A METHOD OF HUMAN CALORIMETRY*

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ABSTRACT

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OBJECT

To develop an improved method of human calorimetry.

RESULTS

The subject was observed in a small chamber. An air conditioning unit supplied a constant flow of air through this chamber at closely controlled temperatures and humidities. Air movement within the chamber was regulated by a fan.

Evaporation was determined by use of an infra-red gas analyzer (12). Metabolic heat production was calculated from the rate of oxygen consumption, measured continuously by a closed circuit apparatus. Radiative transfer was calculated from the average wall and skin temperatures which were measured by specially designed thermocouple assemblies (13). The change in heat content for the entire experiment was determined from changes in the rectal and mean skin temperatures. This value was substituted in the thermal equation, $C = \Delta H/t - (M + E + R)$, to obtain an average rate of convection. This rate of convection was partitioned over short intervals according to the difference between air and mean skin temperatures. The short interval values of convection were then substituted in the thermal equation to give short interval values for ΔH.

CONCLUSIONS

The particular advantages of this method are:

1. Each component of the thermal balance can be determined either continuously or at short intervals.

2. Rapidly changing and high rates of evaporation and metabolism can be determined without difficulty.

3. The method can be applied to a wide variety of experimental conditions.

RECOMMENDATIONS

It is recommended that this method, or portions thereof, be considered by agencies planning to undertake problems of human calorimetry.

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I. INTRODUCTION

A. Previous Methods

The two best known methods of human calorimetry are respiration calorimetry (1,2,3) and partitional calorimetry (4,5). The former is the more accurate, but the latter can be applied to a much wider variety of experimental conditions (6,7,8,9,10,11). In both methods evaporation and metabolism are determined at relatively long intervals, making it impossible to measure rapid changes in thermal balance.

B. Method to be Described

The method to be described minimizes these difficulties by use of a new apparatus for the continuous measurement of evaporation (12), new thermocouple assemblies for the measurement of skin temperatures (13), a simple experimental chamber, a modified closed circuit metabolic apparatus, and a modified method of calculation of results.

II. EXPERIMENTAL

A. Apparatus and Methods

1. Experimental Chamber

a. Description

The experimental chamber (Fig. 1) consisted of a heavy wooden frame, 8 x 3 x 3 feet, supporting double walls of thin plastic sheeting. The subject lay inside on a waterproofed netting, and was observed through the transparent walls of the chamber door. He breathed into a mouthpiece connected to rubber tubes, and these passed through the walls to a metabolic apparatus outside. Leads from a potentiometer entered the chamber and terminated in multiple contact plugs for the attachment of thermocouple assemblies.

A constant flow of air was maintained through the chamber, and an even distribution of the stream was ensured by a thick baffle of hair felt just beyond the air inlet.

The experimental chamber was placed in a large, air-conditioned room.

b. Control of Environment

The temperature and humidity of the entering air were closely regulated by a Carrier air conditioner. This unit delivered about 60 cubic feet a minute and, since the volume of the chamber was only 70 cubic feet, the replacement of air was rapid. A fan at the foot of the chamber, when operating at low speed, merely mixed the air at the outlet; conditions inside were those of a well ventilated but not windy room. Greater wind movement could be obtained at higher fan speeds.

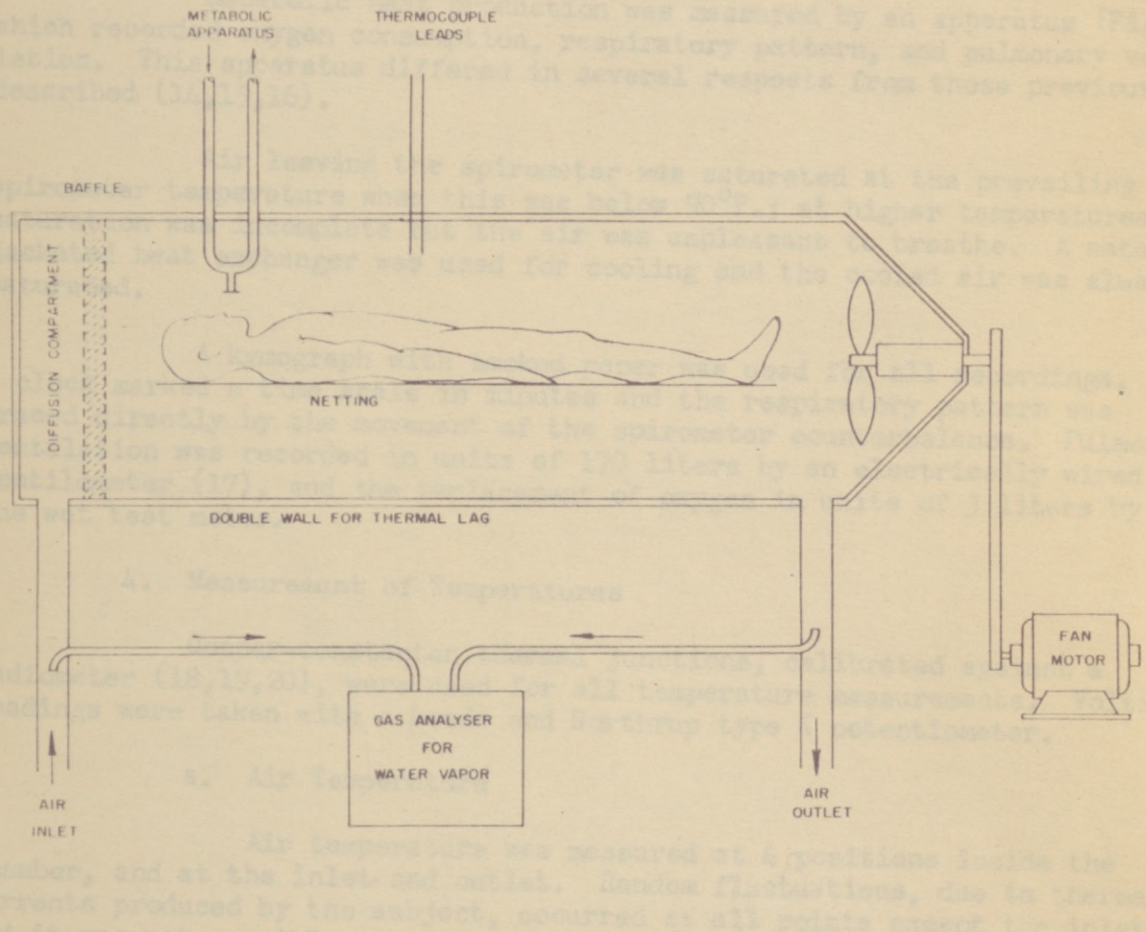

FIG. I. EXPERIMENTAL CHAMBER

The room and chamber were conditioned to approximately the same temperature, and the thermal lagging of the chamber made the internal environment independent of small fluctuations in external temperature. The internal environment was not always uniform, however, because air currents of varying temperature and vapor pressure were produced by convection and evaporation from the subject's body.

2. Determination of Evaporation

Evaporation was determined continuously and nearly instantaneously by means of an infra-red gas analyzer (12) described elsewhere.

3. Determination of Metabolism

Metabolic heat production was measured by an apparatus (Fig. 2) which recorded oxygen consumption, respiratory pattern, and pulmonary ventilation. This apparatus differed in several respects from those previously described (14,15,16).

Air leaving the spirometer was saturated at the prevailing spirometer temperature when this was below 90°F.; at higher temperatures, saturation was incomplete but the air was unpleasant to breathe. A water-jacketed heat exchanger was used for cooling and the cooled air was always saturated.

A kymograph with smoked paper was used for all recordings. A clock marked a time scale in minutes and the respiratory pattern was traced directly by the movement of the spirometer counterbalance. Pulmonary ventilation was recorded in units of 170 liters by an electrically wired ventilometer (17), and the replacement of oxygen in units of 3 liters by the wet test meter.

4. Measurement of Temperatures

Copper-constantan thermal junctions, calibrated against a radiometer (18,19,20), were used for all temperature measurements. Voltage readings were taken with a Leeds and Northrup type K potentiometer.

a. Air Temperature

Air temperature was measured at 4 positions inside the chamber, and at the inlet and outlet. Random fluctuations, due to thermal currents produced by the subject, occurred at all points except the inlet and it was not possible, therefore, to develop a satisfactory weighting formula for the average air temperature. The best index of this average was the temperature of the inlet air, and this was used for the calculation of convection.

b. Wall Temperature

The temperatures of the inside surfaces of the chamber were measured at 4 points by thermocouples fastened firmly to the long walls above and below the subject, and by thermocouples in the air near the

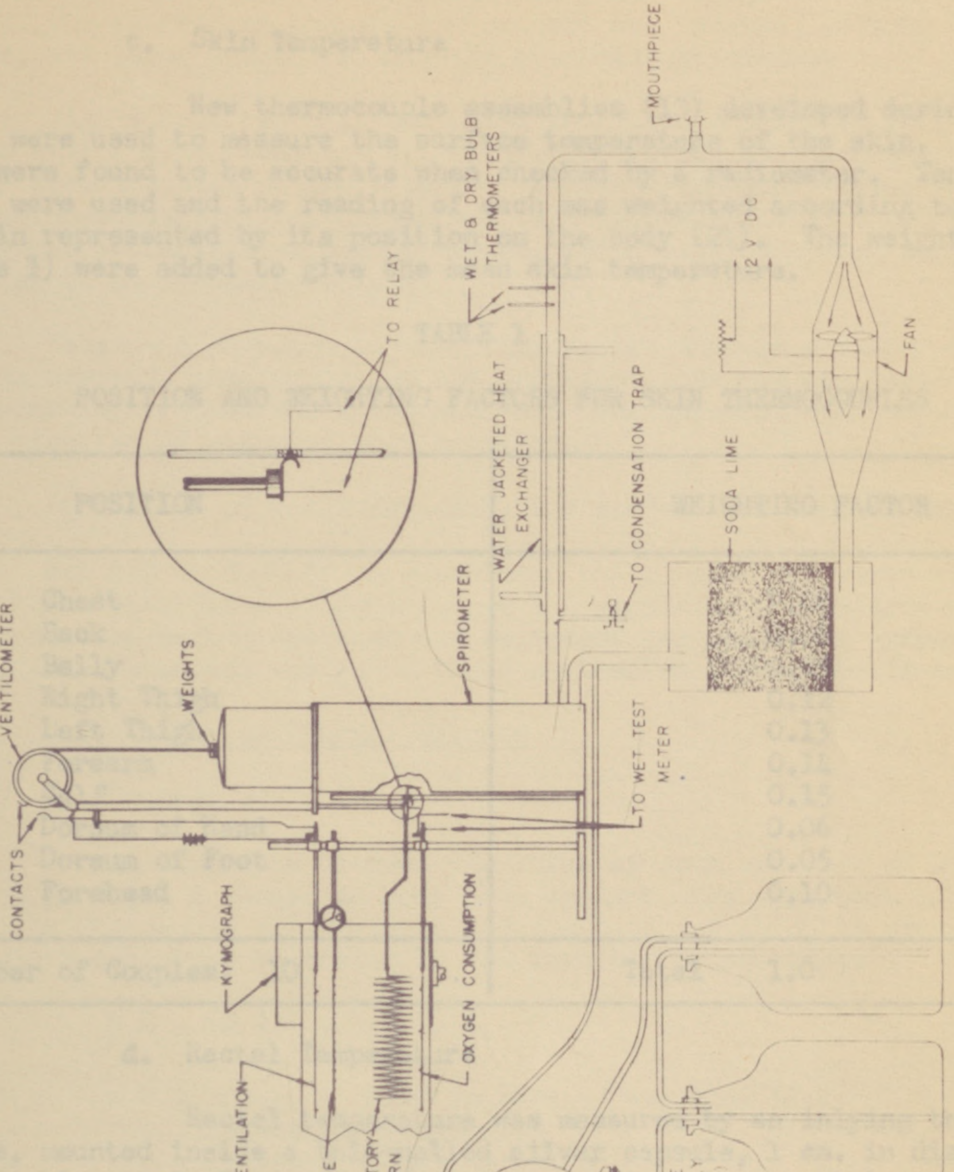

FIG. 2. APPARATUS FOR MEASURING OXYGEN CONSUMPTION

end walls. The measurements agreed satisfactorily with simultaneous readings by a radiometer. The average surface temperature was obtained from a formula in which the long walls were weighted 4 times as heavily as the small end walls.

c. Skin Temperature

New thermocouple assemblies (13) developed during this study were used to measure the surface temperature of the skin. The readings were found to be accurate when checked by a radiometer. Ten assemblies were used and the reading of each was weighted according to the area of skin represented by its position on the body (21). The weighted values (Table 1) were added to give the mean skin temperature.

TABLE 1

POSITION AND WEIGHTING FACTORS FOR SKIN THERMOCOUPLES

POSITION	WEIGHTING FACTOR
Chest	0.08
Back	0.08
Belly	0.09
Right Thigh	0.12
Left Thigh	0.13
Forearm	0.14
Calf	0.15
Dorsum of Hand	0.06
Dorsum of Foot	0.05
Forehead	0.10
Number of Couples: 10	Total 1.0

d. Rectal Temperature

Rectal temperature was measured by an inlying thermocouple, mounted inside a thin-walled silver capsule, 1 cm. in diameter and 4 cm. in length.* Four thermal junctions, wired in parallel, were cemented around the inside wall of the capsule near the distal end. This assembly gave accurate readings and had a very short response time. It was inserted at least 7 cm. (22).

* We are grateful to Dr. S. M. Horvath and Mr. D. Little for the design and construction of this mounting.

B. Procedure

About 45 minutes were required to stabilize the temperatures and humidities of the environments inside and outside the chamber. During this time the thermocouples were attached to the subject's skin. At the start of the experiment proper, the subject was weighed, entered the chamber, and began breathing into the metabolic apparatus.

Significant readings could not be obtained for 5 to 10 minutes because of the time necessary for clearance of room air from the chamber and for stabilization of the altered inside environment. Evaporation was measured continuously; metabolism was recorded by units of 3 liters of oxygen; and a complete series of rectal, skin, wall, and air temperatures was taken at 15 minute intervals.

Water was supplied at body temperature through a rubber tube lead- into the box and, when urination was necessary, the box was opened and the experiment interrupted for a few minutes. The quantity and temperature of fluids ingested or excreted were measured.

At the end of the experiment, the subject was weighed immediately.

For the conduct of an experiment three operators were desirable. One of these recorded all temperatures and regulated the environmental conditions; the second operated the equipment for measuring evaporation; and the third observed the subject and controlled the metabolic apparatus.

C. Calculation of Thermal Balance

1. General

An imbalance between the rates of gain and loss of heat by the body produces a change in body heat content, the magnitude of which depends on the degree of imbalance and the time for which it persists. This relationship can be stated in the form of the equation:

$$\Delta H = (M + C + R + E)\, t,$$

where
ΔH = change in heat content of the body (Cal)
M = metabolism (Cal/hr)
C = convection (Cal/hr)
R = radiation (Cal/hr)
E = evaporation (Cal/hr)
t = time (hr)

When heat flows into the body through any channel the rate is considered positive, and when heat flows out of the body it is considered negative.

Two other factors in rates of heat transfer could be added to this equation: (1) conduction; (2) ingestion or excretion of matter. These were negligible in this method.

The principles by which the individual components of the equation were calculated have been reported from the Russell Sage Institute (21,23,24), the Pierce Laboratory (5,7,25,26,27,28) and elsewhere (9,10,11).

2. Primary Calculations

a. Metabolism (M)

Metabolic heat production was calculated from the rate of oxygen consumption, recorded by units of 3 liters of moist gas, using an arbitrary R.Q. value of 0.84 (29).

b. Evaporation (E)

Evaporation from the lungs was calculated from the vapor pressure difference between inspired and expired air and ventilation rate; evaporation from the skin was determined from the difference in water vapor concentration at the chamber inlet and outlet and the flow of air through the chamber (13).

c. Changes in Heat Content (Δ H)

The change in body heat content for the entire experiment was calculated from the change in average body temperature, which was computed from the changes in rectal (deep tissue) and mean skin (peripheral tissue) temperatures. The formula used was developed by Burton (30) and modified by Hardy and DuBois (31). The change in rectal temperature was weighted 4 times as heavily as the change in mean skin temperature.

The change in average body temperature, multiplied by the mass and specific heat of the body, gave the change in heat content. The specific heat was considered to be 0.83 (30) and the mass was the average of the initial and final balance weights.

d. Radiation (R)

Radiation was calculated by the principles outlined by Hardy and DuBois (21). The details of the calculations are contained in an earlier report from this laboratory (9). The radiation profile of the nude subject in the supine position was taken as 0.8 of his total surface area.

e. Pulmonary Convection

Pulmonary convection was calculated from the temperature difference between inspired and expired air, ventilation rate, and the specific heat of air (approximately 0.0003 Cal/liter). This value was so small that it could be neglected generally, otherwise it was added to the value for skin convection.

3. Secondary Calculations

a. Convection (C)

Average convection for the entire experiment was computed by substituting the results of the primary calculations in the thermal equation and solving for C:

$$C = \frac{\Delta H}{t} - (M + R + E)$$

The value of ΔH was subject to error because the changes in rectal and mean skin temperatures were imperfect indices of the change in average body temperature. When t was large, the expression $\frac{\Delta H}{t}$ became small, and the intrinsic error in ΔH had a negligible effect on the value of C. This was not the case, however, when t was small, and it was necessary to adopt another method of computing C for short intervals.

This calculation was based on the principle that the rate of convective heat exchange was proportional to the square root of the wind velocity and the difference between the air and mean skin temperatures (10,26). Since wind velocity was constant, convection was a function of the temperature gradient only. Average convection calculated from the thermal equation, was divided by the average gradient for the whole experiment, and a coefficient was obtained expressing the rate of heat transfer in Cal/hr/°C. Convection over a short period was then computed by multiplying this coefficient by the temperature difference for the interval.

b. Change in Heat Content (ΔH)

H for short intervals was then obtained by substituting the short-term value of convection in the thermal equation.

4. Practical Considerations

About 4 man-hours were required for the analysis of 1 hour of data collection.

D. Application

The method was used in 27 experiments in which the thermal balance, of reclining normal or febrile subjects, was determined in studies lasting 6 to 8 hours. Test environments ranged in temperature from 27° to 43°C. with a vapor pressure of about 7 mm. Hg and a wind movement of 15 feet per minute. The results of these experiments will be reported separately (32). Pilot experiments were conducted on clothed and working men.

III. DISCUSSION

The reliability of the method rested fundamentally on the primary determination of M,R,E and ΔH. Only a small error was introduced into the calculation of metabolic heat production by failure to determine an R.Q. value.

The reliability of the method for measuring evaporation has been discussed previously (12).

An error was incurred in the primary short-term calculation of ΔH. These values lagged behind those yielded by secondary calculation during

times of large and rapid change. The primary short-term calculations were obviously incorrect since these values, substituted in the thermal equation, yielded highly inconsistent and sometimes absurd results for convection. Hence, the primary calculation of Δ H was applied only to long periods of time in which rapid changes in temperature had no effect.

Several errors present in the measurement of radiation were due chiefly to imperfect temperature measurements and failure to account for changes in the radiation profile.

The accuracy with which average convection could be determined depended on the long-term measurements of the primary factors. The least reliable of these was radiation and, in the final evaluation of the method, the partition of C and R was the least satisfactory procedure. Analysis of all runs suggested that an overall error of 10-15 per cent might occur but this was not generally a serious drawback, since C and R were parallel functions. In partitioning convection over short intervals, another error was superposed due to the fact that the effective wind velocity was altered when the pattern of muscular activity was changed.

The short-term calculation of Δ H also reflected the errors due to changes in effective wind velocity, but it was not affected by errors in the basic partition of C and R, since it was calculated from the sum of these components.

IV. CONCLUSIONS

The particular advantages of this method are:

A. Each component of the thermal balance can be determined either continuously or at short intervals.

B. Rapidly changing and high rates of evaporation and metabolism can be determined without difficulty.

C. The method can be applied to a wide variety of experimental conditions.

V. RECOMMENDATIONS

It is recommended that this method, or portions thereof, be considered by agencies planning to undertake problems of human calorimetry.

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