CHAPTER IX

THE HUMAN ENGINE: FUELLING

In the previous chapters we considered some of the important chemical reactions that take place in the human body. In this chapter we shall deal with the method by which the body maintains a wonderfully constant temperature and how it converts energy into mechanical work. Regarding mechanical work, it should be understood at the outset that the very act of living is rendered possible through the various internal organs of the body being able to derive sufficient energy to keep them in continual action. Indeed, organs such as the heart and the lungs are mechanisms that are always performing work, in other words they are converting energy into work. Work done by the internal machines we shall call "internal work." But the individual may do work besides the involuntary driving of his internal machines. This work we shall term "external work." Now in order to do such work he must have stored within his body energy which, by some means, can be made available at the times demanded in order that it may be transformed by the muscles of his arms or legs into some form of actual work. This brings us to the question: whence does the body obtain the energy it requires to drive its many machines and also the energy which it may expend in doing external mechanical work? The answer lies in the chemical reactions that take place within the body. Looked at in a general way, these reactions when considered in terms of the final products, e.g., carbon dioxide and urea, may be considered as oxidations or combustions of the food products assimilated by the body. Hence the relationship of food to the body is often regarded as being the same as that of fuel to the engine. In the case of the mechanical engine, the heat is derived from the burning of the fuel and is converted to a greater or lesser extent into effective work. Even the most efficient engine, however, cannot convert all its heat energy completely into mechanical work. This is due to the insurmountable difficulties encountered in the design of the engine, and the choice of the fuel and other materials used, and also to the fact that heat can only be absorbed by the working medium if the temperature at which the heat is generated is higher than that of the working medium, otherwise, although quantities of heat may be generated, it is incapable of promoting mechanical action. In other words, if the source of heat should be at a lower temperature than the substance which actually converts heat into work, no heat can, of course, flow from the lower temperature to the higher temperature, and consequently no work can be obtained from the engine. Now in the body the heat is generated by the performance of chemical reactions and some of this heat is taken up by the muscles. They in turn are able to convert this energy into mechanical work, both internal and external. By electrical means, temperature changes in the muscles can actually be detected during periods of muscular activity. We saw in the previous chapter that lactic acid is developed during the activity of muscles and that much of this lactic acid is oxidised to carbon dioxide by the oxygen brought up to the seat of activity by the blood. This lactic acid originates from the carbohydrate-reserves stored in the form of glycogen within the muscle. How this glycogen breaks down into lactic acid is not altogether clear, but there is some evidence that a phosphate of potassium plays an intermediate part. In a general way the reactions may be represented by the following scheme :

$$\text{Glycogen} \longrightarrow \text{Glucose} \longrightarrow \text{Intermediate Products} \longrightarrow \text{Lactic acid} + \text{ENERGY}$$

Then the subsequent reaction is

$$\underset{\text{(from muscles)}}{\text{Lactic acid}} + \underset{\text{(from blood)}}{\text{Oxygen}} \longrightarrow \underset{\text{(to blood)}}{\text{Carbon Dioxide}} + \underset{\text{(to blood)}}{\text{Water}} + \text{ENERGY}$$

Chemical reactions themselves take place because the potential energy stored up within the molecules of the reacting bodies is greater than that which can be contained within the molecules of the substances that will be formed. Hence it is the flow of energy, accompanying a chemical reaction, that makes the reaction possible. Some energy is set free as the result of this degrading of the energy in the reaction system. Usually this liberated energy takes the form of heat, though in some reactions it may appear in the form of work. In some instances, however, heat may actually have to be absorbed from the surroundings. In both the reactions represented above it will be seen energy is developed and this takes the form of heat. In the muscle at rest, some oxidative reactions are proceeding that liberate heat in a quantity sufficient to maintain the appropriate temperature. During contraction of the muscles the lactic acid reaction proceeds more rapidly and a greater amount of heat is liberated. Some of this heat is transformed into muscular work, though some remains to raise the temperature of the muscles. This explains why exercise on a cold day will enable one to keep warm, so much so that the body temperature may even rise a degree or so above normal. As the very act of living involves the continuous exertion of an intricate muscular system, it will be understood that the maintenance of life is intimately wrapt up in the types of food taken. Those which lead to the maximum production of heat are fats and carbohydrates.

As an engine, the body is not very efficient. It is not able to convert a large portion of its heat into work, probably never more than 25%. The remainder, 75%, of the heat is utilised in keeping the body at 98·4° F. and in cold weather this will require much heat as large quantities are radiated from the body to the surrounding atmosphere. If the temperature diverges much either way from 98·4° F. it becomes an indication of trouble. It is an astonishing fact that the body-temperature should be so much higher than the prevailing temperature of the atmosphere.

Treatises on dietetics usually refer to the calorific values of foods. Unfortunately it is not often realised what a large amount of valuable meaning is contained in these calorific values, and consequently they are passed over unheeded except by the very few. If people realised that these values were intimately linked up with the healthy maintenance of the body, and also in laying aside reserves of potential energy to make growth possible, then it is likely that the subject would receive some consideration, and certainly more than that usually given to the relatively less important question of vitamins.

The unit, *calorie*, used in assessing the fuel value of food is perhaps somewhat confusing. The body requires both *heat* and the *capacity to do work*, which we call *potential energy*. Hence, it happens that this potential energy can be considered in terms of the amount of work which it is actually able to do. Work is measured in terms of *force* and *distance*, for it is equal to the product of the force overcome and the distance through which its point of application has been moved. Furthermore, work can be quantitatively converted into heat. *Heat, however, cannot be quantitatively converted into work, and that is one of the difficulties met with in the working of any engine and certainly of the body.* Because work is convertible into heat, it follows that heat energy and mechanical energy can be expressed in the same units. Quantities of heat, however, can be measured with considerable accuracy and therefore it is more usual to express the heat evolved in the course of a chemical reaction in the terms of heat units, viz., calories. This unit is the amount of heat that must be absorbed by one gram of water in order to raise its temperature by 1° C. In considering the heat requirements of man, this unit is inconveniently small, and therefore the kilogram-calorie, sometimes called "great-calorie," or simply Calorie, spelled with a capital C, is used. This refers to the heat required to raise 1 kilogram (2⅕ lbs.) of water through 1° C, or expressed in terms of mechanical work as the work necessary to lift 3,070 lbs. through a height of 1 foot.

The energy requirement of a human being varies with age, size, sex and nature of work in which he or she is engaged. The average amount of energy per day required by an adult man is about 3,000 Calories, whereas that required by an adult woman is less, about 2,500 Calories. Doing external mechanical work in the open air will require more energy than if the work be done indoors, for there will be a greater amount of heat required to maintain the body at its normal temperature. Thus it has been estimated that 3,600 Calories should suffice for such work as painting or cabinet-making indoors, whereas something like 3,750 Calories will be necessary if the work is to be done outside. Heavy work out-of-doors may require as much as 5,000 Calories. Regarding the calorific value of the daily food required at different stages in the growth of boys and girls, the following table, which gives the estimates of the food actually taken by children and recorded by Emmet Holt, of New York, is of considerable importance.

Age	Boys	Girls	Age	Boys	Girls
1	950	940	10	2330	2195
2	1135	1110	11	2510	2520
3	1275	1230	12	2735	2864
4	1380	1300	13	3040	3210
5	1490	1410	14	3400	3330
6	1600	1520	15	3855	3235
7	1745	1660	16	4090	3160
8	1920	1815	17	3945	3060
9	2110	1990	18	3730	2950

These figures bring out facts that at first sight may seem astonishing. In the first place it is seen that the number of Calories required by a boy is usually greater than that required by a girl, except during the years 11 to 14, when the girl's need is slightly higher. This is caused by the period of adolescence beginning somewhat earlier. During the subsequent years in which considerable growth accompanies sexual maturity, the calorie intake is much greater than that of the adult male. Thus the greatest need is 4,090 Calories in the case of a boy at 16 years, and 3,330 Calories at 14 years in the case of a girl. Compared with 3,000 Calories, the need of the average man, we see that the requirement of a boy at 16 is equal to that of more than 1⅓ men.

In view of the importance of the calorific values of food-stuffs, we shall briefly consider how these values are actually obtained. They are measured by means of a contrivance known as a Bomb Calorimeter. It is a metallic vessel, in the shape of a bomb, in which a plentiful supply of oxygen is placed and also a small crucible in which the substance is to be burnt. A carefully weighed amount is taken and electric wires are so placed that the food can be ignited by means of an electric spark. This ignition can be made to take place spontaneously and complete combustion can be insured by having a high pressure of oxygen in the bomb. If the bomb is placed in a vessel, carefully insulated as regards any possible escape of heat, containing a definite weight of water, it is possible by observing the rise in temperature of the water as the result of the combustion to ascertain the quantity of heat actually emitted. The following figures give some idea of the quantity of heat emitted during combustion of one gram of the various substances :

Starch	4·1 Calories	Protein	5·6 Calories
Cane sugar	3·4 Calories	Urea	2·5 Calories
Fat	9·4 Calories		

It would therefore appear that weight for weight fat is the most heat-producing food. This is the case. If proteins underwent complete oxidation in the body, then pure proteins would easily occupy the second place as heat-givers. In the body, fats and carbohydrates are burnt up to water and carbon dioxide and they, therefore, are completely oxidised and eventually give out the same amount of heat as in the act of direct combustion. It must be understood, however, that the complete decomposition process occurring in the body is the result of many oxidations, each bringing the original complex food-stuff into simpler molecular form. Each of these reactions is accompanied by an evolution of heat, and the total of these separate heats of reaction is equal to that which would have been evolved had the oxidation taken place by simple burning in an atmosphere of oxygen.

The body is unable to bring about the complete oxidation of proteins, so much so that every single part of protein yields about one-third of its weight of urea, $CO(NH_2)_2$. This urea, which on combustion yields 2·5 Calories per gram, is lost to the body for it is excreted in the urine. Hence the heat actually received by the body from the oxidation of 1 gram of protein is 5·6 Calories *less* the heat of combustion of one-third of a gram of urea, viz., $\frac{1}{3} \times 2{\cdot}5 = 0{\cdot}83$ Calories. The body should therefore obtain 5·60—0·83 or

4·77 Calories from each gram of protein absorbed. This estimate is certainly too high, for the decomposition of proteins often stops when other nitrogeneous substances, e.g., uric acid, creatinine, are formed and which are subsequently cast off both in the urine and in the fæces. The figure 4·0 is generally regarded as representing the true heat value of protein matter. As stated in earlier chapters, proteins are essential to the body for other purposes, such as tissue building. Despite their incomplete oxidation, they must therefore constitute a prominent portion of one's daily food.

Many attempts have been made to arrive at the most satisfactory proportion of protein to fat to carbohydrate in the daily dietary. From a scientific point of view an estimate may be made from a consideration of the amounts of decomposition products in the urine and those eliminated from the lungs. The amount of carbon dioxide which is ejected daily from the lungs of the average man varies from 250 grams to 280 grams, but may be very much increased during periods of great muscular activity. On the contrary, the amount of urea in the urine remains fairly stationary and corresponds to about 15 grams to 18 grams of nitrogen. These products originate either from the decomposition of food or from the break-down of tissues. If we take the case of the man doing a moderate amount of manual labour or muscular exercise then we find that he is losing combined carbon and nitrogen in the ratio of 16·6 to 1. The food eaten should therefore be such as to make good this loss. Although proteins vary considerably in the way they have been synthesised, the ratio of carbon to nitrogen they contain remains remarkably constant, namely 3·5 to 1. Taken alone, proteins would be grossly deficient in carbon, and consequently this must be made good by means of non-nitrogeneous substances such as fats and carbohydrates. Dr. Hutchinson considers that the standard amounts of the different foods required daily are: 100 grams of protein, 450 grams of carbohydrate and 75 grams of fat. Calculation shows that these would, if absorbed, furnish 2,950 Calories. Another diet due to Voit is: 120 grams of protein, 100 grams of fat and 333 grams of carbohydrate, which theoretically should produce 2,805 Calories. According to Halliburton and McDowall (*Handbook of Physiology*, 1928, page 428) 65 Calories will be dissipated in raising the water (2·6 kilograms) in the food to the temperature of the body; 96 Calories will be required to heat the air (16 kilograms) entering the lungs; 366 Calories, in evaporating 630 grams in the lungs; and the remainder, 2,277 Calories are required to maintain the body temperature and also to be converted into internal and external mechanical work. According to Plimmer the diet of an adult should contain 3½ ounces to 4½ ounces of protein, 2 ounces to 3 ounces of fat, and 14 ounces to 18 ounces of carbohydrate.

Although fat is a very powerful fuel-food some people are unable to digest it in the usual quantities, though it is extremely probable that in such people its digestion is often increased when the fat is accompanied by carbohydrates.

We shall now consider the amounts of these three main classes of food that are present in the ordinary foodstuffs. Water constitutes a considerable proportion of nearly every article of food, and the essential mineral matter is usually found in amounts up to about 1%. The composition of the different meats differ greatly in their proportions of protein and fat. On cooking, meat loses some of its water, with the result that it becomes a more concentrated food. Foods of vegetable origin take up large proportions of water, making it necessary to take relatively large quantities in order to obtain reasonable amounts of their nutritive material. In regard to its protein and carbohydrate contents, bread is a valuable food. It is, however, low in its fat content, as shown by the following analysis: protein, 6·5%; fat, 1·0%; carbohydrate, 51·2%; cellulose, 0·3%; mineral matter, 1·0%. Wholemeal bread contains less carbohydrates and about 1·5% of cellulose. The spreading of butter or margarine, each of which contains 80% to 85% of fat, on bread makes up for the deficit. Cheese contains roughly one-third of protein and one-third of fat, the remaining one-third being water. Though cheese is a concentrated food as regards both protein and fat, it has one disadvantage in that the fat is infiltrated throughout the protein. Unless the cheese is thoroughly converted into the liquid condition in the mouth, digestive difficulties may arise in the subsequent organs owing to the digestive juices being unable to penetrate the cheese lumps. Considered as a whole, eggs contain about 15% of protein and 10% of fat. Potatoes are rich in carbohydrates, the analysis being: protein, 2·2%, fat, 0·1%, carbohydrates, 11·5%. Oatmeal is a particularly rich food. In the dry, uncooked form, it contains 14·6% of protein, 10·1% of fat, 65·1% of carbohydrates and 2% to 3% of cellulose. Unfortunately the cellulose matter adheres tenaciously to the cell contents, and as the human digestive system is unable to deal with the cellulose coverings, there is a distinct tendency for the enveloped nutrients to be lost. Another disadvantage of oatmeal lies in the fact that it contains appreciable amounts of nitrogeneous bodies belonging to the class known as "purines," of which uric acid is an important member. For this reason, oatmeal should be avoided by people having rheumatic tendencies. Oatmeal is now rendered more digestible by subjection to treatment with hot rollers, which brings about the disruption of the cellulose membranes. Cocoa and chocolate are useful energy-producers. They are rich in fat and carbohydrates and also contain some protein. As sources of vegetable protein, pulses, viz., peas, beans, lentils, are valuable. Their chief drawback lies in their high content of cellulose matter. Peas, for example, contain 4·0% of protein, 0·5% of fat, 16% of carbohydrates and 0·5% of cellulose. Though cellulose is not digested by human beings, its presence in food in small proportions is not without advantage, for it tends to stimulate the intestines to action in expelling waste products.

Some idea of the relative merits of various articles of food as energy producers may be obtained from the following table, which gives the number of ounces that must be taken to supply 100 Calories.

Food	*No. of ounces*	*Food*	*No. of ounces*
Beafsteak	2·3	Cabbage	11·1
Lean ham	1·2	Potatoes	4·2
Bacon	0·6	Apples	5·6
Salmon	1·7	Almonds	5·3
Oatmeal	0·9	Olive oil	0·4
White bread	1·3	Sugar	0·9

In this table, almonds have been included as an example of the nutritive value of nuts. Dried nuts provide a very concentrated form of food as they contain only from 4% to 5% of water. Fat comprises from 50% to 60%, protein from 15% to 20%, carbohydrates, 9% to 12%; cellulose, 3% to 5%; and mineral matter, 1%. The relatively high proportions of fat and cellulose, however, often render nuts difficult to digest. Advantage is taken of the high fat content of nuts in the manufacture of substitutes for butter, and sold either as nut-butter or after incorporation in margarine.

In concluding this chapter, some reference will be made to the mineral requirements of the body. Though it is probable that they do not supply energy, they certainly play an all-important rôle in assisting in the absorption of food, in tissue and skeleton-building, in the proper functioning of the blood and other body fluids, and in maintaining various glands, e.g., the thyroid, in a healthy condition. With the exception of common salt, mineral matter is not taken directly. It is received in the many food-stuffs and it is probable that the mineral content of a well-balanced diet is usually sufficient. The following figures, based on recent estimates, give some indication of the daily need of the chief inorganic substances: combined phosphoric acid, 3 to 4 grams; combined sulphuric acid, 2 to 3½ grams; caustic potash, 2 to 3 grams; caustic soda, 4 to 6 grams; calcium oxide, 1 to 1·5 grams; magnesia, 0·3 to 0·5 grams; combined hydrochloric acid, 6 to 8 grams; and iron, 0·006 to 0·012 grams. In addition, iodine should be mentioned, which is required in traces by the thyroid gland. It is not easy to say precisely the source from which this essential ingredient is derived in view of the very minute traces in which it sometimes occurs in food substances. The addition of small amounts of potassium iodide to certain table salt has undoubtedly proved beneficial to people having tendencies to goitre. One of the chief advantages of soup lies in its high mineral content, which incidentally plays a dual part. Besides supplying the body with valuable matter, it imparts to the soup an osmotic pressure of between 7 and 9 atmospheres, which is higher than the osmotic pressure of the body fluids, being about 6 atmospheres. Hence one of the chief effects of taking soup will be an attempt to raise the osmotic pressure of the body-fluids. It is estimated that half-a-pint of soup will raise the osmotic pressure by one-half of an atmosphere. This increase in osmotic pressure is caused by an increased diffusion and absorption of dissolved substances from the intestinal tract.