BAINBRIDGE
AND MENZIES

ESSENTIALS OF
PHYSIOLOGY

TENTH EDITION

EDITED AND REVISED BY
H. HARTRIDGE &
J. L. D'SILVA

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PREFACE TO THE TENTH EDITION

New editions of this book appeared with fair regularity about once every four years during the period between the two world wars, but in 1940 they stopped and no new edition has appeared since, owing to war and post-war conditions, until the present day.

When it was written by its original authors, Professor Bainbridge and Dr. Menzies, it was intended for the use of the ordinary medical student, large enough to supply him with the fundamental knowledge of physiology required by his profession, but not so large that it produced discouragement and boredom. This idea has been preserved by the present editors and in consequence essentials have been retained while non-essentials have been omitted.

Owing to the large interval of nearly sixteen years since the last edition, drastic revision has, of course, been necessary in order to bring the text up to date. The entire content has been revised and many chapters have been completely rewritten. One of the features of previous editions has been the division of the text into paragraphs, each of which had a title in large capital letters. This arrangement has been replaced by a more continuous text because many students told us that they found the numerous sub-titles disturbing. In this and other respects we have consulted the wishes of our readers.

We owe much to Miss Jean Barton and Mrs. D'Silva for the parts they have played in preparing the manuscript.

H. HARTRIDGE
J. L. D'SILVA

August, 1956.

PREFACE

Our object in writing this book has been to bring together in a concise form the fundamental facts and principles of Physiology, primarily with the object of meeting the requirements of the medical student preparing for a pass examination in the subject of Physiology. Considerations of space have led us to exclude as far as possible histological details and descriptions of chemical and experimental methods which form part of each student's laboratory course, and for which separate text-books are used. We have also omitted, for the same reason, all matter of purely historical interest.

In view of the transitional state of anatomical nomenclature, we have, after much consideration, retained the terminology hitherto used in this country, and have inserted the Basle nomenclature in brackets.

While it is impossible to mention all the sources upon which we have drawn, we wish to acknowledge our especial indebtedness to Prof. E. H. Starling, not only for permission to use many figures from his *Principles of Physiology*, but also for advice and information on many points. Our thanks for permission to use figures, which are as far as possible separately acknowledged in the text, are also due to Prof. Sir E. Sharpey Schafer (*Quain's Anatomy* and *Essentials of Histology*), Professor J. N. Langley (*Journal of Physiology*), Dr. M. S. Pembrey (*Practical Physiology*), J. Barcroft, Esq. (*Respiratory Function of the Blood*), Dr. A Hurst, Dr. Homans, Dr. W. E. Hume, Professor R. Howden (*Gray's Anatomy*), and the Council of the Royal Society. We must also thank the publishers and others who have kindly supplied us with blocks, namely, Messrs. J. & A. Churchill, Hodder & Stoughton, Macmillan & Co., Ltd., Mr. Edward Arnold, the Cambridge University Press, Messrs. Baird & Tatlock, Ltd., and Messrs. Hawksley.

Finally, we are indebted to Miss F. H. Miller for her unwearying efforts in the production of the original illustrations, and to Messrs. Longmans, Green & Co., for the great pains they have taken in the reproduction of the figures.

F. A. BAINBRIDGE
J. ACKWORTH MENZIES

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CHAPTER 1

ENERGY METABOLISM AND BODY TEMPERATURE

ENERGY METABOLISM

Life is accompanied by the evolution of energy of the following types: (1) mechanical energy, for example that seen in the movements of the limbs, the rhythmic contraction of the heart and the peristalsis of the bowel; (2) heat energy, for example that continually lost by the body at its external surfaces; (3) electrical energy, for example that recorded in the electrocardiogram; (4) acoustic energy, for example that produced by the voice. All these together represent the energy output of the body.

Of the various types of energy mentioned above, two, namely heat and muscular work, represent together nearly the whole amount produced by the human body. The amounts put out as electrical energy or acoustic energy are small in comparison and can be neglected. The amount of muscular work performed by a man and the amount of heat he produces can be measured separately.

Energy metabolism at rest. To measure the *heat output*, the man is placed in a calorimeter such as that shown in Fig. 1. The Atwater-Benedict calorimeter is a chamber the walls of which conduct heat badly. Passing across the upper part of the chamber are pipes (A, Fig. 1) through which cold water flows at such a rate that the temperature of the room remains constant. The heat evolved by the subject's body heats the water in the pipes. From a knowledge of the rise in temperature of the water and the volume of water passing through the pipes, the amount of heat evolved can be calculated. For instance:

Mean rise of temperature of water = 5° C.

Volume of water passed through chamber in 24 hr. = 410 *l.*

Therefore heat evolved by the subject in 24 hr. = 410 × 5 = 2050 Calories.

Note: 1 Calorie (large heat units) = 1000 calories (small heat units).

The Measurement of Work Done. The subject pedals a stationary bicycle (a 'bicycle ergometer') the movement of the rear wheel of which is restrained. Many devices have been used to apply a brake to the rear wheel, but all of them enable the restraining force (F) to be measured in kilograms. If the number of revolutions (N) made by the wheel in one minute is recorded, and the circumference (L metres) of the wheel is known, the work done (W) is given by the expression

$$W = F \times N \times L \text{ kg.m. per min.}$$

The *heat equivalent* of this amount of work is given by the expression W/425 Calories per minute.

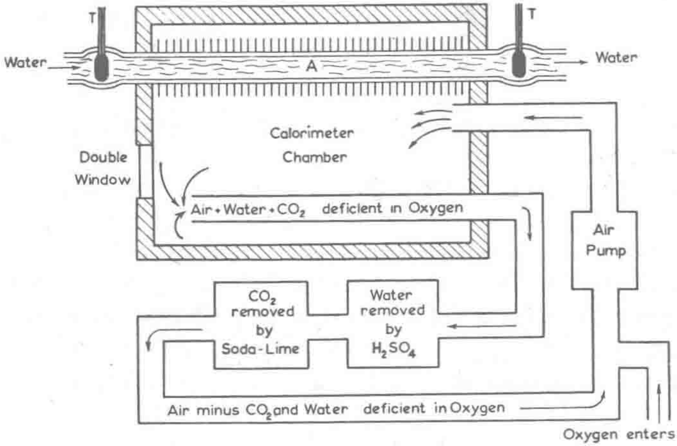

FIG. 1.—Diagram to show the principle of the Atwater-Benedict calorimeter. (After Halliburton).

Energy metabolism during exertion. If the subject pedals the bicycle ergometer inside the calorimeter chamber, he produces much more heat than he does at rest. The increased heat production bears a relationship to the amount of muscular work done. Only some 20–30 per cent. of the energy produced by the active muscles appears as mechanical work. The remainder is dissipated as heat. *The mechanical efficiency of man* can be calculated as follows: A man at rest evolved 2397 Calories, while the same man when working evolved 4574 Calories. There was an increase of 2177 Calories. But this did not represent the work the man did, for measurement showed this to be the equivalent of only 546 Calories. Of the increase of 2177 Calories only 546 appeared as work; the remaining 1631 Calories appeared as additional heat which represented the extra work done by the heart, and the heat evolved by the muscles, etc., during the performance of the 546 Calories of work. The percentage of the total heat produced which appears as work is known as the *mechanical efficiency*. In this example, it was $\frac{546}{2177} \times 100 = 25 \cdot 1\%$.

Energy metabolism during starvation. The Table shows the heat produced daily by a starved man at rest. We observe (*a*) that even on the 5th day of starvation the amount of heat he produced in 24 hr. was only 11·3 per cent. less than when the experiment started (column 2) and (*b*) when the heat produced was divided by the subject's body weight, the quotient soon became constant (column 3).

No. of days starvation	*Output of Calories per day*	*Calories per kg. of body-weight per day*
1	2231	33·3
2	2112	32·1
3	2032	31·3
4	2003	31·3
5	1979	31·4

Experiment has shown that during starvation the tissues of the body are oxidized and this is the source of the heat evolved. Ordinarily, the food we eat is absorbed from the alimentary canal and is oxidized to provide heat for the tissues.

The energy value of foodstuffs. The amount of heat evolved by the oxidation (burning) of food can be ascertained by means of the bomb calorimeter (Fig. 2). A known weight of food is placed in the container A. The cast-steel bomb, F, is then closed. Oxygen is admitted until a high pressure is reached inside the bomb. An electric current is passed through the platinum wire, B, by means of the leads, *h* and *h'*. This heats the wire, which in its turn ignites the food which now burns in the oxygen. The heat evolved heats the bomb

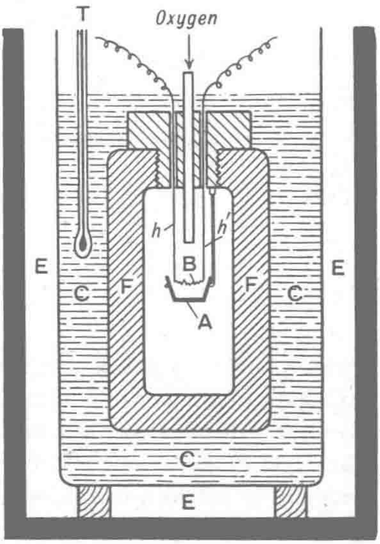

FIG. 2.—Bomb calorimeter.

and the water, C, round it. Heat loss is prevented by the air space E. The rise of temperature is recorded by the thermometer, T.

By means of a separate experiment, the amount of heat produced by the passage of the electric current through the platinum wire is determined. This quantity must be subtracted from the total heat produced which served to heat the bomb calorimeter and the water which surrounded it. The number of Calories of heat produced when 1 gm. of carbohydrate, protein, or fat is burnt in oxygen can then be calculated.

When using the bomb calorimeter the following values are obtained: for proteins 5·6 Calories per gm., for fats 9·3 Calories per gm., and for carbohydrates 4·1 Calories per gm. In the body, proteins are not burnt as completely as they are in a bomb calorimeter. The excretory products of proteins (for example, urea) have a heat equivalent which may also be measured by the bomb. The value obtained is 1·5 Calories per gm. The effective heat value of protein in the body is therefore $5 \cdot 6 - 1 \cdot 5 = 4 \cdot 1$ Calories per gm. The final figures are thus:

Food	*Calories per gm.*
Protein	4·1
Fat	9·3
Carbohydrate	4·1

From a knowledge of the weight of each food eaten during the day and the Calorie value of each food, the total Calorie intake per day may be calculated. Thus:

Food eaten	*Weight per day in gm.*	*Calories per gm.*	*Intake in Calories*
Protein	100	4·1	410
Fat	100	9·3	930
Carbohydrate	500	4·1	2050
			3390

Such an intake should be adequate for a man doing moderate work.

Indirect calorimetry. Since the heat put out by the body is derived from the oxidation of food, and is accompanied by the evolution of carbon dioxide, it would be anticipated that there would be a relationship between the output of heat, the intake of oxygen, and the output of carbon dioxide. Experiments show that this anticipation is justified. It is found that for every 5 Calories of heat evolved, about 1 *l.* of oxygen is absorbed from the air breathed in and rather less carbon dioxide is breathed out. The ratio

$$\frac{\textit{volume of carbon dioxide breathed out}}{\textit{volume of oxygen absorbed}}$$

in unit time is known as the *respiratory quotient* (R.Q.) (p. 156).

R.Q.	*Calories per litre of oxygen absorbed*
1·00	5·05
0·90	4·94
0·80	4·83
0·70	4·72

If we can measure the oxygen absorption of a man and his output of carbon dioxide in unit time, we can calculate his R.Q. Then, from

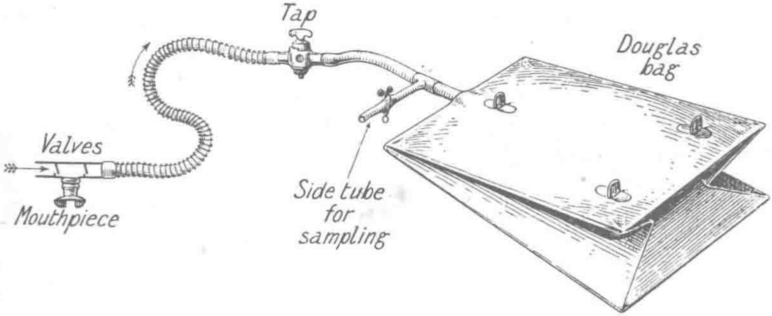

FIG. 3.—Diagram of Douglas bag arranged for collection of the expired air.

the number of litres of oxygen absorbed, we can calculate approximately the number of Calories he is putting out without placing him in a calorimeter. This process is known as *indirect calorimetry*. In practice, it is usually sufficiently accurate to determine the number of litres of oxygen absorbed and to assume that 5 Calories of heat are produced for each litre of oxygen absorbed. An example will show the method: By means of a mouthpiece with appropriate valves the air expired from the lungs during 5 min. was collected in a large collapsible airtight canvas (Douglas) bag (Fig. 3). Some of this expired air was subjected to chemical analysis, as also was some of the air from the room. It was found that the subject had absorbed 4·57 per cent. of oxygen from the room air. The total volume of expired air was then measured and was found to equal

30 *l*. The volume of oxygen absorbed in 5 min. was therefore $\frac{30 \times 4 \cdot 57}{100} = 1 \cdot 371$ *l*. Since about 5 Calories of heat are evolved for each litre of oxygen absorbed, $5 \times 1 \cdot 371$ Calories were evolved in 5 min. or $\frac{5 \times 1 \cdot 371}{5} \times 60 \times 24 = 1974$ Calories in 24 hr.

The following is another method of indirect calorimetry.

The Benedict-Roth Spirometer. The apparatus consists of a light metal bell which floats in water, and is counterpoised, rather like a

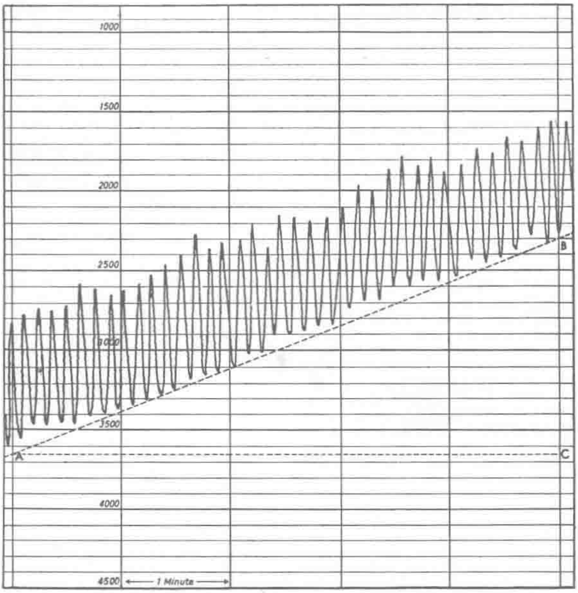

FIG. 4.—Spirometer tracing.

gasometer. The air (or oxygen) confined in the bell is connected by means of two tubes with the mouthpiece of the apparatus. Suitably placed valves are arranged in the tubes to ensure a one-way circulation of gas when the subject breathes gas from the apparatus and then expires into it. The expired air passes through a container which removes carbon dioxide and in this way the bell of the spirometer sinks deeper in the water as the oxygen it contains is used up. The up-and-down movements of the bell (in time with the subject's respirations) are recorded on a slowly moving drum and produce a graph like that shown in Fig. 4. The rate at which oxygen is absorbed by the subject is given by the slope of the line AB (Fig. 4). If the recording paper is calibrated suitably, the amount of oxygen absorbed per minute can be determined directly. In Fig. 4, the oxygen consumption is represented by the distance BC (1·35 *l.*) in the time AC (5 min.) i.e. 0·27 *l.* per min. Thus 0·27 × 5 = 1·35 Calories of heat were produced by the subject per min.

The heat evolved by a man at rest is generated in order to keep up the temperature of the body, which is always tending to fall owing to loss of heat by the skin to the surrounding air. Experiment shows that the loss of heat *per square metre* of skin is approximately the same for man and animals though the total amount of heat lost varies greatly. Some values are given in the following Table:

BASAL METABOLIC RATE OF DIFFERENT ANIMALS

Animal	*Weight in kg.*	*Calories per day per kg.*	*Calories per day per sq. m.*
Horse	441	11·3	948
Pig	128	19·1	1078
Man	64·3	32·1	1042
Dog	15·2	51·5	1039
Mouse	0·018	212	1188

We find that a big man loses more heat than does a small man in proportion as his skin surface is larger.

The effect of food on the energy metabolism of the body. It has already been stated (p. 4) that when the three primary foodstuffs, protein, carbohydrate, and fat are metabolized in the body, heat is produced. It is found by experiments on men and animals that the taking of certain foods has a stimulating effect on metabolism. Thus a man at rest who is being fed for a few days on a synthetic diet with a small stimulating effect may require no more than 2000 Calories in order to maintain his body weight. The same man on a diet with a large stimulating effect may require 2400 Calories. This stimulating effect of food is called the *specific dynamic action*. It is large for protein, sometimes as much as 30 %, and is much smaller for fat (3 %) and carbohydrate (1·4 %).

The basal metabolic rate is defined as the *number of Calories* produced by a subject *per hour per square metre of body surface* when the subject is at complete *mental and physical rest* and in *the post-absorptive state*, that is, some 12–18 hr. after the last meal.

It has been stated above that *exercise* and the *specific dynamic action of food* both increase heat production, so, from the definition above, we may regard the basal metabolic rate as that minimum rate of metabolism which results from the functioning of the subject's 'vital processes.'

The subject lies at rest, lightly clad, in a warm room. His Calorie output may be determined by direct (p. 1) or indirect (p. 4) calorimetry. His surface area is obtained from a knowledge of his height (in cm.) and weight (in kg.) by means of the nomogram shown below.

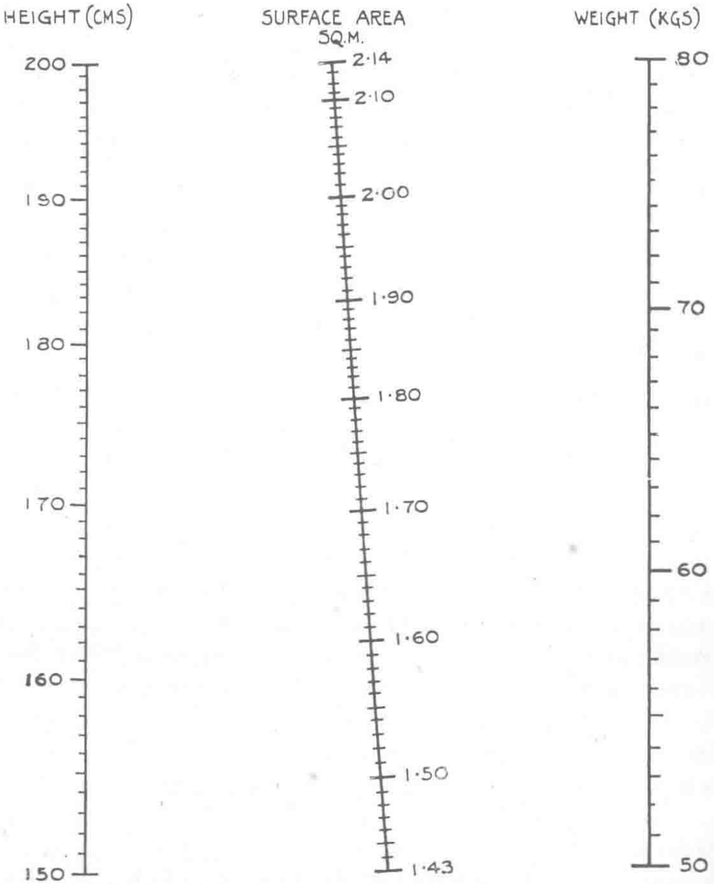

FIG. 5.—Nomogram for calculation of body surface. (Smart.) Place a ruler so that it lies on the points for weight and height and note the surface area. (From Starling's *Principles of Physiology*.)

Suppose his height was 180 cm. and his weight 72 kg., then his surface area from the nomogram would be 1·9 sq. m. If his heat production per hour was found to be 76 Calories, his Calorie output per hour per square metre of body surface would be $\frac{76}{1\cdot 9} = 40$. Values for the basal metabolic rate per square metre of body surface area per hour at different ages are given below:

Age	*Output in Calories per hr. per sq. m. of body surface*
10–13	50
13–16	46
16–30	40
30–80	37

The Table shows that the basal metabolic rate (B.M.R.) of young adults is about 40 Cals./sq.m./hr. Children have a higher, and elderly people a somewhat lower, B.M.R.

BODY TEMPERATURE AND ITS REGULATION

The temperature of primitive creatures (e.g. bacteria) and cold-blooded animals (e.g. lizards) follows, and is closely similar to, the temperature of their environment. Warm-blooded animals (e.g. man), however, have a body temperature which is usually higher than the temperature of their surroundings. The bacteria and other elementary living organisms will often stand, for a short time at all events, the application of quite extreme degrees of heat and cold. Many species of bacteria can be heated to the temperature of boiling water and can be cooled far below the freezing point of water and will show afterwards normal activity and growth. Their spores are frequently more resistant than they are themselves. Plant seeds can withstand quite big temperature variations from the normal.

The group of cold-blooded animals which comprises the invertebrates, the fish, and the amphibia (frogs, for example), cannot stand such large temperature variations as the above group. If they are heated to a temperature much above 40° C or much below freezing point they perish. Their temperature is usually about the same as that of their surroundings. Cold-blooded animals are better off than man in being able to live without having to keep themselves warm, while they are worse off than man in being forced in cold weather to be torpid and sluggish. It is only in warm weather that they can be active. The cause of this change in behaviour is the effect of temperature on the speed of conduction of the nervous impulse and the rate of contraction of their muscles. It can be shown experimentally that both are increased about 1·8 times for a rise in body temperature of 10° C. Thus a frog at 10° C can be 1·8 times speedier in its movements that it is at 0° C. At 30° C it can be $1{\cdot}8 \times 1{\cdot}8 \times 1{\cdot}8 = 5{\cdot}8$ times more speedy than it is at 0° C.

The warm-blooded animals (man, other mammals and birds) can withstand somewhat larger temperature variations than cold-blooded animals, but they can only do this because they have a mechanism for keeping the internal temperature of their bodies constant and independent of the temperature of their environment. Thus travellers explore the polar regions where the temperature is much below 0° C. Bakers and stokers work where the temperature is very high. But their internal temperatures are found to remain approximately constant at about 37° C.

The body temperature is measured at its external surface, for example, in the groin, or in the axilla, or in one of its external orifices, for example in the mouth, or in the rectum. The mouth gives more reliable values than do the groin or axilla. The rectum is more reliable still. The instrument used is a mercury thermometer which records the highest temperature reached. It is important when taking a subject's temperature to allow the thermometer to be in position long enough to register its highest reading. Three minutes is usually sufficient.

Heat gain and loss. Heat may be gained or lost at the surface of the body in three different ways: convection, conduction and radiation. It may also be lost by evaporation of sweat and gained by the condensation of hot vapour, e.g. steam, on the body. In addition, as we have said, heat is gained by the oxidation of the constituents of the food. It is lost by the excreta. It is lost by the breath if the air breathed in is colder and drier than that breathed out; it is gained by the breath if the air breathed in is warmer than that breathed out. We may therefore summarize as follows the conditions under which *heat is gained*: oxidation of the food we eat; exercise in hot air contact with the skin; skin in contact with hot bodies; the application of radiant heat to the body surface; breathing moist air above body temperature; condensation of hot vapours on the body.

Heat is lost under the following conditions: the evaporation of sweat; cold air in contact with the skin; contact with cold bodies;