THE JOURNAL OF INVESTIGATIVE DERMATOLOGY
Copyright © 1972 by The Williams & Wilkins Co.

Vol. 59, No. 2
Printed in U.S.A.

CARBON DIOXIDE EMISSION OF THE HUMAN ARM AND HAND*

GEORGE W. FRAME, A.B., WALTER G. STRAUSS, M.D.† AND HOWARD I. MAIBACH, M.D.†

ABSTRACT

Carbon dioxide emission from human skin was measured with a Luft Infrared Analyzer. Emission rate was 3.4×10^{-5} ml $CO_2/cm^2/min$ for the arm and forearm combined, 4.6×10^{-5} ml $CO_2/cm^2/min$ for the hand only, and 1.8×10^{-5} ml $CO_2/cm^2/min$ for the forearm only. Emission rate of the arm and forearm increased to 8.6×10^{-5} $CO_2/cm^2/min$ after vigorous exercise, and 9.1×10^{-5} ml $CO_2/cm^2/min$ after wetting the skin.

In an attempt to define the role of cutaneous emission of carbon dioxide in attracting mosquitoes, we found it necessary to measure the rate of carbon dioxide emission from the forearm and hand.

Shaw, Messer, and Weiss (1, 2, 3), using a plethysmograph and a Haldane apparatus, measured the carbon dioxide emission of the arm and hand (Table I). They found the rate at which carbon dioxide is given off through the human skin is dependent upon temperature, humidity, individual characteristics, seasonal changes, and gas tensions in the air surrounding the skin. A rise in the temperature of the air in contact with the skin caused an increase in carbon dioxide emission from the skin. Above a critical temperature of 34° C, the rate of carbon dioxide emission became six times as rapid per degree of temperature increase as at lower temperatures. They also noted that an increase in humidity within the arm chamber resulted in a corresponding increase in carbon dioxide output; this effect was attributed to a diminished rate of evaporation and less cooling.

Ernstene and Volk (4) used apparatus and technical procedures that were similar to those employed by Shaw and Messer. Repeated measurements were made of the rate of carbon dioxide elimination through the skin of 38 normal subjects (Table I); they found much individual variation but no correlation with sex or season of the year. Accelerated rates of gas exchange through the skin at higher temperatures were attributed primarily to an increased rate of cutaneous metabolism. In 17 subjects the average amount of carbon dioxide excreted through the skin was 2.7 percent of that excreted through the lungs. Comparative measurements, made on persons with widespread cutaneous lesions (5), showed a higher mean rate of carbon dioxide elimination (27×10^{-5} ml $CO_2/cm^2/min$) compared to the normal rate of 20×10^{-5} ml $CO_2/cm^2/min$. They explained this as a consequence of increased metabolic rate of the skin.

Reviewing the literature from 1795 to 1943, Schulze (6) summarized the work on carbon dioxide movement through the skin and prepared a table of carbon dioxide emission rates obtained from 18 references. Various experimental procedures were employed by these authors, and temperatures varied from 10–36° C. Their results all fell within the range of $5–70 \times 10^{-5}$ ml $CO_2/cm^2/min$. Schulze's table was later reproduced by Rothman (7).

The mechanism of trans-dermal gas exchange with the atmosphere was reviewed by Rothman (7); he described this as a passive process of diffusion, primarily dependent upon the following three factors: differential gas tension within the body and the atmosphere, the permeability of the skin, and the rate of blood flow. Increased carbon dioxide emission from the skin at high temperatures was attributed to increased cutaneous blood flow resulting from increased metabolism of eccrine sweat gland cells.

Fitzgerald (8) examined the literature and reported that total respiration through the skin surface was calculated at one percent or less by 19th century workers, but more recent experimenters have established carbon dioxide losses from the skin as high as 2.7 percent of the total respiration. Summarizing, he said that carbon dioxide emissions from the skin surface come partly from the skin itself and partly from blood in superficial blood vessels, and theorized that cutaneous respiration is an adaption to protect skin from anoxic damage.

Petrun (9) used a modified Ors gas analyzer, which he stated gave 15 times greater accuracy than the Haldane apparatus for measurement of carbon dioxide. Areas of the body that he studied were chest, abdomen, and thigh (Table I).

Gas transport was shown by Klocke (10) to be limited by diffusion through the skin barrier, and to be affected only indirectly by changes in cutaneous blood flow in individual capillaries. He reported minimal gas flow below 28° C, with a linear increase accompanying rising temperatures above 28° C. This increased gas transport is made possible by the opening of additional capillaries

---

* From the Letterman Army Institute of Research, Presidio of San Francisco, San Francisco, California and the †Department of Dermatology, University of California School of Medicine, San Francisco, California 94122. (Reprint requests to Doctor Maibach.)

This investigation was supported by the U. S. Army Medical Research and Development Command, Department of the Army, under Contract #DA-49-193-MD-2466.

Received November 29, 1971; accepted for publication February 16, 1972.

TABLE I

Carbon dioxide emission through the skin as determined by several authors

Conditions ambient; subjects at rest.

Author	Mean (ml CO_2/ cm^2/min)	Area of body
Shaw *et al.* (1929)	14×10^{-5}	arm and hand
Shaw and Messer (1930)	11×10^{-5}	arm and hand
Ernstene and Volk (1932)	20×10^{-5}	arm and hand
Petrun (1958)	13×10^{-5}	thigh
	18×10^{-5}	chest
	22×10^{-5}	abdomen
Adamcyzk *et al.* (1966)	$370 \times 10^{-5*}$	axillae
	$94 \times 10^{-5*}$	forehead
	$33 \times 10^{-5*}$	arm (volar surface)
	$15 \times 10^{-5*}$	chest
Pototskii and Dyachenko (1967)	19×10^{-5}	—
This study	3.4×10^{-5}	forearm and hand
	4.6×10^{-5}	hand
	1.8×10^{-5}	forearm

* Calculated to normal temperature and pressure (NTP).

and increased diffusing capacity at elevated ambient temperatures.

A mass spectrometer was employed by Adamcyzk *et al.* (11) to measure the skin excretion of carbon dioxide and other gases. While the subject breathed various gas mixtures, several body sites were measured. Sites of maximum carbon dioxide emission were axillae and forehead, while the lowest value was obtained from the chest (Table I).

The most recent contribution on carbon dioxide emission rates from human skin was provided by Pototskii and Dyachenko (12) during a study of eczema patients (Table I).

The results obtained by these authors show the carbon dioxide emission of human skin to be a passive process of diffusion, dependent upon four major factors: gas tensions, skin permeability, blood flow, and skin metabolism.

MATERIALS AND METHODS

The hand and forearm are inserted into a glass sleeve; dry nitrogen gas flows through the sleeve and the amount of carbon dioxide is measured by a Luft Type Infrared Analyzer (MSA Model 200, Mine Safety Appliances, Pittsburgh, Pa., U. S. A.). The Infrared Analyzer determines the concentration of one component of a mixture by measuring infrared absorption. A compound's infrared absorption is characteristic of the type and arrangement of the atoms composing its molecules. Dissimilar compounds, such as carbon dioxide and water vapor, absorb on widely different spectral regions. Certain gases such as oxygen and nitrogen do not absorb infrared energy and therefore their presence has no effect on the Luft Infrared Analyzer.

Three healthy caucasian men, ages 21–29 years, without special preparation or conditioning, were our experimental subjects. They inserted their hand and most of their forearm into the end of a glass cylinder, 9 cm in diameter by 37 cm long, closed at the opposite end. Beaks were prevented by sealing the opening between the arm and cylinder end with a latex surgical glove from which the fingers had been removed. The seal was firm, but without constriction of blood circulation. Dry nitrogen gas containing not more than 2 ppm carbon dioxide flowed at 2.0 l/min through a small inlet near the elbow. From the outlet near the hand, nitrogen, carbon dioxide, water vapor, and other gases produced by the forearm and hand exited through 6.4 mm inside diameter Tygon tubing into the infrared analyzer which measured the carbon dioxide. Only a negligible amount of carbon dioxide permeated the system from the atmosphere through the latex seal and Tygon tubing. Full scale deflection was 100 ppm carbon dioxide.

Because we wanted to simulate the conditions used in some of our mosquito experiments, we controlled only the room temperature and allowed the chamber gas temperature to vary daily in response to each human subject's physiology. Room temperature varied between 25–28° C, but was constant during each 15-minute replicate. Within the chamber, gas temperature was normally 26–32° C, when the subject was at rest, 29–35° C after exercise, and 25–31° C after wetting. During individual 15-minute replicates, the gas temperature within the chamber normally rose one or two centigrade degrees.

A humidity sensor monitored the gas mixture as it flowed from the arm chamber to the infrared analyzer. Under the three separate conditions of rest, exercise, and wetting (and maintaining a 2.0 l/min dry nitrogen flow), the chamber relative humidity remained constant during each 15-minute replicate. However, there was a day to day variation of relative humidity, which was between 54–100 percent when the subject was at rest, 72–100 percent after vigorous exercise (when the skin was wet with perspiration), and 68–100 percent after wetting the arm and hand with water.

Carbon dioxide measurements were made at 30-second intervals for 15 minutes. Room concentrations of carbon dioxide were normally about 520 ppm. Hence, when the arm and hand were sealed into the chamber, it was necessary to equilibrate the system by allowing pure nitrogen to flow for about three minutes until the carbon dioxide reading in the infrared analyzer reached its minimum. The mean was computed from 31 readings in each 15-minute period to provide a single representative value for ppm of carbon dioxide. This method is accurate to ±2 ppm carbon dioxide.

An estimate was made of the surface area of the fingers, hand, and part of the arm enclosed by the glass cylinder by making a masking tape cast. Each cast was opened and flattened by cutting, and its area measured planimetrically. The hand and forearm were measured separately.

We measured the rate of carbon dioxide production from the forearm and hand for 63 fifteen-minute replicates among the three persons (Table II). For 21 of these replicates, paired readings were taken of the hand alone (Table III). This was accomplished by resting the extremity at ambient conditions for 15 minutes. Seven replicates, over a several-month period, were obtained for each person. The amount of carbon dioxide emitted from the forearm alone was determined by subtraction.

Carbon dioxide was measured after exercise, which consisted of vigorously running up and down stairs for

TABLE II

Rate of carbon dioxide emission from the hand and forearm

At rest; conditions ambient.

Subject	$CO_2 \times 10^{-5}$ ml/cm²/min			Number of 15-minute replicates
	Mean	±SD*	Range	
A	3.6	1.0	1.9–7.1	35
B	3.7	1.2	2.2–5.8	14
C	2.8	0.6	1.7–3.6	14
Mean	3.4			Total 63

* SD = standard deviation.

TABLE III

Rate of carbon dioxide emission from the hand and forearm compared to the hand only

At rest; conditions ambient.

Subject	$CO_2 \times 10^{-5}$ ml/cm²/min						Number of paired 15-minute replicates
	Arm + hand			Hand only			
	Mean	± SD*	Range	Mean	± SD*	Range	
A	4.1	1.6	2.6–7.1	4.7	1.2	2.9–6.2	7
B	3.7	1.3	2.2–5.4	5.9	1.9	3.5–8.4	7
C	2.4	0.4	1.7–2.9	3.3	0.6	2.4–4.4	7
Mean	3.4			4.6			Total 21

* SD = standard deviation.

10 minutes followed by 40 pushups. This experiment was replicated five times for each of the three persons over a period of several months.

Because Shaw and Messer (2) suggested that water vapor per se could affect carbon dioxide emanation, this effect was studied by soaking the forearm and hand in 37° C water for one minute. A wet crumpled paper towel was placed in the chamber with the wet forearm and hand so that the skin could be maintained wet throughout the 15-minute period. Five replicate determinations of carbon dioxide emission were made for each person throughout several months.

All measurements are expressed as milliliters of carbon dioxide emitted per cm² of skin per minute.

RESULTS

The average resting emission of carbon dioxide resulting from 63 measurements of forearm and hand combined in three individuals was 3.4×10^{-5} ml CO_2/cm²/min (Table II). For 21 replicates the hand only was measured, giving an average of 4.6×10^{-5} ml CO_2/cm²/min (Table III). By subtraction, values were determined for the carbon dioxide emission rate of the forearm of each individual, and the mean for the three subjects combined was 1.8×10^{-5} ml CO_2/cm²/min.

Exercise raised the resting value of the forearm and hand from 3.4×10^{-5} ml CO_2/cm²/min (15 measurements) to 8.6×10^{-5} ml CO_2/cm²/min (Table IV).

Wetting the skin caused an increase in carbon dioxide emission similar to the effect of exercise. The mean of 15 measurements before wetting was 3.0×10^{-5} ml CO_2/cm²/min, and after wetting 9.1×10^{-5} ml CO_2/cm²/min (Table V). No additional carbon dioxide emission could be induced by wetting the skin after vigorous exercise.

An analysis of variance was performed, and the data before and after exercise and wetting were statistically significant (Table VI). Analysis confirmed that the increased carbon dioxide emission caused by exercise is not significantly different from the effect of wetting the skin.

DISCUSSION

Our measurements establish values of carbon dioxide emission lower than those in the current literature. They also illustrate the more important observation of the variability of carbon dioxide emission with exercise and relative humidity changes. Higher values obtained by previous workers may have been a consequence of the accumulation of emission products (particularly moisture) in their closed experimental chambers, exercise, or contamination with atmospheric CO_2. In our experimental design, emission products were removed by dry nitrogen gas as quickly as they were excreted. Petrun (9) showed that high nitrogen concentrations (when compared to normal air) alter the carbon dioxide emission rate by not more than 4–19 percent, depending upon the part of the body studied. We

TABLE IV

Effect of exercise on the rate of carbon dioxide emission from the hand and forearm

Conditions ambient.

Subject	$CO_2 \times 10^{-5}$ ml/cm²/min						Number of paired 15-minute replicates
	Before exercise			After exercise			
	Mean	± SD*	Range	Mean	± SD*	Range	
A	3.5	0.9	1.9–4.3	9.2	2.0	6.6–10.9	5
B	3.5	0.8	2.2–4.2	8.3	1.4	6.7–10.0	5
C	3.2	0.6	2.7–3.6	8.3	2.3	5.1–10.8	5
Mean	3.4			8.6			Total 15

* SD = standard deviation.

TABLE V

Effect of wetting skin on the rate of carbon dioxide emission from the hand and forearm

Conditions ambient.

Subject	$CO_2 \times 10^{-5}$ ml/cm²/min						Number of paired 15-minute replicates
	Before wetting			After wetting			
	Mean	± SD*	Range	Mean	± SD*	Range	
A	4.0	1.9	1.9–7.1	11.3	2.4	9.0–14.7	5
B	2.6	0.6	2.2–3.6	10.2	1.6	7.8–11.7	5
C	2.5	0.7	1.7–3.6	5.8	0.6	5.1–6.6	5
Mean	3.0			9.1			Total 15

* SD = standard deviation.

TABLE VI

Analysis of variance of carbon dioxide emission from the hand and forearm of three men under conditions of rest, exercise, and wetting

Source	SS	df	MS	F	
I. Between subjects	495.176	9	—	—	
A = Before vs. after	477.426	1	477.426	215.154	$P < 0.0001$
Error A	17.750	8	2.219	—	
II. Within subjects	184.013	50	—	—	
B = Exercise vs. wet	0.064	1	0.064	n.s.	
AB	2.234	1	2.634	n.s.	
B × Error B	28.458	8	3.557	—	
C = Subject$_1$ vs. Subject$_2$ vs. Subject$_3$	41.832	2	20.916	13.916	$P < 0.01$
AC	15.144	2	7.572	5.038	$P < 0.01$
C × Error C	24.015	16	1.503	—	
BC	23.666	2	11.833	5.496	$P < 0.01$
ABC	13.749	2	6.875	3.193	$P < 0.05$
Error BC	34.451	16	2.153	—	

checked our system by measuring transepidermal water loss and found this within the generally reported range.

Rothman (7) suggested that increased carbon dioxide production by muscle during exercise and passive diffusion through the skin probably accounts for much of the increased carbon dioxide emission after exercise. A second contributing factor, he speculated, may be increased metabolism of eccrine sweat gland cells. In our experiment the upper extremities were exercised and may have contributed.

The similar effect of vigorous exercise (sweating) and wetting the skin is less easily explained. Apparently, wetting the skin by perspiring, increasing relative humidity (2), or applying water, increases its permeability to carbon dioxide and allows a greater exchange with the atmosphere. We measured a known concentration of carbon dioxide with and without humidification and found no effect from increased humidity, thus eliminating artifact. Our explanation remains speculative, and a satisfactory answer must await further experimentation. The ease with which the permeability of human skin to carbon dioxide is altered may also have relevance to cutaneous disease. Carbon dioxide emission may be a suitable companion to transepidermal water loss as an index of skin integrity. We do not know if enough sweat was produced to wet the stratum corneum and increase CO_2 output in this way. We hope to repeat this study in subjects with congenital ectodermal defect to verify this.

Extrapolating our value of carbon dioxide excretion (3.4×10^{-5} *ml* $CO_2/cm^2/min$) to the total skin surface of a 1.5 square meter human (and *ignoring the fact that various body parts have different carbon dioxide emission rates*), we derive a value of 0.5 ml CO_2/min. This is obviously a very small portion of the amount excreted by the lungs, amounting to about 0.25 percent for normal skin and 0.75 percent for wet skin.

The authors are grateful to Derek L. Skidmore (Department of Dermatology, University of California Medical Center, San Francisco), and James A. Williams (Letterman Army Institute of Research, Presidio of San Francisco) for their assistance in this study. John M. Polich and Jessie A. Logan (Letterman Army Institute of Research, Presidio of San Francisco) performed the statistical analyses. Col. Wm. Akers, MC provided valuable guidance.

REFERENCES

1. Shaw, L. A., Messer, A. C. and Weiss, S.: Cutaneous respiration in man, I. Factors affecting the rate of carbon dioxide elimination and oxygen absorption. Amer. J. Physiol., *90:* 107, 1929.
2. Shaw, L. A. and Messer, A. C.: Cutaneous respiration in man, II. The effect of temperature and of relative humidity upon the rate of carbon dioxide elimination and oxygen absorption. Amer. J. Physiol., *95:* 13, 1930.
3. Shaw, L. A. and Messer, A. C.: Cutaneous respiration in man, III. The permeability of the skin to carbon dioxide and oxygen as affected by altering their tension in the air surrounding the skin. Amer. J. Physiol., *98:* 93, 1931.
4. Ernstene, A. C. and Volk, M. C.: Cutaneous respiration in man, IV. The rate of carbon dioxide elimination and oxygen absorption in normal subjects. J. Clin. Invest., *11:* 363, 1932.
5. Ernstene, A. C. and Volk, M. C.: Cutaneous respiration in man, V. The rate of carbon dioxide elimination and oxygen absorption in subjects with diseases of the skin. J. Clin. Invest., *11:* 377, 1932.
6. Schulze, W.: Untersunchungen uber die Alkaliempfindlichkeit, das Alkalineutralisationsvermogen und die Kohlenseureabgabe der Haut. Arch. Derm. Syph., *185:* 93, 1943.
7. Rothman, S.: Pp. 580–581, *Physiology and Biochemistry of the Skin.* University of Chicago Press, Chicago, 1954.
8. Fitzgerald, L. E.: Cutaneous respiration in man. Physiol. Rev., *37:* 325, 1957.
9. Petrun, N. M.: The effects of increased oxygen, carbon dioxide, and nitrogen partial pressures on cutaneous respiration in man. Neklady Akad. Nauk SSSR; (Biol. Sci. Sect. Transl.) *118*(1/6): 108, 1958.
10. Klocke, R. A., Gurtner, G. H. and Farhi, L. E.: Gas transfer across the skin in man. J. Appl. Physiol., *13:* 311, 1963.