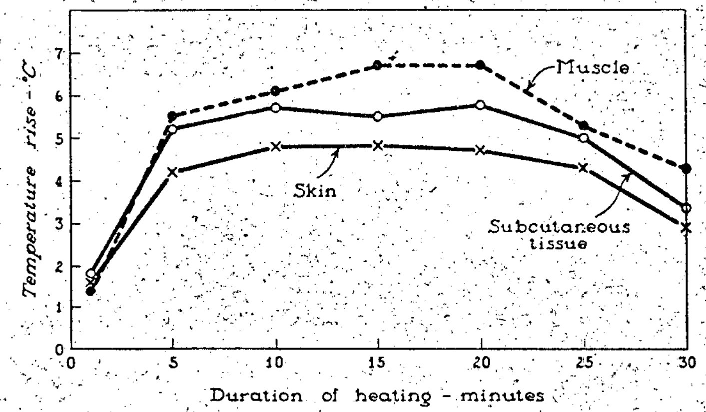


Chart 2. — Effects of exposure to microwaves (80 watts) on tissue temperature in the treated extremity. Temperature readings were taken one minute after microwaves had been turned off. Each point is the average of 10 to 26 observations, as indicated in table 1.

skin in 1 observation, highest in the subcutaneous tissue in 2, highest in the muscle in 21 and the same in subcutaneous tissue and muscle in 1.

Twenty-Five Minutes of Exposure at 80 Watts (10 Observations): The average rise of cutaneous temperature was 4.3 degrees C., with a range from 3.5 to 5.8 degrees; the average rise of subcutaneous temperature was 5.0 degrees, with a range from 4.3 to 6.6 degrees; the average rise of muscle temperature was 5.3 degrees, with a range from 4.1 to 6.5 degrees. The

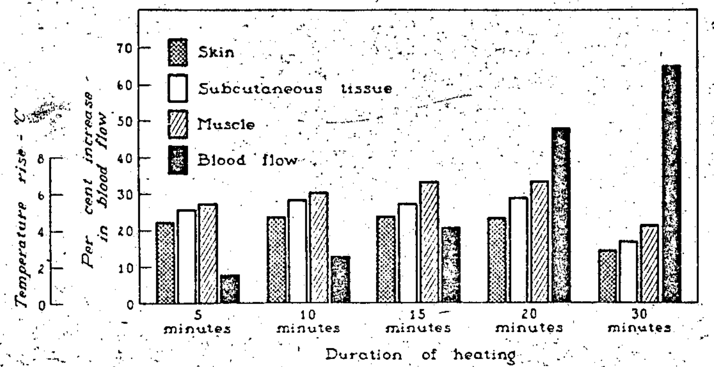


Chart 3. — Effects of exposure to microwaves (80 watts) on blood flow and on tissue temperature in the treated extremity. Blood flow readings were taken five minutes after the microwaves had been turned off. Temperature readings were taken one minute after the microwaves had been turned off. The height of each bar represents the average of 9 to 26 observations, as indicated in tables 1 and 3.

maximal temperature reached was 38.9 C. in the skin, 39.7 C. in the subcutaneous tissue and 41.0 C. in the muscle. The greatest rise of temperature took place in the subcutaneous tissue in 4 observations and in the muscle in 6. The temperature was highest in the muscle before and after exposure to microwaves in all 10 observations.

Thirty Minutes of Exposure at 80 Watts (10 Observations): The average rise of cutaneous temperature was 2.9 degrees C., with a range from 1.0 to 4.3 degrees; the average rise of subcutaneous temperature was 3.4 degrees, with a range from 0.8 to 4.9 degrees; the average rise of muscle temperature was 4.3 degrees, with a range from 1.3 to 6.0 degrees. The maximal temperature reached was 36.7 C. in the skin, 38.7 C. in the subcutaneous tissue and 40.3 C. in the muscle. In 1 observation the greatest temperature rise occurred in the subcutaneous tissue, while in the other 9 the greatest increase took place in the muscle. In all 10 observations the highest temperature was in the muscle both before and after exposure to microwaves.

Fifteen Minutes of Exposure at 60 Watts (10 Observations): The average rise of cutaneous temperature was 4.1 degrees C., with a range from 3.2 to 5.4 degrees; the average rise of subcutaneous temperature was 4.8 degrees, with a range from 3.2 to 6.0 degrees; the average rise of muscle temperature was 6.2 degrees, with a range from 5.1 to 6.9 degrees. The maximal temperature reached was 38.3 C. in the skin, 40.2 C. in the subcutaneous tissue and 41.3 C. in the muscle. In all 10 observations the greatest temperature rise occurred in the muscle. Before exposure to microwaves the temperature was highest in the subcutaneous tissue in 1 observation, highest in the muscle in 7 observations and identical in the two tissues in 2 observations. After exposure to microwaves the temperature was highest in the muscle in all 10 observations.

Twenty Minutes of Exposure at 60 Watts (10 Observations): The average rise of cutaneous temperature was 5.0 degrees C., with a range from 3.8 to 5.8 degrees; the average rise of subcutaneous temperature was 5.4 degrees, with a range from 3.7 to 7.0 degrees; the average rise of muscle temperature was 6.6 degrees, with a range from 5.5 to 7.8 degrees. The maximal temperature reached was 38.5 C. in the skin, 40.1 C. in the subcutaneous tissue and 42.1 C. in the muscle. The greatest rise of temperature took place in the subcutaneous tissue in 1 observation and in the muscle in 9 observations. The preheating and the postheating temperatures were highest in the muscle in all 10 observations.

Thirty Minutes of Exposure at 60 Watts (10 Observations): The average rise of cutaneous temperature was 3.7 degrees C., with a range from 2.3 to 4.2 degrees; the average rise of subcutaneous temperature was 4.0 degrees, with a range from 2.2 to 5.2 degrees; the average rise of muscle temperature was 5.4 degrees, with a range from 4.0 to 6.4 degrees. The maximal temperature reached was 37.4 C. in the skin, 39.6 C. in the subcutaneous tissue and 41.3 C. in the muscle. The greatest rise of temperature occurred in the muscle in all 10 observations. Both the preheating and the postheating temperatures were highest in the muscle in all 10 observations.

Rate of Cooling: In 51 observations the temperatures of the skin, subcutaneous tissue and muscle were recorded every minute for five minutes after the microwaves had been turned off. For all three tissues the rate of reduction of temperature decreased with the passage of time. During the second minute after the microwaves had been turned off, the greatest reduction of temperature occurred in the subcutaneous tissue. After that the fall of temperature was greatest in the muscle (table 2; chart 4). In 11 observations the temperatures were recorded for fifteen minutes or longer after the termination of exposure to microwaves. In 9 of these observations exposure was for five minutes at 80 watts, and in 2 it was for twenty minutes at 60 watts. In 1 of these 11 observations the subcutaneous temperature returned to the control level forty-five minutes after the microwaves had been turned off. In no other instance did the temperature return to the control value during the period of observation.

Site of Highest Temperature: Temperature studies of the tissues were done in 146 observations. The control temperature was highest in the subcutaneous tissue in 12, was highest in the muscle in 128 and was the same in subcutaneous tissue and muscle in 6. After exposure to microwaves the temperature was highest in the skin in 2, in the subcutaneous tissue in 10 and in the muscle in 133 and was the same in subcutaneous tissue and mus-

TABLE 2. — *Change of Tissue Temperature After Cessation of Heating.*

Time After Cessation of Heating, Minutes	Temperature Decrease, Degrees Centigrade		
	Skin	Subcutaneous Tissue	Muscle
1 to 2	0.46	0.72	0.64
2 to 3	0.36	0.44	0.53
3 to 4	0.23	0.30	0.41
4 to 5	0.19	0.20	0.33

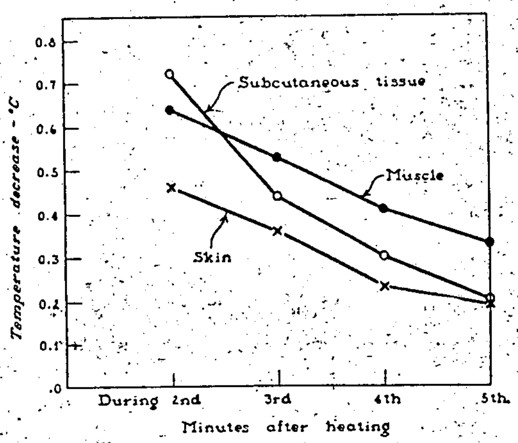


Chart 4. — Decrease of temperature of skin, subcutaneous tissue and muscle after microwaves had been turned off (for example, the temperature decrease during the second minute after the microwaves had been turned off is equal to the temperature at one minute minus that at two minutes). Each point is the average of 51 observations.

cle in 1. In these 146 observations the preheating temperature gradient was changed in only 8 observations as a result of exposure to microwaves. In these 8 observations the changes of temperature gradient were as follows: In 5 the preheating temperature was the same in subcutaneous tissue and muscle, while, after heating, the temperature was highest in the muscle; in 1 the highest control temperature was in the subcutaneous tissue, and, after heating, it was in the skin; in 1 the highest control temperature was in the subcutaneous tissue, and, after heating, it was in the muscle; in the remaining 1 the highest preheating temperature was in the muscle, while the highest temperature after heating was in the skin.

Blood Flow Studies (Tables 3 and 4; Charts 1 and 3). — Five Minutes of Exposure at 80 Watts (20 Observations): There was an average increase of 8 per cent in the blood flow in the exposed extremity, with a range from -25 per cent to +44 per cent. In the unexposed extremity there was an average decrease of blood flow of 2 per cent. The average increase of cutaneous temperature in the exposed extremity was 5.0 degrees C. immediately after and 4.2 degrees one minute after the microwaves had been turned off. The average rise of cutaneous temperature in the unexposed extremity was 0.2 degree C. In 6 observations in which oral temperature was taken before and after exposure to microwaves, it averaged 98.5 F. both before and after exposure.

Ten Minutes of Exposure at 80 Watts (20 Observations): There was an average increase of 13 per cent in the blood flow in the exposed extremity, with a range from –5 per cent to +40 per cent. In the unexposed extremity there was an average decrease of blood flow of .5 per cent. The average rise of cutaneous temperature in the exposed extremity was 5.2

Table 3. — *Effects of Microwaves on the Blood Flow in the Treated Extremity*

Output, Watts	Duration of Heating, Min.	Observations	Flow Before Heating, Cc. Per Min. Mean	S.D.	Flow After Heating, Cc. Per Min. Mean	S.D.	Increase of Flow, Cc. Per Min. Mean	S.D.	Percentage* Increase of Flow Mean	S.D.	Flow Before Heating, Cc. Per 100 Cc. Mean	S.D.	Flow After Heating, Cc. Per 100 Cc. Mean	S.D.	Increase of Flow, Cc. Per 100 Cc. Mean	S.D.	Percentage† Increase of Flow, Mean
80	5	20	161	59.4	176	75.9	15	31.0	8	17.5	9.16	3.14	9.94	4.04	0.8	1.9	8
80	10	20	162	57.3	179	75.2	17	21.9	12	13.3	9.10	3.58	10.30	3.82	1.2	1.3	13
80	15	9	109	39.3	135	50.0	26	26.1	25	19.3	7.76	2.42	9.42	1.93	1.7	1.5	21
80	17	10	96	26.0	127	20.1	31	18.5	38	29.5	5.67	1.21	7.59	1.31	1.9	1.4	33
80	20	20	104	50.2	151	61.8	48	26.1	55	37.0	6.90	2.50	10.20	2.62	3.3	1.7	48
80	25	10	95	23.8	158	25.3	63	21.0	75	48.4	5.50	1.21	9.25	1.74	3.7	1.5	67
80	27	10	91	21.8	150	34.7	59	20.0	67	21.8	6.68	2.46	10.61	3.04	3.9	1.2	59
80	30	10	109	59.2	173	59.5	63	40.0	76	57.3	6.93	2.42	11.45	3.32	4.5	3.1	65
60	15	10	117	31.9	153	41.4	36	23.6	33	22.9	8.27	2.98	10.76	3.63	2.5	1.6	30
60	20	13	81	31.6	97	36.5	17	22.9	27	33.6	6.58	2.08	8.12	3.26	1.5	2.3	23
60	30	12	98	43.1	124	49.0	26	23.1	37	36.5	6.84	2.46	8.71	2.12	1.9	1.7	27

* Average of the percentage increase for all observations in a group (as indicated under the number of observations).
† Ratio of the average increase of flow after heating to the average flow before heating, in cc. per 100 cc. of tissue.

degrees C. immediately after exposure to microwaves and 4.5 degrees one minute after. The average rise of cutaneous temperature in the unexposed extremity was 0.1 degree C. Oral temperature was taken in all 20 observations. The average oral temperature remained the same before and after heating — namely, 98.4 F.

Fifteen Minutes of Exposure at 80 Watts (9 Observations): The average increase of blood flow in the exposed extremity five minutes after the microwaves had been turned off was 21 per cent, with a range from —10 per cent to +48 per cent. Ten minutes after heating the average increase

Table 4. — *Effect of Microwaves on the Blood Flow in the Untreated Extremity.*

Output, Watts	Duration of Heating, Minutes	Observations	Flow Before Heating, Cc. Per 100 Cc. Mean	S.D.	Flow After Heating, Cc. Per 100 Cc. Mean	S.D.	Change of Flow, Cc. Per 100 Cc. Mean	S.D.	S. E.* Cc. Per 100 Cc.	t	P	Change of Flow, Percent
80	5	20	9.87	4.00	9.65	4.54	—0.22	1.98	0.45	0.49	0.7–0.6	—2
80	10	20	9.10	3.59	8.60	3.40	—0.50	1.07	0.24	2.08	0.05	—5
80	15	9	7.76	2.50	6.96	2.18	—0.80	1.13	0.38	2.18	0.1–0.05	—10
80	17	10	7.12	1.73	7.13	1.66	+0.01	1.33	0.42	0.02	>0.9	0
80	20	20	7.60	3.24	8.00	3.52	+0.40	1.41	0.32	1.25	0.3–0.2	+5
80	20†	26	8.20	2.04	7.30	2.26	—0.90	2.72	0.53	1.70	0.1	—11
80	25	10	5.60	1.17	6.24	1.37	+0.64	0.77	0.24	2.66	0.05–0.02	+11
80	27	10	6.65	1.64	6.66	1.01	+0.01	1.34	0.42	0.72	>0.09	0
80	30	10	7.24	2.73	7.79	1.82	+0.55	2.24	0.71	0.77	0.5–0.4	+8
60	15	10	8.05	2.36	8.29	2.39	+0.24	2.12	0.67	0.36	0.8–0.7	+3
60	20	13	7.06	3.30	6.05	1.83	—1.01	2.73	0.76	1.33	0.3–0.2	—14
60	30	12	6.79	2.18	7.03	2.44	+0.24	1.85	0.54	0.44	0.7–0.6	+4

* Standard error of mean change.
† Blood flow readings in this group of observations were taken on an average of 6.8 minutes after cessation of exposure to microwaves.

of blood flow in the treated extremity was 14 per cent. In the unexposed extremity there was an average decrease of blood flow of 10 per cent. In the exposed extremity the average rise of cutaneous temperature immediately after the microwaves had been turned off was 6.0 degrees C., while, one minute after, it was 5.1 degrees. The average rise of cutaneous temperature of the unexposed extremity was 0.6 degree. In 19 observations (which included the group in which temperature studies were made) the average oral temperature both before and after heating was 98.4 F. The average pulse rate in these observations was 67 per minute before and remained the same after microwave diathermy.

Seventeen Minutes of Exposure at 80 Watts (10 Observations): The average increase of blood flow in the exposed extremity was 33 per cent, with a range from -4 per cent to +93 per cent. In the unexpected extremity there was no change of blood flow.

Twenty Minutes of Exposure at 80 Watts (46 Observations): In 20 of the 46 observations the first blood flow readings after heating were made five minutes after the completion of the twenty-minute exposure to microwaves. The average increase of blood flow in these 20 observations was 48 per cent, with a range from —4 per cent to +174 per cent. At ten minutes the average increase of blood flow was 43 per cent. In the unexposed extremity there was an average increase of blood flow of 5 per cent. In 26 of the 46 observations the first studies were made on an average of 6.8 minutes after the twenty-minute exposure to microwaves. In these 26 observations the average increase of blood flow was 40 per cent, with a range from -37 per cent to +120 per cent. In the unheated extremity there was an average decrease of blood flow of 11 per cent. Immediately after heating, the average rise of cutaneous temperature in the heated extremity was 5.6 degrees C., while, one minute after, the rise was 4.8 degrees. The rise of cutaneous temperature of the unheated extremity was, on the average, 0.7 degree C. Oral temperature was taken before and after heating in 30 observations. The average preheating temperature was 98.2 F., while the average postheating temperature was 98.3 F.

Twenty-Five Minutes of Exposure at 80 Watts (10 Observations): The average increase of blood flow in the treated extremity was 67 per cent, was with a range from +30 per cent to +202 per cent. Although it is this value (67 per cent), which is plotted in the curve analysis to be considered later, it should be noted that 1 observation was far above the range of increase of the other 9 observations. If this value (+202 per cent) is omitted, the average increase of blood flow becomes +59 per cent, with a range from +30 per cent to +88 per cent. This value is much closer to the theoretical curve derived. In the unexposed extremity there was an average increase of blood flow of 11 per cent.

Twenty-Seven Minutes of Exposure at 80 Watts (10 Observations): The average increase of blood flow in the extremity exposed to microwaves was 59 per cent, with a range from +32 per cent to +98 per cent. In the unexposed extremity the average flow before exposure to microwaves was the same as that after exposure.

Thirty Minutes of Exposure at 80 Watts (10 Observations): The average increase of blood flow in the heated extremity five minutes after the microwaves had been turned off was 65 per cent, with a range from +11 per cent to +199 per cent. At ten minutes the average increase of flow was 59 per cent. In the unheated extremity there was an average increase of blood flow of 8 per cent. Immediately after exposure to microwaves the average rise of cutaneous temperature in the heated extremity was 4.4 degrees C., while at one minute the average rise was 3.6 degrees. The average rise of cutaneous temperature in the unheated extremity was 0.3 degree. Oral temperatures were taken in 19 observations (including the group in which temperature studies were made). The average preheating temperature was

98.3 F., while the average postheating temperature was 98.5 F. In these 19 observations the average pulse rate before heating was 67 per minute, while after heating it was 65 per minute.

Fifteen Minutes of Exposure at 60 Watts (10 Observations): The average increase of blood flow in the heated extremity five minutes after the microwaves had been turned off was 30 per cent, with a range from –3 per cent to +73 per cent. Ten minutes after exposure to microwaves the average increase of blood flow was 37 per cent. In the unexposed extremity there was an average increase of blood flow of 3 per cent. In 12 observations (including the group in which temperature studies were made) the average preheating oral temperature was 98.1 F. and the average postheating temperature was 98.2 F. In these 12 observations the average pulse rate before heating was 66 per minute and, after heating, it was 67 per minute.

Twenty Minutes of Exposure at 60 Watts (13 Observations): Five minutes after exposure to microwaves the average increase of blood flow of the heated extremity was 23 per cent, with a range from –30 per cent to +92 per cent. Ten minutes after heating, the average increase of flow was still 23 per cent. In the unheated extremity there was an average decrease of blood flow of 14 per cent. Immediately after exposure to microwaves the average rise of cutaneous temperature in the heated extremity was 5.9 degrees C., while after one minute the average rise was 5.2 degrees. The average rise of cutaneous temperature of the unheated extremity was 0.5 degree. In 14 observations (including the group in which temperature studies were made) the average preheating oral temperature was 98.4 F., while the average temperature after heating was 98.5 F. The average control pulse rate in 8 observations was 65 per minute and, after heating, it was 69 per minute.

Thirty Minutes of Exposure at 60 Watts (12 Observations): Five minutes after the microwaves had been turned off there was an average increase of the blood flow of the heated extremity of 27 per cent, with a range from –28 per cent to +104 per cent. At ten minutes the average increase of blood flow was 19 per cent. In the unexposed extremity there was an average increase of blood flow of 4 per cent. Immediately after the microwaves had been turned off, the average rise of cutaneous temperature in the heated extremity was 4.9 degrees C. and one minute after, it was 4.2 degrees. The average rise of cutaneous temperature of the unheated extremity was 0.7 degree. In 13 observations (including the group in which temperature studies were made) the average preheating oral temperature was 98.3 F. while after heating it was 98.4 F. The average control pulse rate was 67 per minute, and the pulse rate remained unchanged after heating.

Statistical Analysis of Data

Although the average increase of temperature was greater for muscular tissue than for skin or subcutaneous tissue in every group but one (exposure for one minute at 80 watts), it was important to determine how significant this difference in temperature rise was. In tables 5 and 6 a comparison between the heating of skin, subcutaneous tissue and muscle is given. The temperature rise of muscle was significantly greater than that of subcutaneous tissue, while the temperature rise of subcutaneous tissue was significantly greater than that of skin.

Another important problem was the comparison of blood flow and tissue temperature after identical periods of exposure, but at different outputs. Chart 5 shows the difference in effect between 60 watt and 80 watt exposure.

Tables 7 and 8 give the statistical data which enable one to compare the effect of the two outputs used in this study.

After comparing the effects of different outputs at any given time interval, we studied the effect of various durations of heating at one output. The temperature changes after exposure of the forearm for different periods at 60 and at 80 watts and the change of blood flow after exposure at 60 watts

TABLE 5. — *Comparison of Temperature Rise of Skin, Subcutaneous Tissue and Muscle After Exposure to Microwaves.*

Data Compared	Observations	Difference Between Means, °C.	Standard Error, °C.	*t*	*P*
1 minute heat; 80 watts	10 + 10				
Subcutaneous > skin		0.2	0.20	1.00	0.4–0.3
Subcutaneous > muscle		0.4	0.16	2.50	0.02
Skin > muscle		0.2	0.17	1.18	0.3–0.2
5 minutes heat; 80 watts	26 + 26				
Subcutaneous > skin		0.7	0.33	2.12	0.05–0.02
Muscle > subcutaneous		0.3	0.35	0.86	0.4–0.3
Muscle > skin		1.0	0.30	3.33	0.001
10 minutes heat; 80 watts	25 + 25				
Subcutaneous > skin		0.9	0.46	1.96	0.05
Muscle > subcutaneous		0.4	0.47	0.85	0.4–0.3
Muscle > skin		1.3	0.40	3.25	0.01–0.001
15 minutes heat; 80 watts	10 + 10				
Subcutaneous > skin		0.7	0.93	0.75	0.5–0.4
Muscle > subcutaneous		1.2	0.86	1.39	0.2–0.1
Muscle > skin		1.9	0.66	2.88	0.02–0.01
20 minutes heat; 80 watts	25 + 25				
Subcutaneous > skin		1.1	0.49	2.24	0.05–0.02
Muscle > subcutaneous		0.9	0.50	1.80	0.1–0.05
Muscle > skin		2.0	0.48	4.16	<0.001
25 minutes heat; 80 watts	10 + 10				
Subcutaneous > skin		0.7	0.32	2.19	0.05–0.02
Muscle > subcutaneous		0.3	0.34	0.88	0.4–0.3
Muscle > skin		1.0	0.36	2.78	0.01
30 minutes heat; 80 watts	10 + 10				
Subcutaneous > skin		0.5	0.52	0.95	0.4–0.3
Muscle > subcutaneous		0.9	0.58	1.56	0.2–0.1
Muscle > skin		1.4	0.52	2.70	0.02–0.01
15 minutes heat; 60 watts	10 + 10				
Subcutaneous > skin		0.7	0.40	1.74	0.1
Muscle > subcutaneous		1.4	0.37	3.78	0.01–0.001
Muscle > skin		2.1	0.32	6.56	<0.001
20 minutes heat; 60 watts	10 + 10				
Subcutaneous > skin		0.4	0.42	0.95	0.4–0.3
Muscle > subcutaneous		1.2	0.40	3.00	0.01–0.001
Muscle > skin		1.6	0.31	5.16	<0.001
30 minutes heat; 60 watts	10 + 10				
Subcutaneous > skin		0.3	0.33	0.91	0.4–0.3
Muscle > subcutaneous		1.4	0.38	3.68	0.01–0.001
Muscle > skin		1.7	0.32	5.30	<0.001

for 15 and 20 minutes are analyzed from a statistical standpoint in table 9. The changes of blood flow after exposure at 80 watts will be treated separately.

In charts 6 and 7 the change of blood flow in the exposed extremity (at 80 watts) is related to the duration of exposure. In chart 6*a* this change is expressed in cubic centimeters per minute, while in chart 7*a* it is expressed as a percentage increase. The curve forms are similar and are more or less symmetrical and sigmoid. This type of function is known as a logistic function and may be represented by the following formula:

TABLE 6. — *Comparison of Temperature Rise of Skin, Subcutaneous Tissue and Muscle After Exposure to Microwaves at 80 Watts.*

Data Compared	Mean Difference °C*	Standard Error, °C.	*t*	*P*
Muscle > subcutaneous	0.5	0.20	2.50	0.05–0.02
Subcutaneous > skin	0.7	0.11	6.36	<0.001

* Mean of average difference in rise of temperature after 80 watt exposure for one, five, ten, fifteen, twenty, twenty-five and thirty minutes.

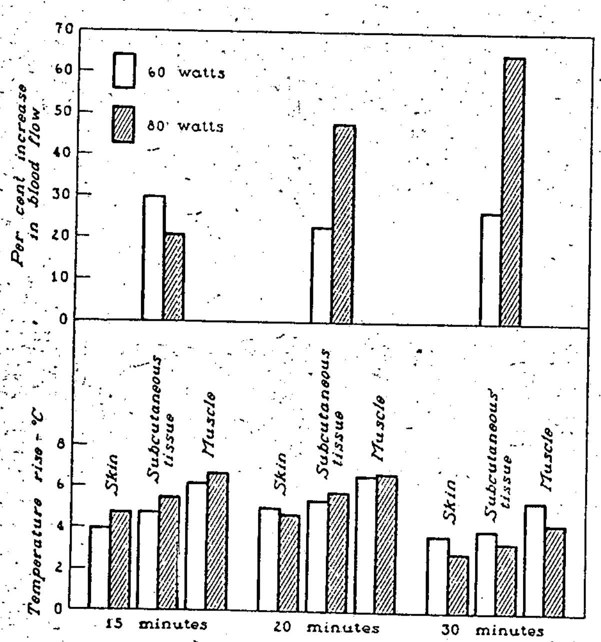
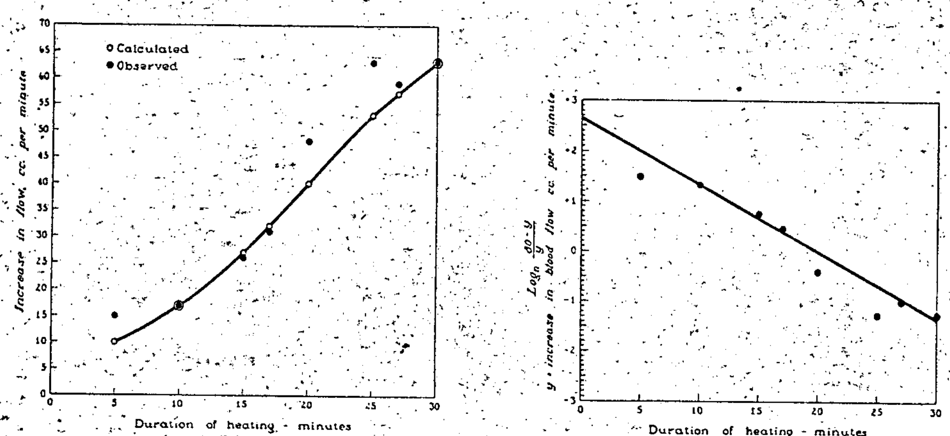


Chart 5. — Comparison of effects of exposure to microwaves at 60 and 80 watts on blood flow and on tissue temperature in the treated extremity. Blood flow readings were taken five minutes after the microwaves had been turned off. Temperature readings were taken one minute after the microwaves had been turned off. The height of each bar represents the average of 9 to 26 observations, as indicated in tables 1 and 3.



6a 6b

Chart 6. — Effect of exposure to microwaves (80 watts) on blood flow in the treated extremity. In *a* the ordinate indicates the increase of flow in cubic centimeters per minute, while in *b* the ordinate indicates a logarithmic function of the increase of flow in cubic centimeters per minute. Blood flow readings were taken five minutes after the microwaves had been turned off. Each observed point in figure 6*a* is the average of 9 to 20 observations.

TABLE 7. — *Comparison of Effect on Tissue Temperature of Exposure to Microwaves at 60 and at 80 Watts.*

Data Compared	Observations	Difference Between Means, °C.	Standard Error, °C.	*t*	*P*
15 minutes heat 60 and 80 watts	10 + 10				
Skin (80 >60)		0.7	0.63	1.11	0.3–0.2
Subcutaneous (80 >60)		0.7	0.82	0.85	0.5–0.4
Muscle (80 >60)		0.5	0.45	1.11	0.3–0.2
20 minutes heat 60 and 80 watts	10 + 25				
Skin (60 >80)		0.3	0.41	0.73	0.5–0.4
Subcutaneous (80 >60)		0.4	0.50	0.80	0.5–0.4
Muscle (80 >60)		0.1	0.40	0.25	0.8
30 minutes heat 60 and 80 watts	10 + 10				
Skin (60 >80)		0.8	0.37	2.16	0.05
Subcutaneous (60 >80)		0.6	0.50	1.20	0.3–0.2
Muscle (60 >80)		1.1	0.48	2.29	0.05–0.02

TABLE 8. — *Comparison of Effect of Exposure to Microwaves at 60 and at 80 Watts on Blood Flow.*

Data Compared	Observations	Difference Between Means, Cc. Per 100 Cc.	Standard Error, Cc. Per 100 Cc.	t	P
15 minutes heat (60 >80)	9 + 10	0.8	0.70	1.14	0.3–0.2
20 minutes heat (80 >60)	13 + 20	1.8	0.73	2.46	0.02
30 minutes heat (80 >60)	10 + 12	2.6	1.10	2.36	0.05–0.02

$$y = \frac{K}{1 + Ce^{rt}}$$

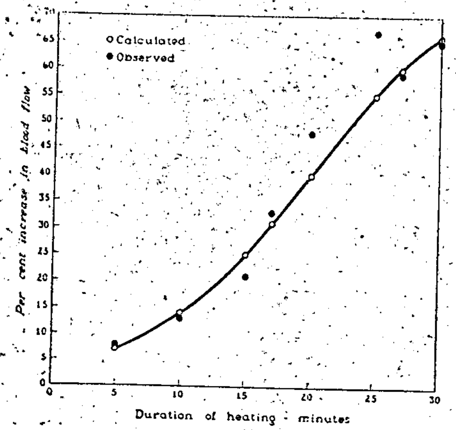
where y is the dependent variable (increase of blood flow),
t is the independent variable (duration of exposure),
K is the distance between the two asymptotic values of y.
If the lower asymptote is at $y = 0$, then K represents the value of the upper asymptote.
r is a parameter associated with the rate of the reaction, and
C is a constant of integration.

The value of the parameters may be determined graphically by plotting $\log \frac{K-y}{y}$ against the duration of exposure. Various values for K are chosen and a curve is plotted for each value of K. That value of K is chosen which gives a linear relationship which fits the experimentally determined points most closely. The line thus obtained can be used to obtain the parameters r and C. The lines fitting the data obtained in this study most closely are shown in charts 6*b* and 7*b*. The equations which result are the following:

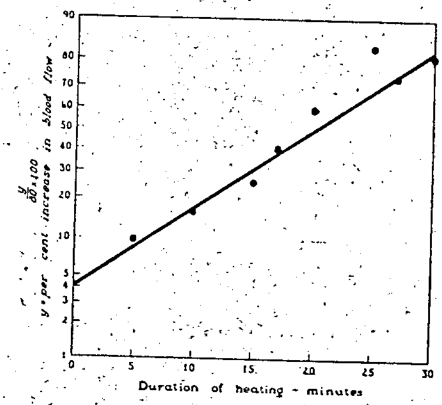
$$y = \frac{80}{1 + 14.3e^{-0.133t}}$$ (where y is the increase of blood flow in cubic centimeters per minute)

$$y = \frac{80}{1 + 23.1e^{-0.153t}}$$ (where y is the increase of blood flow in per cent)

The theoretical curves obtained from these equations are compared with the experimentally determined points in charts 6*a* and 7*a*. It is to be noted that the greatest discrepancy occurs at time equal to twenty-five minutes. At this point there was one unusually high value. The point which would be



7a



7b

Chart 7. — Effect of exposure to microwaves (80 watts) on blood flow in the treated extremity. In *a* the ordinate indicates the increase of flow in per cent, while in *b* the ordinate indicates a function of the percentage increase of flow. Blood flow readings were taken five minutes after the microwaves had been turned off. Each observed point in figure 7*a* is the average of 9 to 20 observations.

obtained with this value omitted would be much closer to the theoretical value.

This equation may be interpreted in the following manner. At time equal to plus infinity, the blood flow approaches an asymptote of 80 cc. per

TABLE 9. — *Comparison of Effects of Different Durations of Exposure to Microwaves on Blood Flow and on Tissue Temperature.*

Data Compared	Observations	Difference Between Means	Standard Error	t	P
60 watts—15 & 20 minutes heat (15 >20)	10 + 13	0.99 cc. per 100 cc.	0.80 cc. per 100 cc.	1.24	0.3–0.2
80 watts— 5 & 20 minutes heat	25 + 26				
Skin (20 > 5)		0.2° C.	0.39° C.	0.52	0.6
Subcutaneous (20 > 5)		0.6	0.45	1.35	0.2–0.1
Muscle (20 > 5)		1.2	0.42	2.86	0.01–0.001
80 watts—20 & 25 minutes heat	25 + 10				
Skin (20 > 25)		0.4° C.	0.41° C.	0.98	0.4–0.3
Subcutaneous (20 >25)		0.8	0.42	1.91	0.1–0.05
Muscle (20 > 25)		1.4	0.44	3.18	0.01–0.001
80 watts—25 & 30 minutes heat	10 + 10				
Skin (25 > 30)		1.4° C.	0.40° C.	3.50	0.01–0.001
Subcutaneous (25 >30)		1.6	0.45	3.56	0.01–0.001
Muscle (25 > 30)		1.0	0.49	2.04	0.1–0.05
60 watts—15 & 20 minutes heat	10 + 10				
Skin (20 > 15)		0.9° C.	0.35° C.	2.58	0.02
Subcutaneous (20 >15)		0.6	0.47	1.27	0.3–0.2
Muscle (20 > 15)		0.4	0.28	1.43	0.2–0.1
60 watts—20 & 30 minutes heat	10 + 10				
Skin (20 > 30)		1.3 °C.	0.31° C.	4.20	<0.001
Subcutaneous (20 >30)		1.4	0.44	3.18	0.01–0.001
Muscle (20 > 30)		1.2	0.33	3.64	0.01–0.001

minute increase of blood flow, or 80 per cent increase of blood flow. An inflection point in the curve is present at $K/2$. At this point, which occurs after twenty minutes of heating, the increase in cubic centimeters per minute or in percentage is 40. The slope of the curve is maximal at this point, which is the point of symmetry. Before this point is reached the curve is concave up, whereas beyond this point it is convex up.

General Observations

No harmful effects were noted in any of the subjects. Minimal cutaneous erythema was present in some subjects who had fair skins. This erythema disappeared in all cases within one hour after the termination of the exposure to microwaves. The only sensations noted were those of local and general warmth. While heating with an output of 80 watts, it was noted that the subjective feeling of warmth decreased at some time during the period of exposure to microwaves. In 6 subjects who were exposed for twenty minutes or longer this sensation of decrease of local temperature appeared between thirteen and twenty minutes after the beginning of exposure to microwaves. Of 18 subjects who were exposed to microwaves for fifteen minutes, only 2 noted any subjective local cooling. This occurred at nine and ten minutes after exposure to microwaves had been started.

Comment

The amount of energy absorbed by muscle after exposure to microwaves is greater than that absorbed by subcutaneous tissue or skin, as indicated by the greater rises of temperature occurring in muscular tissue one minute after the microwaves had been turned off. The rise of temperature alone does not indicate the disparity of energy absorption between muscle and subcutaneous tissue. If the specific heats of these two tissues are taken into consideration, the difference in the amount of energy absorbed becomes even greater. Muscle, with a higher specific heat (0.82) than subcutaneous tissue[10] (0.4-0.5) has a smaller rise of temperature than subcutaneous tissue for equal amounts of energy absorbed. This apparently greater effect of microwaves on muscular tissue than on subcutaneous tissue may be due to the fact that the conductivity of muscle is greater than that of fatty tissue.[11]

On comparing the findings at 60 and at 80 watts, certain observatons concerning the relation between energy output, peripheral blood flow and rise of temperature may be made. After fifteen minutes of exposure, the increases of blood flow are approximately the same for 60 and for 80 watts. The rise of temperature, however, is greater at the 80 watt output than at the 60 watt output, corresponding to the greater energy output of the former. After twenty minutes of exposure the tissue temperatures following 60 watts were greater than at fifteen minutes. With exposure at 80 watts, however, the temperatures of the tissues do not rise above the fifteen-minute level. Further increase of temperature has been prevented by the increase of blood flow at this time. After thirty minutes of exposure the increase of circulation is sufficient to remove heat from the tissues faster than it is accumulating, thus leading to a decline of tissue temperature from the twenty-minute level. The increase of blood flow was much greater at 80 watts than at 60 watts, and the fall of the temperature of the exposed tissues was correspondingly greater at 80 watts than at 60 watts.

10. DuBois, E. F.: Basal Metabolism in Health and Disease, ed. 3, Philadelphia, Lea & Febiger, 1936, pp. 69-70. Bürker, K.: In Tigerstedt, Robert: Handbuch der physiologischen Methodik, Leipzig, S. Hirzel, 1911, vol. 2, pt. 1, pp. 39-41. Rubner, Max: ibid. vol. 1, pp. 168-172.

11. Holmquest, H. J., and Marshall, J. G.: Brit. J. Phys. Med. 11:70, 1936. Osborne, S. L., and Holmquest, H. J.: Technic of Electrotherapy and Its Physical and Physiological Basis, Springfield, Ill. Charles C Thomas, Publisher, 1914, pp. 483-485.

The fall of temperature of subcutaneous tissues during the second minute after the microwaves had been turned off is greater than that of muscle or skin. Subsequently, the decrease of temperature in the muscle is greater than in the subcutaneous tissue.[1] The low specific heat of subcutaneous tissue may be a factor, for a relatively small amount of energy loss will result in a relatively great temperature decline. In addition, some of the factors responsible for the cooling of muscle may not be operating maximally immediately after completion of the exposure. Leden and her co-workers[6] found, in the dog, that the blood flow in the femoral vein usually did not reach its peak until some time after the microwaves had been turned off. Finally, continued production of heat within the muscle after exposure may alter its cooling pattern.

In this study the logistic curve was used to describe the increase of blood flow resulting from 80 watt exposure for various durations. The logistic curve has been used to describe growth of population[12] and of organisms,[13] data on bioassay[14] and autocatalytic reactions.[15] In the autocatalytic reaction the acceleration during the early phase is explained by the formation of a substance which is either a product or a by-product of the main reaction and which accelerates the reaction. The phase of retardation may be the result of exhaustion of the substrates of the reaction and the accumulation of the reaction products with acceleration of the reaction in the reverse direction. With this in mind, some suggestions may be offered to explain the acceleration and retardation phases in the increase of circulation resulting from exposure to microwaves. Heat may cause vasodilation by direct action or by action on vessels through the axon reflex.[6] The accelerative factor may be found in the metabolites which are formed within the tissues. As the temperatures within the tissues increase, the metabolism increases and the production of metabolites is enhanced. These metabolites aid in the dilation of the vessels. Two factors may be present which act to retard the circulatory increase. One is the presence of a maximal vascular bed. The other is the removal by the circulation of the factors which increase the blood flow — namely, heat and metabolites. Thus, as the circulation increases, it exerts a damping effect on further increase. It is to be noted that the retardation phase in the increase of blood flow and the decrease of tissue temperature occur at the same time.

If the "flushing action" of an increase of blood flow is desired for therapeutic purposes, exposure at 80 watts for thirty minutes may prove more desirable than exposure at 80 watts for twenty minutes and is also preferable to 60 watt exposure for any of the durations used in this study (this is true for the hemispherical director of 9 cm. diameter placed 5 cm. from the skin). The advantage of the 80 watt exposure for thirty minutes is indicated by the decrease of tissue temperature from its peak value at twenty minutes.

Summary

Two hundred and fifty-four observations were made on 50 normal human subjects concerning the effects of microwave radiations (2,450 megacycles per second) on the peripheral circulation and on the temperature of skin, subcutaneous tissue and muscle. The director used was hemispherical and about 9 cm. in diameter and was 5 cm. from the skin during the period of

12. (a) Pearl, Raymond: Introduction to Medical Biometry and Statistics, ed. 3, Philadelphia, W. B. Saunders Company, 1940, pp. 459-470. (b) Thompson, D. W.: On Growth and Form, New York, The Macmillan Company, 1942, pp. 140-171, 255-261.
13. Robertson, T. B.: The Chemical Basis of Growth and Senescence. Philadelphia, J. B. Lippincott Company, 1923, pp. 1-16, 81-91, 138-150.
14. Berkson, Joseph: J. Am. Statist., A. 39:357, 1944.
15. Reed, L. J., and Berkson, Joseph: J. Phys. Chem. 33:760, 1929. Thompson.12b. Robertson.13.

exposure. The output used was 60 or 80 watts, and the duration of exposure varied from one to thirty minutes. The following observations could be made:

1. Significant increases of blood flow and of tissue temperature in the exposed extremity resulted with both outputs and all durations used. There were minimal general effects and no ill effects.

2. The greatest amount of energy absorbed was, on the average, in the muscle.

3. After absorption of energy reached a certain point, the increase of blood flow was sufficient to remove heat at a greater rate than it was accumulating, resulting in a fall of tissue temperature from the peak reached at twenty minutes of exposure. The greater the increase of circulation, the greater the decrease of the temperature of exposed tissues from the maximal values reached. After thirty minutes of exposure significantly greater increases of blood flow resulted from 80 watt exposure than from 60 watt exposure.

4. The curve relating increase of blood flow to duration of exposure at 80 watts is S shaped and indicates an early phase of acceleration of the increase of blood flow, followed by a phase of retardation.

We acknowledge with gratitude the helpful suggestions and guidance given by Dr. Berkson and Mr. Gage in the statistical analysis of the data.

Discussion

Dr. Stafford L. Osborne (Chicago): I think all of us who have been here this morning have really had an intellectual treat, not the least of which is the paper to which we have just listened. I should like to congratulate Dr. Gersten on his able presentation. The only thing I regret is that we have only a meager fifteen minutes to present such valuable and important data. Therefore, I am sure that some of the points which I shall bring up, when the work is in final published form, will have been answered.

The first question I should like to ask is about the statistical method which was used to determine the significance of these changes which occurred in temperature and blood flow.

Second, the essayist states that the average temperature rise was greater in muscle than in the subcutaneous tissues and the temperature rise was higher in the subcutaneous tissues than the rise on the surface of the skin. In other words, the heating gradient was reversed.

If this is actually true, then the microwave diathermy might very well be a dangerous method to use clinically, because dangerously high temperatures might be secured in the deeper structures with a tolerable surface temperature. Our own studies do not show this reversal of the heating gradient. I wonder (and it is pure conjecture) if these differences are not more apparent than real and due in large measure to differences in the technic used by the laboratories in taking the temperature readings. One certainly cannot question the results which are presented to us.

Third, I should like to know whether you found, Dr. Gersten, a good correlation between temperature rise and blood flow, if you worked out a correlation factor. Our own studies, which were presented this week, apparently do not show a good correlation factor.

The material was presented rapidly, and I had the good fortune to go over Dr. Gersten's paper, which he kindly sent me well in advance, so it was easy for me to sit down and listen. I am one of those individuals who have to get things by the eye; at least I get them much better by the eye than I do by ear, and so Dr. Gersten, I am sure, will be able to put me right if I misunderstood, or if he did not make the statements, or if it was not clear to me.

Dr. Gersten, I believe, stated that after fifteen minutes' exposure at 60 or 80 watts the blood flow is approximately the same, although there was a greater temperature increase at 80 watts. It was stated that with additional time exposure at 80 watts there was no further increase in temperature because of the increased blood flow. Yet it is stated that after twenty minutes' exposure at 60 watts there was an increase in the temperature rise.

I just wonder whether this is an error, or whether I have not read correctly. If I have read correctly, I am sure Dr. Gersten can clear up that slight apparent discrepancy.

Probably what I am going to say next is a little trite, but there are many of us who are using these things clinically; we are essentially a group of clinicians, and some of us in the laboratories are so familiar with certain terms that familiarity breeds contempt. So if the laboratory workers will pardon my presumption for once, I should like to raise this point.

It would seem wise, I think, in most of our papers, when we write them, to point out that the increased temperature and blood flow are produced only — and Dr. Gersten, I think, brought that out fairly well — by the absorption of energy by the tissues, and that the output of a generator — we hear so much about the output, without realizing that it is only that energy which is absorbed that can produce an effect — does not bear a direct relationship.

I think I have played with high frequency currents quite a little bit, and I certainly would not be so bold as to presume that, because I had exposed one person to 60 watts' output, the next person whom I exposed to 60 watts' output would show the same absorption. There may be a better relationship than I know, but I rather doubt it.

Hence, one person may absorb as much energy at an output of 60 watts as another one would, let us say, at 80 watts.

Dr. William Bierman (New York): This work presented by Dr. Gersten is of great interest to those of us who have been working with the use of heating energies applied to the animal organism, particularly the human body, in that it corroborates again a fact which has been observed by many of us — namely, that at a certain period the temperature rise in tissues after the introduction of heating energies ceases. We have assumed that this was due to increased removal of heating energy by increased circulation.

Obviously, then, there is no absolute parallelism between temperature and circulation.

I was interested in observing the data presented this morning in that the rather abrupt change in temperature gradient occurs in these instances in about twenty minutes. With other forms of heating energy, including the so-called short wave current, applications of radiant energy — and I think the method of heating is an incidental factor — we have observed a rather sharp alteration at periods of twelve minutes and fifteen minutes.

There obviously is some sort of a trigger mechanism, because the change is relatively abrupt, and I am wondering whether that trigger mechanism is not influenced by two things: the total amount of heating energies, the amount actually absorbed in the tissue, and also the abruptness of the rise. This is an attempt on the part of nature to protect tissue against thermal destruction. Obviously, if the localized tissue temperature continued to rise, it would reach a point where irreversible alterations would occur.

Dr. Ernst Fischer (Richmond, Va.): If I understood the speaker correctly, he concludes that the energy is absorbed at a greater rate by muscle tissue than by other tissues. That is a possibility, but is this conclusion not a little premature? There exists the theoretical possibility that, especially at the beginning of the microwave exposure, the increase in blood flow is restricted to the superficial tissue. This would produce a greater rate of heating of the limb by the blood flow independently from the absorption of energy by the muscles.

I might be wrong in my physics, but is there not the possibility that these waves are reflected backward from the bones, and a higher heating of the muscles produced in this way? If this is true, you cannot be sure that the muscle tissue itself has a higher absorption rate for microwaves than the other tissues.

Dr. Ludwig W. Eichna (New York): I am glad to see the tendency to talk about the changes which one measures. Here we have a demonstration of a difference in the changes of two associated measurements, temperature and blood flow, both considered at times to measure the same function.

The point I raise is as follows: If I understand correctly, the microwaves were directed toward the forearm. The temperature measurements were made in the area to which the energy was directed, the forearm. The blood flow, however, if I understood again correctly, is a summation of the effects which occurred within the forearm and hand, because this is a forearm plus hand plethysmograph. Therefore, the plethysmograph is measuring the blood flow contribution of an area which was subjected to the microwave energy, the forearm, plus an area which was not subjected to the microwave energy, the hand.

Therefore, one wonders whether the temperature measurements and the blood flow measurements can really be compared, because, after all, there are measurements, in the one case, of the area which received the energy — that is the temperature changes — and, in the other case, a summated effect of the area which received the energy and an area which did not receive the energy, the blood flow.

Dr. Louis B. Newman (Chicago): This paper on the heating and circulatory effects of microwaves was very interesting and informative. However, there are several questions that enter my mind.

Since the distance of the applicator from the tissues, the position of the patient, the room temperature and the frequency of the microwaves were kept constant during the experiments, I am wondering whether the beneficial effects would be enhanced if the distance of the applicator from the tissues were increased and the treatment time prolonged. Also, would these beneficial effects be further enhanced by exposing a greater volume of tissue to the effects of the microwaves?

It was observed by the authors that the temperature of the tissues dropped after approximately twenty minutes of treatment, while the blood flow increased. Would the temperature of the tissues continue to drop still further if the treatments were given for longer than twenty minutes?

Another question that I should like to ask is regarding the effects of microwaves on the temperature of the tissues, as well as circulation when markedly traumatized tissues are exposed to these high frequency waves:

Dr. Gersten (closing): I do not know whether I can answer all the questions; I will try:

The statistical method which was used was the accepted one of determining the standard deviation, standard error and *t* value, and we accepted as significant any change in which the *p* value was 0.02 or smaller; 0.05 was accepted as borderline, and anything above that was insignificant.

We found that the normal preheating gradient was not changed by microwaves. The preheating temperature was, on the average, greatest in the muscle and least in the skin, and the final temperature also was greatest in the muscle. This was true for all durations and both outputs.

As far as burning is concerned, we found that the highest average temperature in the muscle was achieved after twenty minutes of exposure at 80 watts and that at this point it was 41.4 C. This did not approach the temperature at which normal tissues are burned.

The question of the correlation between increase in temperature and blood flow has been answered to a great degree by Dr. Bierman. I wish I could diagram here what we feel we have determined.

This sigmoid curve which was described today, and which has been called a logistic function, is typical of the autocatalytic reaction. If heat is one stimulus for an increase in blood flow, the autocatalytic reaction would require the presence of another factor which would enhance the reaction and, thus, cause an acceleration of the increase in blood flow. We feel that this catalyst is represented by metabolites in the tissue. As the temperature rises, the metabolism in the tissue increases, the production of metabolites increases, and we have an added factor which causes an increase in blood flow. Therefore, we can say that during this early period, the period up to twenty minutes, there is a direct relation between the energy output, the temperature rise and the increase in blood flow.

At this point, however, it seems that the increase in circulation is so great that the factors which are causing an increase in the flow — namely, the metabolites and the heat, are being removed at a greater rate than they are accumulating. Thus, even though the blood flow rises further, the temperature declines as a result of this increase in blood flow. Therefore, after this twenty-minute period we can say that the relationship between the increase in blood flow and the temperature is no longer a direct one but that, as the blood flow increases further, the temperature will decline more and more.

Dr. Fischer mentioned the rate of energy absorption. We did not want to mention the rate of absorption of energy; the only thing we could say was that the quantity of energy absorbed was greater in the muscle. The evidence for this lies not only in the greater rise in temperature of the muscle but also in the difference in specific heats between muscle and subcutaneous tissue. With subcutaneous tissue having a much smaller specific heat than muscle — for muscle it is 0.8 and for subcutaneous tissue about 0.5 — the amount of energy absorption by muscle is greater for an equivalent rise of temperature. For the explanation of this we feel that the conductivity of muscle is an important factor, for tissues of greater conductivity would absorb greater amounts of the electromagnetic radiation.

Dr. Eichna is right in saying that we have taken the flow of two areas, the hand and the forearm. We have tested the hypothesis in other experiments, and we have found that the increase in flow in cubic centimeters is approximately the same when we take the flow in the forearm alone or the combined flow of forearm and hand. As far as the percentages are concerned, the percentage change would be much greater if we took the flow in the forearm alone, but the cubic centimeter change would be approximately the same. We have plotted the data from the standpoint of cubic centimeters per minute increase and per cent increase of flow and found that the curve shapes were approximately the same.

Dr. Newman questioned what might occur with an increase in the distance of application. We are not quite certain. It is possible that the decrease in energy output, as with the 60 watt output, might be an example of what would happen if we used 80 watts at an increased distance. In other words, we got temperature rises which were approximately the same as with 80 watts but blood flow changes which were not as great. That may or may not have been the case had we increased the distance rather than decreased the output.

The effect on the other extremities was consistently insignificant. There were no increases or decreases of blood flow greater than 14 per cent.