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Some quantitative interrelationships among thermal environment, human metabolism and nutrition

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When a healthy man is exposed to an environmental extreme, to restriction of water, and to caloric deprivation, all at the same time, dramatic changes may occur in the efficiency of the body as a whole, and in the function of individual organs and systems. Important work has been published in this country and abroad on this 'survival problem', especially on two important aspects: environmental protection and the nutritional physiology of men living on survival rations. We shall not attempt to summarize comprehensively the work of others, but will confine this presentation to a few quantitative generalizations on metabolic phenomena, arising largely from our own studies. Details of methods, complete data on clinical, biochemical, physiological and nutritional observations, and practical applications for emergency feeding are to be found in four technical military reports (Sargent, Sargent, Johnson & Stolpe, 1954, 1955; Sargent, Sargent & Johnson, 1957; Sargent & Johnson, 1958).

Methods

In all, a total of 8698 subject-days is the basis for our conclusions; three major studies were conducted. In 1953, twelve volunteer students lived under temperate conditions and performed moderate daily work. In 1954, 100 volunteer airmen simulated survival in the winter cold of Wisconsin. In 1955, 100 volunteer airmen simulated survival in the moist summer heat of Indiana. Experimental design and measurements were basically the same in all three studies, so that statistically valid comparisons could be made between subjects in any one study, and among regimens in all three studies.

A preperiod of 2 weeks was followed by an experimental period of 2 weeks. There ensued a recovery period of 2 weeks. During the preperiods and recovery periods all subjects lived on the same adequate diet, with unlimited fluids and identical daily moderate work loads. During the experimental weeks one or another of the experimental regimens was imposed on different subgroups of subjects. All possible combinations of the following variables were studied simultaneously: water (unlimited or 910 ml./day); total calories (starvation, 1000, 2000 or 3000 Cal./day); proportion of calories from protein, carbohydrate, and fat (pure carbohydrate, low protein—low carbohydrate—high fat, moderate protein—moderate carbohydrate—moderate fat, high protein—low carbohydrate—high fat); daily work load (12 miles marching/day, 3 miles marching/day). In all periods, subjects were under constant metabolic control and medical observation. All food intake was controlled and measured. All urine and faeces were collected daily for subsequent analysis and calculation of the nutrient balance. Numerous techniques of clinical, physiological, nutritional, and biochemical investigation were employed to answer quantitatively the major question—what changes in organ and system function, and the efficiency of the body as a whole, were attributable to the combined effects of regimen, daily work, and temperature? Interpretation of results was greatly helped by the fact that two extreme nutritional situations were included in the experimental design, namely the worst possible regimen, starvation with limited water; and the ideal regimen, unlimited fresh and frozen foods with unlimited water.

To present generalizations in a concise way, we have chosen d'Ocagne (1921) nomograms in which independent variables are represented by the right- and left-hand lines, and the dependent variable by the middle line. In each, a straight line laid between values for the independent variables will intersect the middle line at the value for the dependent variable. These alignment charts have been constructed by empirically fitting our own findings, supplemented by similar data from previous investigations; they should be regarded as descriptions of events under the conditions of our experiments, not as mathematical expressions of universal truth.

Water requirements, temperature, and daily work load

Increased daily work load increases water requirement because of increased loss of water in sweat and in expired air (Fig. 1). An increased average environmental temperature increases the water requirement by raising the rate of sweating for

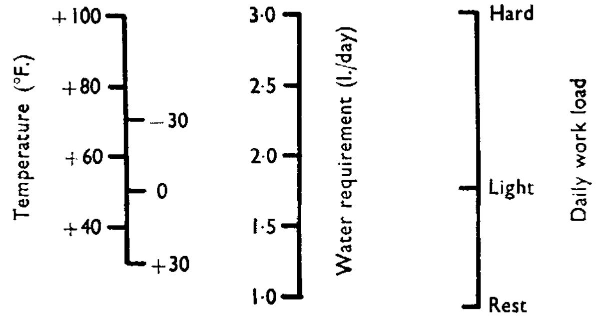

Fig. 1. Interrelations among thermal environment (left, °F. of mean environmental temperature during period of observation), daily work load (right), and water requirement (middle, l./day). The discontinuity at the freezing point is explained on p. 181.

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any given work rate. In hot environments with hard work and given optimal osmotic balance, a minimum of 2·8 l./day is required to prevent cessation of sweating, and ultimate heat stroke (Sargent *et al.* 1957). For light work in hot environments a minimum of 1·9 l./day is required to prevent anhidrosis. Thus we have defined water requirements functionally in terms of the clinical end-result of chronic dehydration. For cold environments, 0·9–1·8 l./day will suffice. When the temperature drops below freezing, although sweating is minimal, more water is lost from the respiratory tract the colder the temperature.

Osmotic balance is fundamental in any consideration of water metabolism. With regimens of very low osmotic effect, such as pure carbohydrate, primary salt depletion ensues, to use Marriott's (1950) terminology, and with it obligatory loss of body water, no matter what the intake. Especially in primary water deprivation, such as our chronic dehydration, there is an optimal osmotic intake which will permit the least loss of body water (Sargent, Johnson, Pandazi, Lichton & Nielsen, 1955). Hence, water requirements can be established only in relation to the osmotic effects of the diet, computed from the sum of protein and mineral intakes. We observed eleven cases of total anhidrosis or severe hypohidrosis (Sargent, Johnson, Huntley, Kosmala & Hanley, 1956). They all occurred in chronically dehydrated subjects whose osmotic intake was very high (high salt or high protein) or very low (pure carbohydrate or starvation). None occurred in subjects whose osmotic intake was optimal at about 0·7 osmoles/day. Because loss of solutes in sweat may exceed that in urine in hot environments, osmotic balance is thus secondarily related to environment.

Calories, work and environment

Energy expenditure is closely related to two factors (Fig. 2). Increased daily work

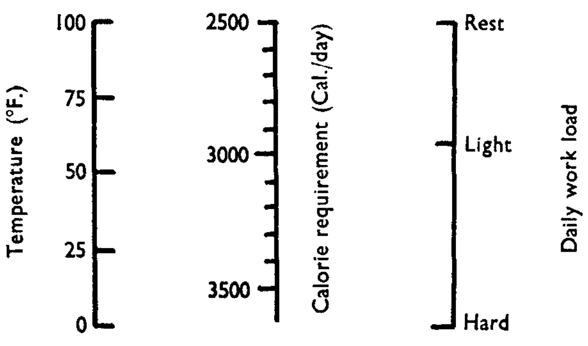

Fig. 2. Interrelations among thermal environment (left), daily work load (right), and daily calorie requirement (middle).

load increases calorie expenditure to accomplish muscular effort. Decreased average environmental temperature in which the human being must live increases calorie requirements for a given daily work load in two ways. First, body temperature must be maintained, requiring the combustion of fuel. Secondly, in the cold more clothes are worn than in the heat. Extra weight requires extra energy for movement; 'hobbling effects' of heavy clothing also imply increased energy to accomplish a given

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movement. Basal metabolic rate does not affect the argument, for effects of cold on it are neither quantitatively striking nor universally agreed upon by various observers.

Johnson & Kark (1947) summarized data on North American infantry in the tropics, temperate environments, and the Arctic. Among groups who were as fit and healthy as the exigencies of war permitted, when enough fresh and frozen food was available to allow virtually an unlimited balanced diet, there was a close inverse correlation between voluntary food consumption and mean environmental temperature, implying an increased caloric requirement in the colder environments. These conclusions have been disputed by Rodahl (1954) and LeBlanc (1956), among others, whose view is that calorie requirements are not much different in the Arctic and in temperate climates. There are two main weaknesses in their argument. First, they did not have data for the same, or similar subjects, under conditions of work and regimen similar for both Arctic and temperate environments. Secondly, the subjects on whom they reported were living on packaged, not fresh and frozen foods, were steadily losing weight and therefore were not in caloric balance. According to the standard teachings of nutrition and environmental physiology, cold must increase calorie requirements, and our opinion is that good evidence exists to support this view.

Specific dynamic action and temperature

Much investigation is still needed on the place of specific dynamic action in human nutrition. It is not yet known for certain even if it can be used for muscular work, but let us assume that it cannot, and speculate on that basis (Fig. 3). For regimens

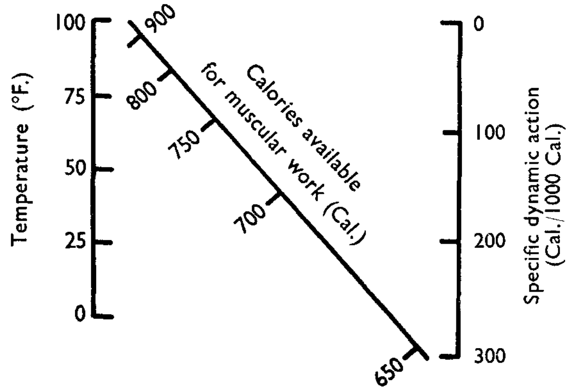

Fig. 3. Interrelations among thermal environment (left), specific dynamic action (right, Cal./1000 Cal. total food intake) and calories available for muscular work.

very low in specific dynamic action, above the zone of thermal neutrality virtually all the calories are available for muscular work. As the temperature diminishes, more and more calories are required to maintain body temperature, and less are available for muscular work. In regimens whose specific dynamic action is high, at and above the zone of thermal neutrality, a substantial fraction of calories is not available for physical work; however, this fraction changes but little as the temperature diminishes. It follows that, from the standpoint of proportion of calories available for physical work, carbohydrate has the advantage at high temperatures, whereas in extreme cold, differences between carbohydrate, fat and protein become inappreciable. These speculations are in accord with the report of Mitchell, Glickman, Lambert, Keeton & Fahnestock (1946) on the relative merits of the three nutrients taken isocalorically in maintaining body temperature in extreme cold.

Another feature of specific dynamic action which has not yet been clarified experimentally is what happens to it in various kinds of undernutrition. With reference to protein, Munro (1951) has presented convincingly the generalization that nitrogen balance is related to nitrogen intake, to total calorie balance, and to a specific advantage of carbohydrate over isocaloric amounts of fat. Under normal circumstances nitrogen balance is improved independently by increased calorie or protein intake. However, in the extremes, the beneficial effect of one can be minimized or prevented by insufficient intake of the other. Our own data are in good agreement with Munro's generalization. Because the calorie balance is related to environment, it follows that the nitrogen balance should also be secondarily affected by environment. A final speculation is that the specific dynamic action of a given amount of protein should also be related to the nitrogen balance, calorie balance, and proportion of fat to carbohydrate in the total calorie intake, because all these factors are related to the proportion of protein nitrogen retained or excreted.

Nutritional ketosis and temperature

Of the eleven different dietary regimens which we studied, five were ketogenic in the sense that they provoked ketonuria with moderate ketonaemia. They were starvation, two regimens high in fat but low in protein, and two regimens high in fat and in protein. All the others were non-ketogenic in the usual sense, being moderately high or very high in carbohydrate. The data on ketone body metabolism concern specimens of urine or blood collected from subjects under standard conditions of rest and recumbency while postabsorptive, and our results will appear in full elsewhere (Sargent, Johnson, Robbins & Sawyer, 1958). They are only summarized here.

Let the independent variables be daily caloric intake and percentage of calories as carbohydrate (Fig. 4), with relative ketonuria as the dependent variable. This last figure is calculated as the ratio between the rate of urinary excretion of total ketone bodies on any given regimen in one environment and that on pure carbohydrate at 2000 Cal./day in the same environment. As the percentage of carbohydrate decreases, the tendency to ketonuria increases. However, absolute calorie intake is of the utmost importance. The higher the caloric intake, the less is the ketonuria for any given nutrient combination. Clearly, the ketogenic effect of a diet must take into account more than just the ketogenic–antiketogenic ratio of Shaffer (1921), but also total caloric intake. For example, the same nutrient mixture, containing 70% of calories as fat, can provoke intense ketonuria at 1000 Cal./day, but much less at 2000 Cal./day.

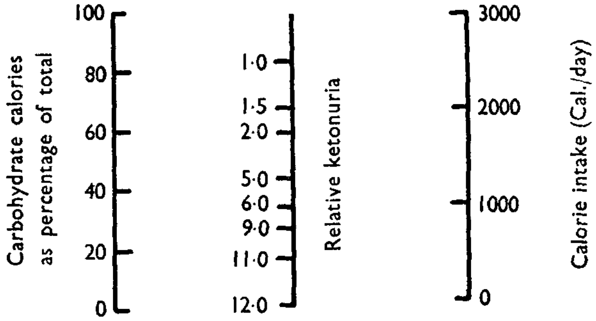

Fig. 4. Interrelations among carbohydrate calories (left, percentage of total calories as carbohydrate), daily calorie intake (right), and relative ketonuria at rest (middle, compared with ketonuria for 2000 Cal. pure carbohydrate at the same environmental temperature).

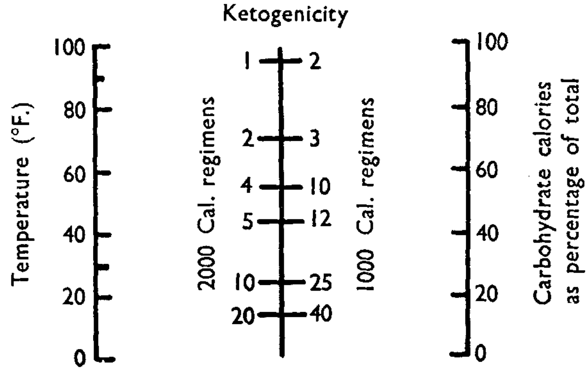

Fig. 5. Interrelations among thermal environment (left), percentage of total intake as carbohydrate (right), and relative ketogenicity at intakes of 1000 and 2000 Cal./day (middle, ratio of ketonuria on any regimen at any environmental temperature and ketonuria for 2000 Cal. pure carbohydrate at 100°F.).

A close correlation exists between the ketogenicity of a regimen, all other factors being constant, and environmental temperature (Fig. 5). Let percentage of carbohydrate calories and environmental temperature be the independent variables, and relative ketogenicity be the dependent variable. This last figure is the ratio between rate of urinary excretion of total ketone bodies per minute for any given regimen at any temperature, and that rate for 2000 Cal./day of pure carbohydrate in the heat, at about 100°F. Starvation and 3000 Cal. regimens are omitted for the sake of clarity in displaying changes in the dependent variable. The relation between absolute calorie intake and relative ketonuria already shown in Fig 4 appears again on the two sides of the middle line in Fig. 5. The effect of increased invironmental temperature is to diminish the ketogenic effect of any given nutrient mixture, all other factors being equal. Nutritional ketosis, then, is markedly affected by environmental temperature in which the subject lives. Unfortunately we have no information on diabetic ketosis or on ketosis which appears in other pathologic conditions.

In short, we feel that the older concept of a ketogenic–ketolytic ratio between non-carbohydrate and carbohydrate precursors as the controlling factor in nutritional ketosis is quite inadequate. Other factors, especially total calorie intake and environmental temperature, must be specified in accounting for the actual ketogenicity of any given regimen. On the physiological causes of these effects we can only speculate; at present, one must invoke the fat-mobilizing factor which the pituitary discharges in response to starvation and, we would now speculate, to cold. Experimental elucidation of the physiology of ketosis in normal men will not be easy, because of its nutritional and endocrinological complexity.

Conclusion

We have touched on a few of the interrelations between thermal environment and the metabolism of water, total calories, nitrogen, and ketone bodies. To these could be added carbohydrate, minerals and vitamins if space permitted. The general thesis we would defend is that in the nutrition of the healthy human being there are many independent variables, which often are interrelated quantitatively to produce a given metabolic end-result. One of these variables, often an exceedingly important one, is the thermal environment. It must be recognized as a possibly relevant variable, we feel, in all studies on human nutrition.

Our own work was conducted under contract AF 18(600)—80 between the U.S. Air Force and the University of Illinois. Many colleagues, too numerous to acknowledge by name, participated in the 5 years' study.

During 1957–8, both R. E. Johnson and F. Sargent, II, were on sabbatical leave from the University of Illinois, the former as a U.S. National Science Foundation Senior Postdoctoral Fellow at Edinburgh University, the latter as a John Simon Guggenheim Memorial Fellow at Oxford University.

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Physiological reactions of cattle to climatic stress

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All the available evidence indicates that cattle are highly resistant to cold, and that temperatures as low as $-18°$ have very little effect on their physiological reactions, although in cold conditions food consumption and heat production increase. High environmental temperatures or heat stress, however occasioned, have marked effects on the grazing behaviour, food and water consumption, milk production, milk and blood composition, cardio-respiratory behaviour, heat production and body temperature of cattle. This brief review is, therefore, largely concerned with the effects of heat stress on cattle.

The basis of work on the environmental physiology of cattle, and its ultimate purpose, is the improvement of cattle productivity in hot countries and the definition of environmental conditions for optimum productivity in cattle shelters in this country. Many studies (Brody, 1948; Findlay, 1950, 1954; Wright, 1954) have shown that there are profound differences in the ability to withstand thermal stress, i.e. in the heat tolerance, of tropical and European breeds of cattle, of different breeds of European cattle and of individuals of any one pure breed. These differences may be based on the anatomy, the nutrition, the heat production or the heat-loss mechanisms of the cattle concerned or on a combination of any or all of these properties.

The most carefully controlled work on the subject has been performed in climatic rooms in which the air temperature and humidity can be varied throughout wide ranges with very fine limits of control. Such work has been largely concerned with elucidating the gross reactions to severe thermal stress of the intact animal and the nature of temperature regulation in cattle. Very little work has been done on the nutritional aspects of bovine physiology with reference to climatic stress but certain important connexions between nutrition and climatic stress can be discerned in the published literature.

The most immediate reaction of cattle to heat stress is to limit their food intake, and this limitation is shown in their grazing behaviour under hot conditions. European breeds virtually cease grazing and seek the shade at air temperatures around 28° or when their body temperatures reach about 39·1°. It was shown, for example, by Seath & Millar (1946) that Jersey and Holstein cows spent only 11% of their time grazing on hot sunny days when the shade temperature was 30°, whereas at night when the shade temperature was 27° they spent 37% of their time grazing. This observation illustrates the added heat burden of solar radiation and emphasizes the need for providing good pasture at night for animals that have to withstand a