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Adaptation to low energy intakes: the responses and limits to low intakes in infants, children and adults

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Reduction in energy intake below the acceptable level of requirement for an individual results in a series of physiological and behavioural responses, which are considered as an adaptation to the low energy intake. This ability of the human body to adapt to a lowering of the energy intake is without doubt beneficial to the survival of the individual. However, what is more controversial is the view held by some that the body can metabolically adapt in a beneficial manner to a lowered intake and consequently that the requirements for energy are variable given the same body size and composition and physical activity levels. Much of this confusion is the result of considerable evidence from studies conducted in well-nourished adults who, for experimental or other reasons, have lowered their intakes and consequently demonstrated an apparently enhanced metabolic efficiency resulting from changes in metabolic rates which are disproportionate to the changes in body weight. Similar increases in metabolic efficiency are not readily seen in individuals who on long-term marginal intakes, probably from childhood, have developed into short-statured, low-body-weight adults with a different body composition. It would thus appear that the generally used indicator of metabolic efficiency in humans, that is a reduced oxygen consumption per unit fat free mass, is fraught with problems since it does not account for variations in contributions from sub-compartments of the fat free mass which include those with high metabolism at rest such as brain and viscera and those with low metabolism at rest such as muscle mass. Metabolic rate per unit fat free mass thus, does not reflect true variations in metabolic efficiency and is due largely to variations in body composition. This finding combined with the evidence that behavioural adaptation in habitual physical activity patterns which occurs on energy restriction is not necessarily beneficial to the individual raises doubts about the role of adaptation to low intakes in determining one's requirement for energy. The evidence is overwhelming that both in children and adults, changes in body size and composition as well as in levels of habitual physical activity may be the most important consequences of a lowered energy intake and cannot be assumed to be a part of a beneficial adaptation that influences energy requirements.

Introduction

The human body responds to a lowered food intake by a whole series of physiological and behavioural responses, which are often interpreted as an adaptation to the stress of reduced energy intake. No attempt will be made in this review to define adaptation or to distinguish it from related terms, such as accommodation. It is generally accepted that the so-called adapted state in response to a lowered energy intake comprises gains and losses, advantages and disadvantages, to the individual. This review will attempt to summarise our current thinking about the physiological responses to a reduction in energy intake both in adults and in infants and children. Responses seen in well-nourished individuals, who may be subjected to a reduction in energy intake imposed either voluntarily or due to circumstances such as famine or war, will be compared with those seen in individuals who subsist on marginal intakes of food mostly in developing countries. The objective is to illustrate that the general notion that responses in the latter are akin to those seen in the former may have contributed much to the controversies in this area of energy metabolism over the last two decades. Responses observed in body size and composition and in all key components of energy expenditure will also be reviewed, and an attempt will be made to outline the costs to the individual and society when energy intake is sustained at marginal levels, namely below the lower limits of acceptable intakes.

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Responses to low energy intakes in adults

Body size and composition

Body size and body composition changes during experimental semi-starvation. Decrease in body weight is a constant feature and the most obvious manifestation of inadequate energy intake in humans. However, the relationship between the degree and duration of inadequate energy intake and body weight changes is not a simple one since important body compositional changes occur during the process. The loss of body weight during energy restriction involves loss of variable proportions of fat, tissue protein and minerals along with changes in the extra-cellular fluid compartment with the body tending to become relatively over-hydrated (Grande, 1964). The changes that occur as a result of semi-starvation in formerly well-fed adults are

best documented in the Minnesota study (Keys *et al*, 1950), in which the average loss of body weight among a group of 32 male subjects amounted to 15.9 kg, or 23.5% of their initial body weight, after 24 weeks of semi-starvation.

Body fluid compartments. In absolute terms, the blood volume decreased by about 7.7% over 23 weeks of semi-starvation; the plasma volume increased 8.9%, while the cell volume decreased, resulting in a considerable degree of anaemia. Expressed per kg body weight, however, both blood and plasma volumes increased over the same period. Estimates of extra-cellular fluid (ECF), using the thiocyanate method, averaged 34% of body weight during weeks 22–24 of semi-starvation, as compared to 23.6% in normal, young controls. In the Minnesota study, it was assumed that the thiocyanate space minus the plasma volume was a measure of the extra-vascular fluid volume including the interstitial fluids and hence a general index of tissue hydration. Since both the ECF volume and the plasma volume expressed per kg body weight increased, it was concluded that the hydration of both the intra- and extra-vascular compartment increased during semi-starvation.

Bone density. Densitometric bone measurements during the Minnesota study lead to the conclusion that a loss of about 24% of body weight was not accompanied by generalised demineralisation of the bones, since bone mineral, which constituted 4% of the initial body weight, remained unaltered throughout the period of semi-starvation.

Adipose tissue, active tissue mass and organ size. The amount of adipose tissue estimated by specific gravity measurements in the Minnesota study showed that fat, expressed as a percent of body weight, decreased from 13.9 to 2.8% by week 24 of semi-starvation, that is an average adipose tissue loss of 6.9 kg (from 9.6–2.7 kg, a reduction of about 70%). The 'active tissue mass' (ATM) which was defined as the difference between the body weight and the sum of fat mass, thiocyanate space and bone mineral mass was reduced by 26.9% over the same period. The changes in the proportion of ATM to the total body weight were not significant as compared to the changes in the percent body fat. Measurements of cardiac size and volume using roentgengrams showed a 12% reduction in the transverse cardiac diameter and an 18% reduction in cardiac volume after 24 weeks of semi-starvation.

Body composition changes in human adults during food restriction associated with natural disasters, famine and war. Severe degrees of food restriction that occurred during disasters such as famines and wars, as well as that suffered by prisoners of war and inmates of concentration camps, have provided most of the information on body weight and body composition changes in humans and have been extensively documented and reviewed by Keys *et al* (1950). Considerable information has been obtained from autopsies carried out on cadavers of people who did not survive these disasters (Winick, 1979).

Body fluid compartments. A universal finding associated with imposed food restriction during famine and war is a relative increase in the water content of the body. Eventually, this increase in body hydration is clinically recognisable as puffiness of the face and ankles and may ultimately progress to generalised oedema. However, this oedema which is referred to as 'famine oedema', 'hunger oedema' or 'war oedema' is not a universal phenomenon seen in all individuals who have limited access to food. Estimates of blood and plasma volume made on inmates of concentration camps who were liberated at the end of the World War II (Mollison, 1946) indicated a reduction in blood volume which was however proportionally smaller than the estimated weight loss. The relative blood and plasma volume per kg body weight appeared to be elevated and was associated with anaemia. Beattie *et al* (1948) provided data on plasma and ECF volumes in two groups of severely undernourished Dutch and German adults. There was little change in the absolute plasma volume although the relative plasma volume per unit of body mass increased in proportion to the body weight loss. The same was true of ECF volume measured as thiocyanate space; the absolute thiocyanate space was only slightly expanded but represented 34.2% of body weight as compared to a mean of 23.5% reported in normal men (Henschel *et al*, 1947). Others likewise concluded that there was little change in the total blood volume of ex-prisoners of war in a state of severe undernutrition despite the marked body weight loss (Walters *et al*, 1947).

Body weight and body fat content. The reduction in body weight varies depending on the duration and severity of imposed food restriction. The maximum weight loss recorded during a 5-month siege of troops during World War I was 15% (Hehir, 1922). It was between 22 and 26% among Russians and Ukrainians during the Russian famine of 1920–22 (Ivanovsky, 1923), 28.4% during a famine in India (Martin, 1928) and between 9.3 and 13.6% among Parisian civilians during World War II (Tremolières, 1948). There are several other reports documenting various degrees of body weight loss during food restriction, associated with such situations. Although estimates of body fat content are not available, autopsy studies of 200 undernourished patients showed a total loss of subcutaneous adipose tissue along with depletion in other fat depots (Schittenhelm & Schlecht, 1918). Several other authors have also described a total loss of subcutaneous adipose tissue with depletion of pericardial and perirenal depots as well as of omental fat (Park, 1918; Simonart, 1948; Winick, 1979).

Muscle tissue and organ mass. Extreme muscle wasting and atrophy is a prominent feature of severe undernutrition and starvation in humans. Autopsies carried out on 359 victims of the Warsaw Ghetto showed severe atrophy of muscles in over 61% of subjects while 36.3% showed a moderate degree of muscle atrophy (Winick, 1979). Severe food restriction results in loss of organ weight and, with the exception of the brain, all organs such as the heart, liver, kidney and spleen were considerably reduced in weight as compared to those of normal individuals (Jackson, 1925). Summaries of autopsy data on famine victims (Porter, 1889) and inmates of concentration and prison camps (Uehlinger, 1948) also showed similar effects with minimal change in the weight of the brain.

Body composition changes in chronic undernutrition in adults. There is relatively limited information on body composition changes in chronically undernourished adults. Although there have been earlier reports on body composition changes in undernourished adults (Gopalan *et al*, 1953; Holmes *et al*, 1956), the best documented data come from adults aged 18–56 y in Colombia (Barac-Nieto *et al*, 1978) and more recently from India (Ferro-Luzzi *et al*, 1997).

Total body water and body fluid compartments. Data on total body water (TBW) and body fluid compartments in adults with varying degrees of undernutrition were compiled by Barac-Nieto *et al* (1978). The mildly undernourished adults had mean body weights of 52 kg and BMIs of 21.4 and were considered to be comparable to normal adults with normal values for body composition. In the severely undernourished, TBW was reduced, although expressed as a percent of the body weight it was significantly higher. ECF volumes were not altered in absolute terms in moderately and severely undernourished adults; however, when expressed as a percent of body weight they significantly increased as undernutrition progressed. Gopalan *et al* (1953) also reported an excess accumulation of fluid in the ECF compartment in adults with severe undernutrition and nutritional oedema. Both TBW and ECF volumes were higher in absolute terms and relative to the body weight, and they remained considerably higher even after the oedema was clinically cleared. Holmes *et al* (1956) also reported high values for TBW and for thiocyanate space in eight malnourished African patients, which subsequently approached normality following nutritional rehabilitation. It thus appears, that there is a marked increase in the proportion of ECF within the TBW pool in chronic undernutrition, even in the absence of oedema (Widdowson, 1985). Plasma volume was not altered in absolute terms but when expressed as a proportion of TBW or body weight it increased progressively as undernutrition advanced (Barac-Nieto *et al*, 1978). On the contrary, intra-cellular water (ICW) was reduced in the undernourished, both in absolute terms and when expressed as a percent of TBW or body weight. The severely undernourished group had a disproportionately larger deficit of ICW. These significant reductions in ICW probably represent deficits in cell mass in undernutrition, the deficits in cell mass being further underestimated if one takes into account the increased hydration of cells which is known to occur in undernutrition (Holmes *et al*, 1956).

Body size, body fat and fat free mass. Chronically undernourished adults have short stature, probably as a result of growth deficits associated with childhood malnutrition. They also have low BMIs since their shorter statures are associated with low body weights. The body fat content (indirectly estimated) is reduced, and reported values vary from about 10–12% (Soares & Shetty, 1991), 9.8–11.7% (Ferro-Luzzi *et al*, 1997) to as low as 6% (Shetty, 1984). Estimates of fat free mass (FFM) also indicate marked reduction in the proportion of active cell mass in these adults with chronic undernutrition. Barac-Nieto *et al* (1978) calculated the body cell mass and cell solids in undernourished adults and reported that both of these are significantly reduced in moderate and severe undernutrition reflecting a deficit in body cell mass. They also concluded that undernutrition was characterised by a loss in body fat, a loss in body cell mass and possibly a small deficit in extra-cellular solids.

Comparisons of the contribution of muscle cell mass and non-muscle or visceral cell mass to the FFM have also been made in chronically undernourished adults. The Colombian data (Barac-Nieto *et al*, 1978) showed that in moderate undernutrition the reduction in muscle cell mass was in proportion to the decrease in total body cell mass. In more severely undernourished individuals, the reduction in muscle mass (41%) was greater than that of body cell mass (29%), while visceral mass was only minimally affected ($< 1.5\%$) (Table 1). More recent estimates of body composition in chronically undernourished adults also support the notion that there is a greater reduction of muscle mass, with visceral mass apparently being spared (Soares *et al*, 1991) until severe energy deficit occurs.

Basal metabolic rates

In this section the terms basal metabolic rate (BMR), resting metabolic rate (RMR) and resting energy expenditure (REE) will be used inter-changeably since several reports in the literature use one or the other term to mean more or less the same.

Responses of basal metabolic rate to experimental or therapeutic energy restriction. Reduction in BMR or RMR is one of the more constant findings in experimentally or therapeutically induced energy restriction, as Apfelbaum (1978) showed in a summary of studies in human subjects since the beginning of the 20th century.

Experimental semi-starvation studies. Experimental semi-starvation studies on well-nourished adult human volunteers carried out by Benedict *et al* (1919), Keys *et al* (1950) and subsequently by Grande *et al* (1958) have invariably shown a reduction in BMR. This consistent finding of a reduced BMR during experimental semi-

Table 1 Changes in body composition of adults with progressive, chronic undernutrition[a]

	Grades of adult undernutrition		
	Normal/mild	*Moderate*	*Severe*
Body weight (kg)	52.0	48.2	42.5
Fat free mass[b] (kg)	42.8	38.3	36.1
Body cell mass[c]			
(kg)	24.1	20.3	17.1
(% body wt)	46.1	41.9	40.3
Muscle mass[d]			
(kg)	17.2	14.6	10.1
(% body wt)	33.1	30.3	23.8
Visceral mass[e]			
(kg)	6.9	5.7	7.0
(% body wt)	13.0	13.4	14.5

[a]Data compiled from Barac-Neito *et al*, 1978.
[b]Fat free mass estimated from total body water measurements.
[c]Body cell mass derived from estimates of intracellular water and their relationship to body cell mass.
[d]Muscle mass estimated from 24 h creatinine excretion assuming lg of creatinine corresponds to 20 kg muscle inclusive of 16% extra-cellular fluid, that is, 1 kg of muscle free of ECF = 60 mg of 24 h of creatinine excretion.
[e]Visceral mass calculated as body cell mass minus muscle mass.

starvation was explained both on the basis of a decrease *per se* in the activity of the metabolically active tissues of the body and as a consequence of the loss of active tissue mass due to loss of body weight. The former was considered as indicating an increase in the 'metabolic efficiency' of the residual active tissue mass and hence evidence of 'metabolic adaptation'. Taylor & Keys (1950) considered the decrease in the mass of metabolically active tissue as the main factor responsible for the reduced BMR and concluded that about 65% of the reduction in BMR can be attributed to the shrinkage of the metabolising mass of body cells and only about 35% to 'metabolic adaptation'. Based on a second series of experimental semi-starvation studies in humans, Grande *et al* (1958) found the reverse distribution with actual decrease in metabolic activity of the cells contributing proportionally more (65–73%) to the reduction in BMR. The differences in the two experimental semi-starvation studies were explained by the differences in the duration of energy restriction in the two studies. In comparison to the long-term semi-starvation study of 24 weeks, the experiments of Grande *et al* (1958) did not exceed energy restriction beyond three weeks. However, the decrease in metabolic rate expressed per unit weight of active tissue in the short-term study was of the same order of magnitude as that observed after 24 weeks of energy restriction. Recalculating the data from the two separate semi-starvation studies, James & Shetty (1982) were able to show that the early fall in BMR seen during energy restriction is mainly accounted for by enhanced metabolic efficiency (Table 2). This reduction in BMR per unit active tissue seen in the first two weeks of energy restriction remained essentially unchanged over the subsequent 22 weeks of semi-starvation. A greater contribution to the fall in BMR during prolonged energy restriction was attributable to the slow decrease in the total mass of active tissues as a result of body weight loss.

Therapeutic energy restriction. Studies on therapeutically restricted diets in obese patients lead to similar conclusions. A comprehensive review by Sims (1986) examining the responses of obese subjects to a reduction in energy intake showed a significant reduction in metabolic rate in most studies. Over the first few weeks, restricted diets in obese patients result in decreases in RMR per kg FFM or lean body mass (LBM) that are comparable to those reported by Grande (1964) in two separate experimental short term semi-starvation studies. However, the degree of reduction seen varies largely with the severity of the dietary restriction and the composition of the diet.

Mechanisms of physiological adaptation. It seems reasonable to assume that the reduction in BMR during energy restriction (experimental or therapeutic) occurs in two different phases. In the initial phase (first 2–3 weeks) there is a marked decrease in the BMR which goes beyond what is attributable to changes in body weight or body composition. This decrease in BMR per unit active tissue is an 'active process' and is thus a measure of the increase in 'metabolic efficiency' of the active tissue mass (ATM) of well-nourished individuals who are energy restricted and hence an indication of metabolic adaptation. With continued energy restriction, the lowered level of cellular metabolic rate remains nearly constant and any further decrease in BMR is accounted for by the loss of active tissue. Therefore, the longer the duration of energy restriction, the more important becomes the contribution of decreased body tissues to the reduction in BMR. This reduction in lean body tissue with prolonged energy restriction is considered to be a 'passive process' and a consequence of body tissues being used as substrates and metabolic fuel.

The biochemical processes and physiological mechanisms involved in the 'active' component, aimed at reducing cellular metabolic rate and resulting in metabolic adaptation, can only be studied during controlled experimental or therapeutic energy restriction. A recent review by Rolfe & Brown (1997) estimates that ~90% of BMR is contributed to by mitochondrial oxygen consumption of which only ~20% is uncoupled by mitochondrial proton leak. The rest of the oxygen consumption (~80%) is coupled to ATP synthesis of which ~25–30% is used by protein synthesis, 19–28% by Na^+-K^+ ATPase, 4–8% by Ca^2 ATPase, 2–8% by actinomysin ATPase, 7–10% by gluconeogenesis, and 3% by ureagenesis, with mRNA synthesis and substrate cycling also making contributions. How much changes in these processes independently may contribute to the 'active' component of BMR during lowered energy intake is not known. Several physiological mechanisms may operate to decrease the metabolic activity of the ATM to enhance its metabolic efficiency.

Factors such as hormonal and substrate alterations may operate and interact to influence this metabolic adaptive

Table 2 Reduction in basal metabolic rate (BMR) and active tissue mass (ATM) during experimental semi-starvation[a]

Experimental semi-starvation studies						
	A (n = 12)		*B (n = 12)*		*C (n = 12)*	
Day of study[b]	*0*	*168*	*0*	*14*	*0*	*19/20*
Body weight (kg)	67.5	51.7	71.6	65.4	69.1	62.4
ATM (kg)	38.8	28.7	44.9	42.2	43.4	40.8
BMR (MJ/d)	6.59	4.20	7.29	5.73	6.62	5.49
Decrease in BMR						
MJ/d	2.39 (36.3%)		1.56 (21.4%)		1.13 (17.1%)	
KJ/kg ATM/d	23.4 (13.8%)		26.4 (16.3%)		18.0 (11.8%)	

[a]Data compiled from Keys *et al*, 1950 and Grande *et al* (1958).
[b]Study A is a long term semi-starvation study conducted by Keys *et al*, 1950; Studies B and C respectively are short term semi-starvation studies conducted by Grande *et al* (1958).

process and have been summarised recently (Shetty, 1990). Since the reduction in this component is manifest in the early phase of semi-starvation the related physiological mechanisms must be apparent during the first 2–3 weeks of energy restriction and are likely to be endocrine in nature. Several hormones are now known to be sensitive to changes in the levels of energy intake, diet composition and the status of energy balance of the individual. Changes in sympathetic nervous system (SNS) activity and catecholamines, alterations in thyroid hormone metabolism and changes in hormones such as insulin and glucagon play an important role in this metabolic response to energy restriction. These changes are not only aimed at lowering the metabolic activity of the active cell mass but are also essential for the orderly mobilisation of endogenous substrates and fuels during a period of restricted availability of exogenous calories. SNS activity is toned down as indicated by the decrease in energy flux, while the negative energy balance lowers insulin secretion and initiates changes in peripheral thyroid metabolism. The reduction in the activities of these key thermogenic hormones acts in a concerted manner to lower cellular metabolic rate (Figure 1). Changes in other hormones such as glucagon, growth hormone and glucocorticoids may influence these changes and at the same time, in association with the insulin deficiency, promote endogenous substrate mobilisation leading to an increase in circulating free fatty acids (FFA) and ketone bodies. The elevated FFA levels, alterations in substrate recycling and protein catabolism will also influence the resting energy expenditure. These hormonal and metabolic changes that accompany energy restriction aid the survival of the organism during energy restriction. Hence these physiological changes may be considered as metabolic adaptations which occur in a previously well-nourished individual and are aimed at increasing the 'metabolic efficiency' and fuel supply of the tissues at a time of energy deficit.

Responses of basal metabolic rate during food restriction associated with natural disasters, famine and war. Measurements of BMR of 70 adults (and children) in the Warsaw ghetto (Winick, 1979) showed that the reduction in BMR depended on the severity of the cachexia observed. BMRs in mild cachexia were within the errors of the methodology used, while the BMR was −30 to −40% of the standard in those with second and third degree cachexia with/without oedema; terminal patients with severe undernutrition had BMRs at −60%. The RQs of these individuals were generally high (0.95–0.98) with the exception of those who were terminal who had RQs of 0.72–0.74. The report indicates that these individuals were on a 1100-calorie diet with no fat and little protein (with no animal protein).

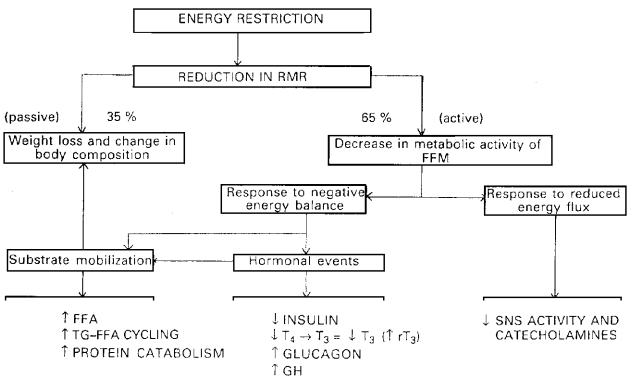

Figure 1 Possible mechanisms involved in the adaptive reduction in resting metabolic rate (RMR) during short-term energy restriction of well-nourished adults. FFA, free fatty acids; FFM, fat-free mass; TG, triacylglycerols; T4, thyroxine; T3, triiodothyronine; rT3, reverse T3; GH, growth hormone; SNS, sympathetic nervous system.

Basal metabolic rate in chronic undernutrition. It is generally assumed that metabolic adaptation occurs in much the same way in the chronically undernourished state and that the physiological and metabolic responses of the adults with chronic undernutrition are similar to the changes that occur during experimental or therapeutic semi-starvation in previously well-nourished adults. Consequently, a reduction in metabolic rate per unit of ATM has been considered to be a definitive index of the existence of metabolic economy or adaptation in the chronically undernourished state (Waterlow, 1986). A decrease in BMR in turn implies that the increase in metabolic efficiency contributes further economy to the other components of total energy expenditure, particularly a decrease in the energy cost of physical activity of the undernourished but adapted individual (Ferro-Luzzi, 1985).

Metabolic efficiency and BMR in chronically undernourished adults. BMR expressed either in absolute terms or expressed per unit body surface area has been found to be lower in the chronically undernourished although these same studies have failed to demonstrate any significant decrease in metabolic rate per kg of ATM (Venkatachalam *et al*, 1954). Ashworth (1968), while reporting a 12% reduction in BMR in Jamaican subjects on low calorie intakes, also confirmed her inability to show evidence of enhanced metabolic efficiency and metabolic adaptation in BMR. These observations in the chronically undernourished are in marked contrast to the invariable demonstration of a decrease in BMR per kg ATM seen during semi-starvation in well-nourished adults.

BMR measurements made in apparently healthy, but undernourished, labourers showed a reduction in the metabolic activity of the ATM which could perhaps be interpreted as evidence of an enhanced metabolic efficiency, although the major share of the fall in BMR was attributable to a decrease in the total mass of active tissues (Shetty, 1984). Recalculation of data from an earlier report by Ramanamurthy *et al* (1962) also showed that the BMR expressed per unit active tissue was considerably lower in undernourished men. However, measurements made more recently in larger samples of chronically undernourished adults with low BMIs do not confirm the existence of an enhanced metabolic efficiency as indicated by a reduced BMR per unit of ATM (Soares & Shetty, 1991). On the contrary, it is now observed that the BMR expressed per kg FFM is higher than in well-nourished individuals. This group of apparently healthy, chronically undernourished adults had short statures, low body weights, low FFMs and low BMIs. They had low energy intakes, belonged to poorer socio-economic groups and were urban or rural labourers. A comparable and equally large series of BMR measurements reported by Srikantia (1985), also showed the same trend, BMR per unit body weight increased as the weight-for-height, expressed as a

percentage of standard, diminished. BMR measurements made in rural South India by McNeill *et al* (1987) were also comparable to those obtained both by Srikantia (1985) and by Soares & Shetty (1991). More recent data from India, in both men and women who had low BMIs and were weight-stable also support this view (Ferro-Luzzi *et al*, 1997). Results of these recent studies with large sample sizes provide no evidence of metabolic adaptation in stable, but low body weight adults from poor socio-economic groups on lower planes of energy intake.

Three serious problems have arisen in attempts to demonstrate the existence of metabolic efficiency in the cellular metabolic rate as proof of metabolic adaptation in chronically undernourished adults in developing countries:

1. In order to compare efficiencies in basal metabolism with those of the well-nourished, BMRs have to be standardised to some estimate of the body composition and ideally to the active tissue mass. Studies where BMR measurements and body composition estimates have been made in the same chronically undernourished individuals are rare. The estimates of ATM or FFM have often been calculated indirectly using body composition predictive equations most often derived from well-nourished Europeans. It is doubtful whether predictions made from estimates of body composition of well-nourished individuals of a different ethnic group provide an accurate estimate of the ATM or FFM. The use of such indirect estimates based on body composition data from Europeans is hence questionable despite the much wider applicability of these predictive equations on a population basis (Norgan & Ferro-Luzzi, 1985).
2. Ravussin & Bogardus (1989) have put forward mathematical reasons why BMR could not be easily standardised between individuals of widely differing body weights and body composition. According to them, BMR should not be divided by the ATM or FFM since the relationship between BMR and ATM/FFM has a y and an x intercept significantly different from zero and these intercepts need be taken into account. Because of the mathematical bias, Ravussin & Bogardus (1989) argue that it is incorrect to express metabolic rate per unit ATM/FFM in order to standardise values for the purpose of comparison between groups of individuals of different body weights or ATMs/FFMs. Since the use of the expression BMR per kg ATM/FFM was aimed at correcting for differences in the body sizes of groups of individuals, it is necessary to eliminate the possible mathematical artefacts by resorting to analysis of covariance (ANCOVA) as Ravussin & Bogardus (1989) propose. Similar arguments that mathematical ratios lead to spurious conclusions regarding age and sex differences in RMR and that RMR data require appropriate standardisation by ANCOVA have been made more recently by Poehlman & Toth (1995). Subjecting BMR data collected by us in chronically undernourished adults (Soares & Shetty, 1991) to ANCOVA suggests that they have a lower BMR when adjusted for body weight or FFM, implying that there may indeed be some covert metabolic economy in the FFM. The fact however, that the estimate of FFM was indirect and derived from well-nourished Europeans throws some doubt on the conclusion of the study by Soares & Shetty (1991), and recent findings in similar groups of adults from the same region with densitometric estimates of body composition failed to demonstrate any differences between adults over a range of BMIs even when standardised for body weight and FFM using ANCOVA (Ferro-Luzzi *et al*, 1997).
3. Differences in BMR per kg ATM/FFM may also not reflect differences in metabolic efficiency since neither ATM nor FFM is a single, uniform metabolic component. Hence differences in metabolic efficiency that one may uncover in the cellular metabolic rate by comparison of the index BMR per unit ATM/FFM may indeed reflect changes in the composition of the ATM or FFM and their differential contribution to the total metabolic rate. The visceral component of the FFM (liver, heart, kidney) has been estimated to utilise nearly 45% of the total oxygen consumption at rest while skeletal muscle which comprises up to 50% of the body weight contributes only 18% to the RMR (Passmore & Draper, 1965). The combined weight of the brain and liver which accounts for 3–5% of the total body weight, utilises as much as 40% of resting oxygen consumption (Keys *et al*, 1973). Elia (1992) has estimated that 40% of the body weight of an adult man is muscle, but contributes only 22% to BMR. Therefore, if the FFM had a significantly greater proportion of the metabolically active visceral mass and a reduction in the mass of the relatively less active muscle, then BMR expressed per kg FFM (or ATM) would be apparently high, while it would appear to be lower if the contribution from muscle increased disproportionately. That differences in BMR per kg FFM are determined by differences in the composition of the FFM is further supported by the observation that an infant has a two times higher BMR per kg body weight than an adult but BMR per kg visceral organ weight (namely, sum of weight of liver, kidney, heart and brain) remains fairly constant throughout the period of growth and development into adulthood (Elia, 1992). Since the exact composition of the body, more particularly the two major components of the FFM may contribute to the variations observed in metabolic efficiencies when nutritional status is altered it may be prudent to discuss this issue in some detail at this stage.

Body composition and BMR. Lawrence *et al* (1988) observed differences in BMR between Scottish, Gambian and Thai women, which could largely be explained in terms of the differences in FFM since individuals in all the three groups with similar FFMs had similar BMRs. Thus differences between the groups in BMR per kg FFM were largely explained by the between-group differences in the mass of the FFM. Within any group, the BMR per kg FFM decreased as the body weight or FFM increased. Lawrence *et al* (1988) suggested that variations in BMR per unit FFM between the heavy and light individuals in any group could indicate that the composition of the FFM was not constant. Owen *et al* (1990) and Weinsier *et al* (1992) have respectively shown that BMR per kg body weight and BMR per kg FFM fall as body weight or FFM increases. Weinsier *et al* (1992) have indicated that the index BMR/FFM does not take into account the fact that the metabolic rate of the FFM is not constant over a wide range of FFM and that the relative proportions of its metabolic components, namely muscle mass *vs* organ mass, may change as the weight of

FFM changes. In a large series of autopsy studies in normal individuals it was recently shown that this is true and that the organ mass (OM) component of FFM is related to the size of the FFM; the OM:FFM ratio increases as FFM decreases in both males and females (Garby & Lammert, 1992).

In the Minnesota semi-starvation study, at the end of 24 weeks, muscle losses were estimated at 41% whereas the reduction in ATM was only 27% (Grande, 1964); a situation quite unlike the changes seen in acute starvation in humans. Studies examining changes in body composition of adults with naturally evolving chronic undernutrition revealed a gradation of changes related to the severity of the deficiency (Barac-Nieto *et al*, 1978). Body cell mass (that is, cell solids and ICW estimated from TBW and ECW) was reduced even with moderate deficiency and the muscle mass was more affected than other cells; muscle cell mass seemed to decrease linearly with the increasing severity of undernutrition, while the visceral organ and cell mass showed little change (Shetty, 1995). Body fat and body cell mass were reduced by 29% while muscle cell mass decreased by 41% in severe undernutrition. Body composition indirectly estimated by creatinine excretion in chronically undernourished adults also indicates a greater reduction in muscle mass with visceral mass apparently being spared. The non-muscle mass/muscle mass ratio was 1.1 in the undernourished as compared to 0.7 in the well-nourished (Soares *et al*, 1991).

Since the visceral component of the FFM (liver, heart, kidney) has been estimated to utilise nearly half the total oxygen consumption at rest while skeletal muscle which comprises up to 50% of the body weight contributes only between 18–22% of the RMR and if the FFM had a significantly greater proportion of the metabolically active visceral mass and a reduction in the muscle mass, then BMR expressed per kg FFM is likely to be apparently high. This may indeed be the case with mild to moderate undernutrition in adults since muscle mass is more likely to be reduced than non-muscle (visceral) mass. As undernutrition progresses, mobilisation of tissue from the visceral or organ mass may occur in the more severe forms of energy deficiency, resulting in the BMR per kg FFM (or ATM) being reduced (Figure 2). Along with these changes in body composition seen during long term energy inadequacy, there is a change in the extra-cellular fluid compartment which will also contribute to influence the BMR expressed per unit FFM (Barac-Nieto *et al*, 1978; Widdowson, 1985). Variations in the body composition of the chronically undernourished, more specifically the relative contributions of non-muscle/organ mass and muscle mass to FFM may account for much of the changes seen when BMR is expressed per unit FFM. If the range of body composition changes seen during the evolution of the chronically undernourished state in the adult influences the parameter 'BMR per unit FFM' undoubtedly then, the index BMR per unit FFM cannot truly reflect a change in the metabolic efficiency or metabolic economy of the residual active tissues of the body.

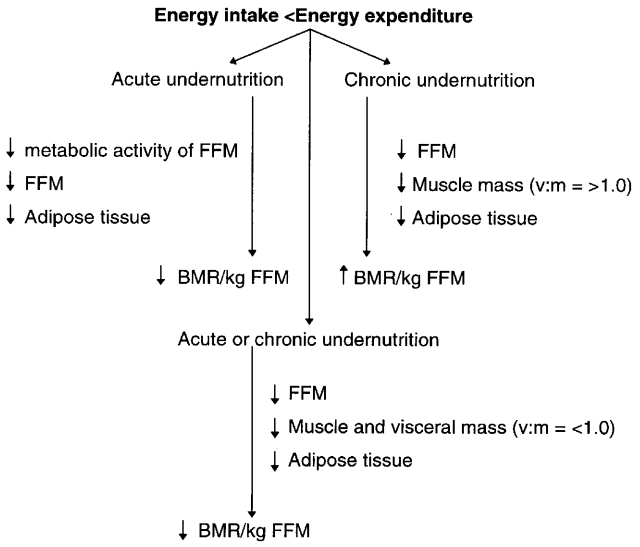

Figure 2 Body composition changes seen in stages of adult undernutrition that may influence the parameter BMR per kg FFM (an indicator of metabolic efficiency). FFM = fat-free mass, V:M = visceral:muscle ratio, BMR = basal metabolic rate.

Metabolic efficiency in substrate oxidation rates in chronic undernutrition. Respiratory Quotients (RQs) of chronically undernourished subjects shows that individuals of poor nutritional status have higher basal, 12 h post-absorptive RQs than well-nourished adults (Shetty, 1992). The higher RQs have generally been attributed to the high carbohydrate containing diets consumed by them and this seems a reasonable assumption. Their Food Quotients (FQs) also corroborate this with the antecedent habitual diets of these individuals being high in carbohydrate content. The high carbohydrate content of these diets can result in a 3% more efficient ATP production than the consumption of mixed diets. It seems apparent, however, that the macronutrient composition of the diet ingested as indicated by the mean FQ of the day is not truly reflected in the fasting RQ of the same day. When substrate oxidation rates are calculated during the post-absorptive, fasted state in the undernourished subjects using indirect calorimetry and urinary nitrogen excretion, it is evident that the undernourished subjects have significantly higher rates of carbohydrate oxidation and lower rates of fat oxidation in the fasted (and in the fed) state than the well-nourished adult (Piers *et al*, 1992). No differences were seen in the rates of protein oxidation; an observation that is in keeping with the evidence of similar rates of protein turnover in these subjects as compared to the well-nourished (Soares *et al*, 1991). It would appear that in the undernourished state the higher RQ is largely the result of selective use of carbohydrate as fuel even in the post-absorptive, fasted state. It is important to recognise that, unlike generally believed, fat is not necessarily the predominant substrate in the post-absorptive fasted state and is certainly not the preferred substrate in the chronically undernourished state. However, the selective utilisation of carbohydrate illustrates how closely carbohydrate oxidation is adjusted not only to its immediate availability as demonstrated in well-nourished individuals (Flatt, 1987) but also relates probably to the antecedent habitual intakes of carbohydrate in the diets of the undernourished. The selective use of carbohydrate as fuel has obvious metabolic advantages to the undernourished individual since carbohydrate (glycogen) oxidation results in more ATP generation than iso-energetic amounts of fat or protein (Elia & Livesey, 1992). Also the metabolisable energy equivalent, that is the energy equivalent of

ATP gained (in kJ per mole ATP), is almost identical to that of fat, that is, 75.3 for glycogen oxidation via glycolysis and the citric acid cycle as compared to 79.2 for fat oxidation via *beta* oxidation and the citric acid cycle (Elia & Livesy, 1992). It is hence not unlikely that the high fasting RQs of the undernourished reflect to some degree the metabolic efficiency of the active tissues of these subjects by resorting to specific metabolic pathways that favour more efficient utilisation of the available metabolic fuel. The RQ of an individual seems to reflect his body composition and more specifically the available fat stores. Flatt (1972) has suggested that the anti-lipolytic effect of insulin is less effective in the presence of an increased fat mass, and an increased level of insulin is thus associated with high free fatty acid levels in obesity. Since fat oxidation has been shown to be directly related to the levels of free fatty acids (Groop *et al*, 1991), it is apparent that low fasting levels of free fatty acids are likely to be associated both with the small fat mass seen in the undernourished and consequently with lower rates of fat oxidation. The low rates of fat oxidation will in turn contribute to the high fasting RQs. The high RQs of the undernourished may thus reflect both a high dietary intake of carbohydrate as well as a predominant dependence on carbohydrate as fuel and a reduced rate of fat oxidation in the presence of the low fat stores observed in these individuals.

Conclusions. It may hence be concluded that the BMRs of chronically and marginally undernourished adults are lower than those of well-nourished adults but not different when corrected for differences in body weight, ATM or FFM. BMR per kg ATM or FFM hitherto considered the definitive indicator of metabolic efficiency does not seem to be altered and there is thus no conclusive evidence of the existence of metabolic adaptation. This index does not truly reflect changes in the efficiency of energy utilisation of the active tissues and is probably an artefact attributable to the changes in body composition in the undernourished state. Either BMR per kg ATM/FFM is not an index of metabolic efficiency as is universally believed (Waterlow, 1986) or metabolic efficiency is neither a characteristic nor a constant feature of chronic adult undernutrition. The situation may be different when acute energy restriction is superimposed on a chronic state of undernutrition as happens during the seasonal cycle or when availability of food is reduced due to famine. In these situations with perturbation of the steady state that has been achieved under conditions of marginal intake, there may be further loss of body weight and a further reduction in BMR with the demonstration of a fall in BMR per unit FFM (Figure 2). It is however important to note that even this demonstration of an enhanced metabolic efficiency in an acute-on-chronic state of undernutrition may be the result of the accompanying body composition changes thus leading to the inevitable conclusion that reduced BMR per unit FFM is not an indispensable indicator of increased metabolic efficiency of the residual tissue mass of the body.

Adaptive thermogenesis

From a conceptual point of view there are two major components of thermogenesis designated as obligatory and facultative; and these are in turn made up of distinct sub-divisions that reflect diverse biochemical processes, fulfil different physiological roles and are regulated by several different combinations of neural and hormonal factors. *Obligatory thermogenesis* represents the minimal heat produced by the sum total of those processes that maintain the organism at thermoneutrality in the fasted, basal state. Measures of BMR provide a rough estimate of essential thermogenesis, an important sub-component of obligatory thermogenesis. This represents the energy utilised by all the biochemical reactions required to maintain the organism in its basal state, that is the synthesis and catabolism of essential cellular constituents, the generation of ionic gradients across cell membranes and the maintenance of organ functions at the basal level. *Facultative thermogenesis* represents heat production in excess of that required to maintain the basal state and is hence highly variable. Important components of facultative thermogenesis include the heat produced during muscular exercise, by shivering or from 'non-shivering thermogenesis (NST)'. Increase in heat production occurs also after a meal and is termed 'diet-induced thermogenesis (DIT)'. DIT has both a facultative as well as an obligatory component. The energy costs of digestion, absorption, transport and storage of the ingested meal constitute the obligatory heat production associated with the metabolic handling of the ingested nutrients. Any additional heat production that occurs following the meal is the facultative component of DIT. Both NST and the facultative component of DIT are mediated by catecholamines and regulated by the activity of the SNS, hence both these processes are mechanistically considered to be similar.

The thermogenic component of human energy expenditure generally refers to the effects of cold exposure, following the ingestion of a meal or induced by thermogenic agents. It is thus specifically composed of the chemically mediated thermogenesis resulting from NST and the facultative part of DIT. In addition, this component also includes the thermogenic responses to drugs, caffeine and stress since they are all mediated through the activation of the SNS, release of catecholamines and stimulation of adrenergic receptors. Since NST is mediated via the SNS, estimations of this adaptive or regulatory component of thermogenesis is carried out by measurement of the excess oxygen consumption over the basal state (BMR), when adrenergic receptors are stimulated by the administration of noradrenaline (NA) or adrenaline. The DIT response to a test meal depends upon its energy density and nutrient composition. There are also several ways of measuring and expressing the DIT response which may alter the interpretation of the results and these need to be standardised to enable comparisons of studies reported in the literature. Hence, while measuring or expressing DIT responses for the purpose of inter-group comparisons, one is confronted with the dilemma of either administering a standard meal or a meal where energy and/or protein content is based on body weight, FFM or BMR. This issue is yet to be resolved, and is further complicated by the fact that the DIT response to the same standard test meal in the same individual may show a large variability from occasion to occasion.

Adaptive thermogenesis in experimental or other forms of imposed energy restriction.

Nonshivering thermogenesis in experimental or therapeutic energy restriction. There are not many studies of NST

responses following energy restriction. In one study NST responses to intravenous NA were found to be unaltered in obese women who lost weight following therapeutic energy restriction (Jung *et al*, 1979).

Diet-induced thermogenesis in experimental, therapeutic or imposed energy restriction. Although DIT was not measured in the subjects in the Minnesota semi-starvation studies, reference has been made to its significance in this situation and the difficulty posed in arriving at any conclusion due to the literature suggesting that 'it is less than, equal to, or greater than in the normal state of nutrition'. The opinion expressed by the authors (Keys *et al*, 1950) was that 'the somewhat better studies indicate that undernutrition does not alter' DIT and that if anything it may be considerably increased in individuals who were 21–40% underweight (Mason *et al*, 1927). There is an extensive literature on DIT responses in adults who lost weight following therapeutic energy restriction and the situation is not any different here either. The answers to the question whether DIT is altered following a period of energy restriction in well-nourished/obese adults are also equivocal since the data are conflicting depending on the study, the method used and the manner in which the results are interpreted. Nevertheless it is now increasingly evident that DIT responses are not altered following weight loss in obese or well-nourished adults (Miles *et al*, 1993). Jewish physicians in the Warsaw ghetto also studied the effects of isocaloric amounts of protein and carbohydrates (Winick, 1979). Glucose loads (200 g) in 20 severely malnourished adults produced a large thermic response with BMRs rising 20–50% within 2 h of ingestion. Protein meals (4–6 eggs) on the other hand demonstrated a lack of thermic response. It is not unlikely that slow gastric emptying in these malnourished adults contributed to no perceptible response over the 2 h measurement period.

Adaptive thermogenesis in chronic undernutrition.

Nonshivering thermogenesis in chronic undernutrition. Studies on NST in chronically undernourished adults were carried out by using graded doses of NA infused intravenously while the increments in oxygen consumption were monitored (Kurpad *et al*, 1989a; 1989b). The undernourished had a significantly lower thermogenic response to the lowest dose, but the effect disappeared with increasing doses and there were no overall differences between the undernourished and well-nourished controls when the entire response was compared. It appeared that the undernourished responded late, there was a steep response factor that allowed for comparable peak oxygen consumption levels and the capacity for NST was retained in the chronically undernourished (Kurpad *et al*, 1992). The preferential substrate for oxidation in the undernourished was carbohydrate both in the basal state and when infused with NA. The apparent suppression in the undernourished was related to the latency of the response while the ability to attain comparable peak responses in heat production was not compromised. Responses to direct cold exposure in undernourished subjects also showed that their ability to increase heat production following a brief cold exposure is not compromised and that their response thresholds are also smaller than in the well-nourished (Vaz *et al*, 1996). These findings are similar to the reports of reduced cold-induced thermogenesis in elderly, undernourished hospitalised patients (Fellow *et al*, 1985).

Undernourished adults have an apparent suppression in thermogenic response to NA, which can be abolished by repeated stimulation. This potentiation may be the result of alterations in several physiological variables such as agonist clearance rates, alterations in hormone-receptor interactions, and changes in blood flow or substrate mobilisation. Although this SNS-mediated component of energy expenditure contributes only a small fraction of the total energy expenditure, its modulation may contribute to energy homeostasis in the energy deficient state. The phenomenon of potentiation may further imply that repeated stress such as infections or exposure to cold in the undernourished state may result in annulment of this adaptive reduction and facilitate maximal heat production when required.

Diet-induced thermogenesis in chronic undernutrition. Differences in facultative DIT have been evoked to explain, to some extent, the adaptive responses to alterations in energy balance in individuals. However, possible alterations in DIT in the undernourished have not been systematically investigated until recently. The earliest report in the literature is by Mason (1927) who administered a fatty meal to an undernourished woman and found an extraordinary rise in heat production, which reached a peak at the end of the second hour. The thermic response was greater than that seen in the same individual when well-nourished. Similar results were obtained when the DIT response of a fatty meal was compared in normal subjects and in patients who were 21–40% underweight (Mason *et al*, 1927). A preliminary report in undernourished adults showed a differential response to a meal stimulus; DIT increased with a protein meal while a glucose load elicited no thermogenic response (Shetty, 1980). Systematic studies were recently reported in a group of undernourished individuals whose DIT response to a standard liquid meal over a 6 h period, was compared with well-nourished controls (Piers *et al*, 1992). The DIT responses to the meal were the largest in the undernourished, both in absolute terms as well as when expressed as a percentage of the metabolisable energy content of the meal. The latter method for the expression of the DIT response has the advantage that the DIT response is corrected for the energy load administered. The non-protein respiratory quotient (NPRQ) and substrate oxidation rates were suggestive of predominant utilisation of carbohydrate as fuel both in the fasted and post-prandial state with little fat or protein being oxidised by the undernourished. Since undernourished subjects showed a lower protein oxidation rate, it is likely that the increase in DIT may in part be due to a greater increase in protein synthesis after the meal. However, it has also been demonstrated that iso-energetic amounts of carbohydrate produce a higher DIT response than fat. Hence, the predominant dependence on carbohydrate as a fuel both before and after a meal may account for the higher response in the chronically undernourished. It would thus appear that DIT responses seen in the undernourished are more representative of the metabolic fate of the predominant nutrient being utilised, which may in turn be influenced by the habitual dietary intake and nutrient composition, rather than variations in facultative thermogenesis.

Recent data on DIT measured over 15 h in Gambian subjects while in a respiration chamber, on the contrary, suggest that DIT responses are blunted in The Gambians during the lean season as compared to European subjects (Minghelli *et al*, 1990). The responses, however, were neither measured using the same standard stimulus nor were they expressed as a percentage of the metabolisable energy in the meal ingested. It is not certain whether the reduced DIT is due to a reduction in facultative thermogenesis or to a change in the obligatory component, possibly due to delayed gastric emptying associated with the habitual diet of the subjects. Paradoxically, the higher RQs of these subjects indicate a greater proportion of dietary carbohydrate utilisation, which might be expected to induce a higher DIT response in the undernourished Gambians during the lean season. Comparisons of DIT in Gambian men between seasons (Minghelli *et al*, 1991) have resulted in the suggestion that the DIT responses may have a possible dynamic role in modulating nutritional or seasonal influences. However, it is important to note that the subjects investigated in both these studies had mean body weights > 60 kg and BMIs of 20 and are therefore not comparable to the chronically undernourished subjects studied elsewhere (Piers *et al*, 1992). In neither season (rainy or dry) did the Gambians qualify to be considered as being undernourished by currently accepted definitions (James *et al*, 1988). These studies do not, therefore, unequivocally prove that DIT response in the chronically undernourished are altered as an adaptive response, and hence contribute to energy saving by increasing the efficiency of energy utilisation.

Physical activity: efficiency, work capacity and productivity

Reductions in either intensity or duration and thus the amount of physical activity can save considerable energy and may hence be a crucial response to energy restriction and an important feature of undernutrition in adults. The nutritional status of an individual influences physical activity and the adaptive changes in this component may be considered under three broad categories: (i) physiological, (ii) ergonomic; and (iii) behavioural.

Physical activity in imposed energy restriction.

Physiological. Studies on cost of physical activity during experimental energy restriction show no change in the maximal oxygen uptake per kg body weight despite a marked impairment in the ability to perform exhausting anaerobic work, for example the Harvard Fitness Test (HFT) (Henschel *et al*, 1954). In the early stages of energy restriction there was neither an impairment in the ability to complete the HFT nor a reduction in maximal oxygen uptake (per kg body weight or FFM) while prolonged semi-starvation (24 weeks) entailed a marked impairment in both (Taylor *et al*, 1957). Taylor & Keys (1950) suggested that only 40% of the decrease is attributable to a decrease in actual costs of performing tasks while 60% of the reduction in energy expended on physical activity was due to a decrease in tasks undertaken. In experimental semi-starvation, behavioural reduction in voluntary activity seems to be quantitatively more important than physiological reduction.

Behavioural. The studies of Benedict *et al* (1919) did not show any substantial decrease in the level of activity of their volunteers on an energy-restricted regimen. The Minnesota studies, however, suggested that semi-starved volunteers undertook less physical work (Keys *et al*, 1950); their work performance was less well maintained with the motivation to work fluctuating widely (Taylor *et al*, 1957) and a reluctance to engage in any form of activity being a common characteristic (Keys *et al*, 1950). A recent analysis of the pattern of an individual's physical activity during a voluntary reduction in food intake has shown that the behavioural response to a deficient intake was associated with a distinct change in the activity pattern suggesting that lower effort discretionary activities were substituted for higher effort discretionary activities with obligatory activities not being affected (Gorsky & Calloway, 1983).

Physical activity in chronic undernutrition.

Physiological. Viteri (1971) and Viteri & Torun (1975) compared the physical work capacity of undernourished young men and showed that they had lower VO_2 max and maximal aerobic power (MAP; that is, VO_2 max corrected for kg body weight and lean body mass) than well-nourished army cadets. However, when compared on the basis of 'cell residue' (that is, body weight less adipose tissue, body water and bone mineral) all differences in MAP between groups disappeared. Viteri (1971) concluded that the observed differences in MAP were the result of differences in body composition and not due to differences in cell function. Spurr (1983) summarised the results of several of his studies in Colombia which showed that VO_2 max was lower in malnourished young adults, the degree of reduction being related to the progressive severity of undernutrition with only the severe cases of undernourished adults demonstrating a significant reduction in MAP as compared to the well-nourished. Spurr (1983) was also able to demonstrate that 80% of the reduction in VO_2 max in the moderate and severe categories of undernutrition were accounted for by differences in muscle cell mass. We have also observed a reduction in VO_2 max in undernourished subjects, which is lower than that of the well-nourished when corrected for body weight differences (Kulkarni & Shetty, unpublished data).

The reduction in maximal aerobic power of skeletal muscle cells in chronic undernutrition suggested by some of the above studies may be the result of a number of changes such as reduced oxidative enzyme content in skeletal muscle—a feature demonstrated in animal models of undernutrition (Tasker & Tulpule, 1964; Raju, 1974). Lopes *et al* (1982) and others have shown that malnourished patients have increased muscle fatigability associated with the possibility of a decreased content of ATP and phosphocreatinine in skeletal muscle. Changes in the glycogen and total energy contents of skeletal muscle have been found in acute and chronic semi-starvation (Heymsfield *et al*, 1982). Alterations in the ratio of slow-twitch to fast-twitch fibres in the skeletal muscle have also been reported in undernutrition. Slow-twitch fibres have been shown to be better preserved (Lopes *et al*, 1982; Russel *et al*, 1984) while a selective reduction in fast-twitch fibres has been shown to occur in undernutrition (Henriksson, 1990). These biochemical and histological changes in

skeletal muscle may account for some of the physiological changes in muscle functions that have been observed in chronic undernutrition.

Assessment of endurance at 70–80% of the VO_2 max has also been made in malnourished individuals (Spurr, 1987). The maximum endurance time (MET) at 80% VO_2 max (T_{80}) was not significantly different in the three grades of undernourished subjects studied by Spurr (1987) and the T_{80} seemed to be reduced significantly following dietary repletion in the severely undernourished. We have also observed no differences in MET at 85% VO_2 max in undernourished subjects as compared to the well-nourished (Kulkarni & Shetty, unpublished observations).

Physiological responses during the recovery phase following VO_2 max or heavy physical activity such as endurance at 85% VO_2 max to exhaustion also shows several interesting features in undernutrition. Chronically undernourished adults recovered early after strenuous exercise (Kulkarni & Shetty, 1992) and showed no enhanced post-exercise rise in basal oxygen consumption the next morning (Kulkarni *et al*, 1991).

Aerobic capacity is considered to be an adequate measure of an individual's work capacity and productivity. Good correlations have been demonstrated between a high VO_2 max and productivity in lumberjacks (Hansson, 1965), and East African and Sudanese sugar cane cutters (Davies, 1973; Davies *et al*, 1976). Productivity is thus affected indirectly by nutritional status through the influence of the latter on height, body fat content and VO_2 max. Since VO_2 max is related to body weight and lean body mass, total daily output and productivity of the undernourished adult is likely to be lower than that of the well-nourished. This is true even in work in industrial situations of less intensity than manual labour, where productivity has been shown to be related to body weight and LBM (Satyanarayana *et al*, 1977).

It has been implied that part of the adaptive responses to chronic undernutrition is related to the greater efficiency at which small sized, undernourished individuals on low energy intakes perform (Edmundson, 1979; 1980). Mechanical efficiency (ME) is the ratio between the work done and the energy expended in doing it and ME is further subdivided into gross mechanical efficiency (GME), net mechanical efficiency (NME) and delta mechanical (or work) efficiency (DME) (Gaesser & Brooks, 1975). Since it is difficult to measure work done in physiological terms, the submaximal VO_2 per unit of body weight required to perform the task has been widely accepted as the criterion for efficiency (Cavanagh & Kram, 1985). Ashworth (1968) reported that undernourished Jamaicans had a significantly higher GME while performing the step test. We have also reported that undernourished individuals have a significantly higher NME than well-nourished controls while stepping (Kulkarni & Shetty, 1992). Other studies from India in undernourished subjects using the treadmill have shown that GME is higher in the rural undernourished (Satyananayana *et al*, 1989b) but that the GME reduces as the load increases and that DME worsens in the undernourished as the load increases (Satyanarayana *et al*, 1989b; Kulkarni & Shetty, 1992). Spurr *et al* (1984) have also reported increases in GME and NME in smaller undernourished individuals as compared to larger controls; however, DMEs were not different between groups. Marginally undernourished migrant adolescents in Brazil were also shown to have lower work capacity associated with poor anthropometry and a 8–15% reduction in muscle mass (Desai, 1989). Cyclo-ergometric assessment of their physical work capacity showed that the undernourished youths had similar increases in oxygen consumption with increasing load and hence uncompromised GMEs. However, it was apparent that they were able to achieve this work at a higher percentage of their maximum work capacity as evidenced by the significantly higher heart rates for the same level of oxygen consumption. The blood lactic acid levels were also higher during exercise suggesting thereby that the available muscle mass was under greater stress to accomplish the same task which might compromise their endurance during longer time periods or higher work loads.

Edmundson (1980) using the bicycle ergometer has reported that at 100 watts, the GME of his low intake Javanese was significantly higher than that of the high intake men. Norgan (1983) has recalculated the NME from Edmundson's data and has pointed out that the high energy intake group of Edmundson had lower values than expected and that the significant differences at 100 watts could be accounted for solely by the low values of the controls. The values obtained for DMEs in Edmundson's study are also lower than those reported for normal subjects by others (Gaesser & Brooks, 1975) and raise doubts about Edmundson's findings.

Ergonomic. NMEs and DMEs of rural Gambians with mean body weights of 60.8 kg (Minghelli *et al*, 1990) have been reported to be significantly lower than those of Europeans of mean body weights of 66.9 kg while walking on a treadmill at 3.2 km/h at 0% and 10% elevation. Subjective observations suggest that the vertical oscillations of the gravity centre may be reduced in Gambian men while walking. Similar ethnic differences in ergonomics may also account for the reductions of 10–17% in the cost of activities such as sitting or standing demonstrated in African and Asian subjects (Geissler & Hamool, 1985; Dieng *et al*, 1980). African women have been shown to carry loads on their heads up to 20% of their body weight, without any extra energy expenditure, which may be attributed to economic patterns of movements in these individuals (Maloiy *et al*, 1986). Similar observations have been made in the low body weight Jamaicans studied by Ashworth (1968). When subjects were asked to move bricks, the energy expenditure involved depended on the number of bricks carried. The results of this study showed that, when the subjects were made to carry smaller loads, the energy cost increased, and the costs involved were in general lowest when they chose the load to be carried themselves, that is the subjects of their own choice carried out the task that was most economical of energy use. Similar observations of reduced energy expenditure (even when corrected for body weight or FFM differences as compared to well-nourished) have been made by us (Kulkarni & Shetty, unpublished observations) in undernourished subjects who were asked to complete a task they were habituated to, such as moving bricks over a fixed distance and period of time while in a calorimeter. There is thus emerging evidence that there may indeed be a component of ergonomic efficiency operating in the undernourished state which may be related to the pattern of locomotion, a reduction in superfluous movements contributing to an unconscious economy of activity and an element of habituation to daily tasks involving moderate to heavy physical

labour. This is the component of 'real life efficiency' (RLE) that Waterlow (1986) has referred to. This component of ergonomic efficiency may also explain the enhanced GME reported while stepping (Ashworth, 1968; Kulkarni *et al*, 1991) and while walking on a treadmill (Minghelli *et al*, 1990). The same ergonomic efficiency may also be operating to explain the effect of a reduction in submaximal VO_2 corrected for body weight differences with age (Pate, 1981). Although short individuals need to take more steps at the same speed than taller subjects, when stepping frequency was used as a covariate the differences persisted, while these differences disappeared when body weight was used as a covariate. Spurr (1987) has demonstrated how in any group of normal individuals walking with or without a load, an apparent decrease in economy, that is, increase in VO_2 per kg body weight, occurs with a decrease in body weight, that is, smaller individuals appear to be uneconomical. If results of comparisons of MEs between well-nourished and undernourished persist despite this body weight effect, then they may be attributable to changes in ergonomic efficiency which is not related to the frequency of stepping in short, undernourished adults. It is however important to remember that measurements of ME in human subjects *in vivo* are full of pitfalls hence accounting for the wide variations and the contradictions observed in the literature. But it is not difficult to concede that there are more and less efficient ways of doing any piece of physical work. It is reasonable to suppose that tradition and experience have enabled people living on marginal intakes and hence likely to be chronically undernourished to find the most economical methods of doing the tasks they have to do (Waterlow, 1990).

Behavioural. The behavioural adaptation that accompanies undernutrition is mainly related to understanding how individuals allocate time and energy to different productive and leisure activities and to estimate biological and economic consequences of this change. In undernutrition more time is given to work activities while leisure and home production activities are reduced (Immink, 1987), and this is an important form of behavioural adaptation. Summarising the INCAP studies, Torun *et al* (1989) also arrived at similar conclusions. Their rural Guatemalan men with lower muscle masses were able to carry out the specific agricultural task allocated to them but took much more time to achieve this. But there were other more interesting changes in their activity behaviour. These individuals took significantly longer time to walk back home after work and they spent around 3 h each day taking a nap and sitting, playing cards or doing other sedentary activities. In contrast, the better nourished age-matched males did not nap, were active at home, played soccer and remained physically active for a significantly greater proportion of the day. Marginally undernourished individuals tend to become more sedentary at the expense of decreased social interactions and discretional non-salaried activities. Latham (1989), in a summary of his experiences in Kenya, also stated that nutritional status had a significant relationship with the time taken to complete a task as seen in 220 male roadworkers. Men with low weight-for-height took a longer period of time to complete the same task than did men with a higher weight-for-height. In this study in Kenyan men, haemoglobin was not a confounding factor. Latham (1989) concludes that energy deficient individuals will be forced over a period of time to limit their activities — they forego activities to conserve energy, some of which they do consciously and wilfully, some they do unconsciously. More recent data based on two concurrent studies (Norgan *et al*, 1989; Branca *et al*, 1993) on seasonal variations in activity patterns of adults (men and women) in rural India and Ethiopia (Ferro-Luzzi *et al*, 1997) showed that a large percentage of individuals with varying grades of undernutrition spent less than 2.0 or 4.5 h per day working as compared to individuals in the same socio-cultural milieu who were better nourished. These observations support the impression that behavioural adaptation of spontaneous, free-living physical activity in fact occurs in undernutrition. Restricting physical activity is an important strategy for low-weight individuals but may jeopardise survival rather than being beneficial under stress conditions where sudden demands are placed on them.

Total energy expenditure (TEE)

Total energy expenditure in imposed energy restriction. The Minnesota semi-starvation study was characterised by a reduction in TEE of the order of 55%. Although a reduction in BMR contributed to about a third of the TEE the major contribution to the reduction in the daily energy expenditure was due to changes in physical activity. The smaller body weight as a result of the imposed food restriction reduced the energy cost of physical activity which contributed 40% to the reduction while 60% was attributable to the lower levels of voluntary activity.

Several studies have looked at TEEs in obese individuals who have been therapeutically energy restricted and have lost weight. More recent studies on obese and non-obese individuals who were energy restricted suggest that a 10% decrease in the usual body weight is associated with a 15% reduction in 24 h TEE corrected for differences in body composition and that TEE adjusted for metabolic mass decreased with the weight loss (Leibel *et al*, 1995).

Total energy expenditure in chronic undernutrition. Measurements of TEE by whole body calorimetry in undernourished adults in The Gambia (Minghelli *et al*, 1990) and in India (Kulkarni & Shetty, unpublished data) suggest that the daily TEE are lower in the undernourished adults as compared to Europeans or well-nourished controls. This is despite the fact that calorimetry imposes not only a limit on the Physical Activity Level (PAL) but also restricts movement thus reducing the behavioural repertoire of activities that may contribute to energy saving in these individuals. It is also pertinent to note that the studies in The Gambia were conducted on adults who had BMIs of about 20 compared with Europeans with similar body fat content while the undernourished in India were compared with local well-nourished controls with a higher fat content than the undernourished who had BMIs suggestive of chronic energy deficiency by current definitions.

Concluding comments on metabolic adaptation in adults. Over the last two decades it has been suggested that the energy metabolism of individuals is variable and adaptable, and several important publications have drawn attention to the possibility of such physiological variability in energy utilisation between individuals. Norgan (1983)

has critically evaluated the four arguments that have been put forward for this variation which is purported to result in adaptation in human energy metabolism and concluded that differences in body size and levels of physical activity may provide explanations for most of these observations suggesting that individuals adapt to varying levels of energy intake. Ferro-Luzzi (1985) summarised our current thinking on the ways in which a chronically undernourished individual may metabolically adapt and respond to a sustained and long-term energy imbalance. Metabolic adaptation was represented as a series of complex integrations of several different processes that occurred during energy deficiency. These processes were expected to occur in phases which could be distinguished and a new level of equilibrium was then achieved at a lower level. At this stage, individuals who had gone through the adaptive processes that occur during long-term energy deficiency, were expected to exhibit more or less permanent sequels or costs of adaptation, which included a smaller stature and body size, an altered body composition, a lower BMR, a diminished level of physical activity and the possibility of a modified or enhanced metabolic efficiency of energy handling by the residual active tissues of the body. In addition to the twin strategies of reduction in body size and the behavioural adaptation aimed at reducing the energy expended on physical activity, enhanced metabolic efficiency in the BMR seems to be an important component of the adaptive response to lowered energy intakes in adults. A decrease in BMR per unit ATM/FFM in turn implied that the increase in metabolic efficiency is demonstrable in the other components of TEE, which is implicit in the model developed by Ferro-Luzzi (1985) (Figure 3). The general assumption is that the physiological and metabolic responses of the human body associated with chronic undernutrition in an adult are similar to, and can be explained on the basis of changes that occur during experimental or therapeutic semi-starvation in previously well-nourished adults. This assumption on which much of our current understanding of adaptation in individuals on marginal intakes in developing countries is based, is in my opinion flawed. There are two basic problems with this approach: (i) The evolution of the adult state of chronic undernutrition characterised by short stature and low body weight is a process that has been influenced by events from birth (or even gestation) and the current stable body size and body composition has been achieved to probably match the energy intakes at current levels. The changes in body size and composition (however unacceptable they are) are the main features of this adaptive response and physiological efficiency contributes quantitatively little if anything to this steady state; (ii) The current steady state has not been achieved by any recent loss of weight. This may be an important factor contributing to increased metabolic efficiency in a well-nourished individual who loses weight but not in an undernourished adult who is maintaining stable body weight and composition. The exception would be if events such as seasonal energy stress were super-imposed on this steady state which may lead to further acute weight loss although this may not exclude the possibility of consequent body compositional changes contributing to an apparent enhancement in physiological efficiency (Figure 2). There is thus a need to reappraise our concepts of metabolic adaptation in chronically undernourished adults and seek new paradigms since the models suggested by Ferro-Luzzi (1985) over a decade ago are not appropriate anymore. The

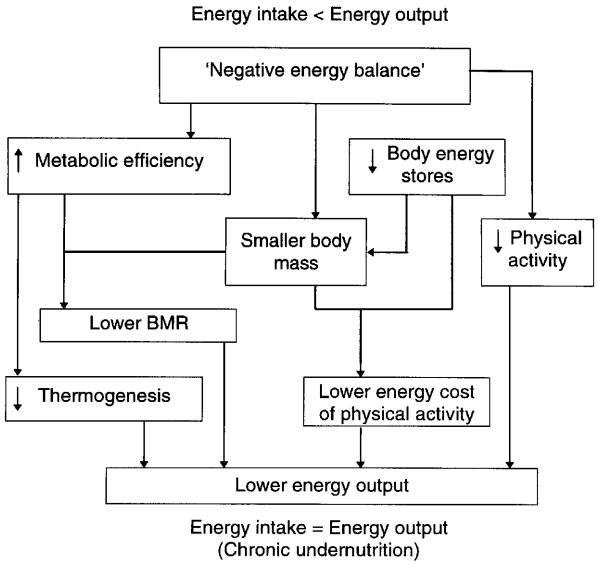

Figure 3 Schematic outline of the postulated changes that lead to a new level of energy balance in chronic undernutrition. (Modified from Ferro-Luzzi, 1985).

evidence so far reviewed on the responses of adults to lowered energy intakes suggest that the physiological responses of well-nourished adults are not comparable to those seen in adults who are chronically on marginal intakes and possibly undernourished since early childhood. The review also indicates that adaptive changes in body size and body composition that is short stature, low body weight, low muscle mass and fat stores, along with changes in spontaneous physical activity by behavioural or life-style responses are important features in the evolution of chronic adult undernutrition.

Responses to low energy intakes in infants and children

To critically evaluate the physiological and behavioural responses during restricted or low intakes of energy in infants and children (including adolescents) would require observations of their responses serially following energy restriction, over a period of time, not unlike the classical semi-starvation experiments in adults (Keys *et al*, 1950). It would undoubtedly be unethical to carry out such studies in infants and children, and to the best of my knowledge no such information exists. Even evidence from energy stress due to seasonal variations in food intake is rather limited in this group. The seasonal decrease in energy intake in young children in an Andean agricultural community was only 10–15% as compared to a reduction of 30% seen in the adults (Leonard, 1989) suggesting that children are protected even from seasonal energy stress by the responses of their families. While examining the data and commenting on adaptation to low energy intakes in infants and children, I shall confine myself to the available information on undernourished and malnourished infants and children. Hence in this section no attempt will be made to either present or discuss data along the three broad lines of evidence presented for adults although the responses will be reviewed for each of the components as in the earlier section. Since the evidence will be largely obtained from studies in infants and children who are malnourished, whatever the primary cause of the lowered food intake, it

is useful to remember that these situations are unlikely to be clean and clear-cut in terms of freedom from other nutrient deficiencies (macro or micro) and are also likely to be complicated by the effects of co-existing infection and other clinical complications. Another serious limitation is that for obvious clinical reasons, the reports in the literature invariably deal with cases of severe malnutrition with barely any mention or description of the interesting features in borderline or marginally undernourished infants and children.

Body size and composition

An undernourished child is not only a smaller sized individual for his or her age, but also manifests body composition changes related to proportions of different tissues as well as their chemical composition, which dramatically alters as the condition becomes more severe. For a number of obvious reasons, there is a general lack of information on body composition changes in mild undernutrition in infants and children, the data being largely confined to that seen in moderate to severe malnutrition. Also the changes seen not only reflect the degree of severity of the protein-energy malnutrition (PEM) the child suffers from but also varies with the type of malnutrition, namely marasmus or kwashiorkor.

Body water and body fluid compartments. Total body water (TBW) measurements have been made in infants and children suffering from severe PEM as well as during and following recovery as a result of nutritional rehabilitation. Isotopic dilution, the most favoured technique for *in vivo* measurements in children, suggests that TBW increases (Garrow *et al*, 1968); and the greater the weight deficit, the higher the TBW content of the body. The increase in TBW in childhood PEM is largely extra-cellular as in the case of severe food restriction in adults. Estimates of the ECF compartment based on measurement of thiocyanate space have confirmed this; ECW was increased in absolute terms and when expressed as a percentage of the body weight (Alleyne *et al*, 1977). An inverse relationship between ECW and body weight has also been demonstrated; a relationship not different from that between TBW and body weight. ICW content of tissue samples obtained at biopsy in malnourished children (with or without oedema) showed increase in water content (Frenk *et al*, 1957). However, values based on muscle biopsies are highly variable and therefore do not confirm whether ICW content is increased in relation to tissue solids in childhood PEM (Waterlow, 1992).

Changes in muscle and organ mass. Due to the marked changes in body water content and its distribution as well as alterations in the concentration of electrolytes such as potassium within cellular tissue, estimates of body fat mass and FFM/LBM based on methods such as TBW or total body potassium are unlikely to provide reliable data. Hence reliable estimates of LBM and fat mass are not available. However, measurements of the structural and cellular components of lean tissue have been made. Measurement of the collagen and non-collagen nitrogen of the lean tissues has shown that the collagen contributed to a much larger proportion of the total body protein in children with PEM (36–48%) as compared to normal values of 27% (Picou *et al*, 1966) suggesting that collagen protein content is maintained despite considerable reduction in the total lean tissue mass. Muscle mass is severely depleted in childhood malnutrition and the catabolism of muscle tissue is greatly increased in PEM. Marasmic infants with body weights at 50% of normality for their age had a total muscle mass which was only 30% of normal and both muscle bundles and individual fibres were reduced proportionately with severe attenuation of individual muscle fibres (Montgomery, 1962a). Cheek *et al* (1970) showed that the reduction in muscle mass was mainly due to a reduction in cell size and cell mass and not due to differences in cell numbers. The weight and size of the heart is reduced in severe PEM and so is the size of the kidneys in children dying of acute PEM. Wasting of organs such as the pancreas and the gastrointestinal tract are also well recognised. The weight and size of the liver varies depending on the presence and extent of fatty infiltration of the liver. The brain and the central nervous system are perhaps the only organ systems to be spared. Kerpel-Fronius & Frank (1949) reported that the weight of the brain was relatively well preserved in children dying of severe malnutrition despite drastic reductions in the weight of most internal organs of the body.

Basal metabolic rate

The measurement of BMR in infants and young children is usually made while they are asleep, a few hours after the last meal. Technically they do not fulfil the criteria for BMR and several factors influence the results. These include how soon after the last meal the measurement was made, whether sedatives were used and the degree of activity during the measurement. The increase in the number of variables that cannot be readily standardised may further influence the measurement of the metabolic rate (MR). In addition to the likely contributions from infections and the clinical status (that is, whether the child was gaining weight during nutritional rehabilitation, whether it had oedema, whether the child had kwashiorkor or marasmus) make interpretation of changes in metabolic rate (MR) of infants and children during undernutrition quite difficult.

Reduction in MR is not an invariable finding in malnourished children. Reductions in MR have been reported in severely malnourished children (Parra *et al*, 1973; Brooke *et al*, 1974); the MR was lower than that of normal children, even when adjusted for total body potassium (TBK) as a proxy for active cell mass (expressed as kcal/mmol K^+/d), and increased during recovery. The reduction in oxygen consumption of the residual active tissues has been variously attributed to depressed cellular respiration (Nichols *et al*, 1968). However there are reports that suggest that MR is in fact increased in marasmic children (Talbot, 1921; Montgomery, 1962b; Monckeberg *et al*, 1964). Both Montgomery (1962b) and Monckeberg *et al* (1964) found MR/kg body weight elevated in marasmic infants and the former attributed this difference to changes in the body composition seen during malnutrition. No attempt has been made to provide data on MR in marginally undernourished infants or children. However, Jaya Rao & Khan (1974) have reported that the control children from the same socio-economic background as the children with PEM had BMRs comparable to well-nourished American children of the same age despite having body weights 17–35% below American standards. Recalculation of data on

BMRs of children aged up to 24 months who served as controls for comparison with children with PEM showed that the BMRs on the whole were comparable to current standards despite several of the controls being underweight for age (Brooke *et al*, 1974).

Adaptive thermogenesis

Post-prandial increases in metabolic rates were small in malnourished children and of the order of 6.5% over 1 h as compared to a significant and substantial increase seen in infants during recovery (Brooke & Ashworth, 1974). Larger post-prandial responses during the phase of rapid catch-up growth have been attributed to tissue synthesis with a high energy requirement probably due to an increase in protein synthesis (Ashworth, 1969). The two studies that have measured post-prandial MRs have both shown that the increase is similar before treatment of the malnourished child and following full recovery when normal growth rates have been resumed (Krieger, 1966; Brooke & Ashworth, 1974). The study by Brooke & Ashworth (1974) also demonstrated that the post-prandial increase in MRs over a 1.75 h period peaked at about 20% both during rapid growth and during recovery when the malnourished infant was still growing rapidly, and that the post-prandial increase was linearly related to the growth rate of the child in g/kg body weight per day. RQ changes were also seen with malnourished children showing a marked increase in RQ following the test meal which tended to slow down as the child recovered following nutritional rehabilitation.

Physical activity in infants and children

That restricted energy intakes reduces the duration and intensity of physical activity in infants, pre-school and school children has been well reviewed recently by Torun (1990). Community-based studies such as the one by Rutihauser & Whitehead (1972) in Uganda showed that undernourished children spent significantly more time sitting and standing and less time walking and running than a small number of European children during two consecutive 5 h daytime periods when they were observed. A study in Guatemala reported by Torun (1990) compared well-nourished with mildly malnourished children and showed that the latter group spent more time in sedentary activities and less time in activities of high and very high intensities.

Physical fitness is also compromised in severe PEM while nutritional rehabilitation leads to an increase in aerobic capacity in 2–4 y old children (Torun *et al*, 1979). Studies on physiological work capacity in malnourished children aged 6–16 y in several developing countries summarised by Spurr *et al*, (1983, 1988) indicate that the reduction in physical work capacity as measured by VO_2 max is largely attributable to the smaller body size and hence smaller muscle mass.

Total energy expenditure (TEE)

Estimates of daily TEE obtained by classical methods of time and motion studies indicate that on average the TEE was lower in undernourished boys and girls of ages 6–8, 10–12 and 14–16 y in Colombia (Spurr & Reina, 1989). Measurement of TEE of undernourished Gambian children aged 1–36 months using the doubly labelled water method also indicated that compared to well-nourished European children of the same age, the undernourished (averaging 79% weight-for-age) had significantly lower TEEs. However, the differences in TEE disappeared when the TEE was corrected for body weight or FFM differences, indicating that this was entirely attributable to the smaller size of the Gambian children (Vasquez-Velasquez, 1988).

Concluding comments on responses to low intakes in infants and children

An examination of the available vast fund of information on malnutrition and undernutrition in infants and children suggests that body size and body composition changes accompany malnutrition resulting from a complex web of factors that cause a disturbance in energy balance. The degree of change in body composition and weight is related to the severity of the malnutrition. MR is lowered in malnutrition in children. Largely due to the clinical interest in moderate to severe malnutrition in children, there is limited information on the MR of marginally undernourished children. It is probably not altered in marginal undernutrition. Physical activity is compromised and total daily energy expenditure is reduced in undernourished children; this is largely attributable to the smaller body size and muscle mass. The inevitable conclusion is that marginal undernutrition probably primarily determined by lowered intakes of energy, results in reduced stature and lowered body weights which contribute to most of the responses observed. In addition, there are behavioural changes in the patterns of physical activities, which is part of the strategy to reduce energy expenditure when intakes are low. Table 3 summarises the responses to low intakes of energy seen in infants and children and adults.

Limits to what? Low intakes? Responses to low intakes? Outcomes and consequences of low intakes?

One of several problems that one encounters when one discusses the adaptive response to low energy intakes is the problem of defining an acceptable range of intakes and delineating the threshold or limit beyond which function is compromised. If the relationships between energy intake and physiological function were sigmoidal one would expect to be able to define a level of input below which a dramatic reduction in function occurs (Waterlow, 1990). The relationship on the other hand may be continuous and show no threshold effect although this is unlikely in the case of energy. It is also important to recognise that some of the functional compromises or costs may be related to one of the principal responses to a sustained lowering of food intake such as a low body weight; a relationship which may also be sigmoidal and show a threshold. There is little doubt that a severe and sustained restriction of energy intakes will impair bodily functions; that mild restriction of food intake may not have costs and may not impair physiological function is more controversial. The latter view is based on the assumption that the body adapts or accommodates to such levels of low intakes that may not produce apparent impairment of function or that the body is capable of responding by increasing its efficiency of utilisation of energy and thus get more energy from food to meet the shortfall. An attempt will be made here to deal with the issues related to limits or threshold levels to which intakes can be lowered and with what consequences and costs which has been recently reviewed extensively (Norgan & Ferro-Luzzi, 1995).

Table 3 Responses to low energy intakes in infants & children and adults

Infants and children	*Adults*
Restriction of growth	Reduced body size
Reduced weight	Low body weight
Reduced length/height	Short stature
Reduced weight for height	Low BMI
Body composition changes	Body composition changes
Loss of fat	Low body fat
Low muscle mass	Lowered muscle mass
Moderate decrease in organ mass	Organ mass better preserved
Basal metabolic rate	Basal metabolic rate
Reduced in absolute	Reduced in absolute
Increased per unit (body weight)	Increased per unit body weight or FFM?
	Decreased in later stages of severe restriction
Adaptive Thermogenesis	Adaptive Thermogenesis
DIT increased?	DIT increased?
Physical Activity	Physical Activity
V Max reduction proportionate to reduced body size	V Max reduced
Behavioural reduction dominates	Physiological endurance unaltered?
	Increase in efficiency?
	Work output and productivity related to reduced body size
	Behavioural reduction dominates

Body size
Achievement of ones genetic growth potential depends upon the stage of development during which the undernutrition occurs as well as its duration and intensity. Restricted intakes of energy during pregnancy and the first 3–5 y of life affect body size considerably. Children are highly vulnerable during this period both to the effects of poor diets and to other factors such as infections and general environmental deprivation. Under such circumstances they grow very poorly at a time when they should demonstrate rapid growth. The adverse influence in the early years is maintained right through to adulthood and height deficits observed at age 5 y continue unchanged into adolescence and adulthood (Satyanarayana *et al*, 1989a). Therefore gain in height during adolescence may not be compromised during the pubertal growth spurt in the undernourished although the pubertal growth spurt, as well as skeletal and sexual maturation, may be delayed. Growth retardation carries a heavy price since the short stature in adulthood will influence physical work capacity, work output and economic productivity in both agricultural and industrial situations.

Infection and morbidity
Infection and malnutrition have a synergistic relationship—infection increases tissue catabolism and causes anorexia, which lowers food intake while malnutrition lowers immunocompetence predisposing to infective episodes. Morbidity and mortality are increased in children and adults who are undernourished, and several studies have shown an increase in morbidity with increasing severity of malnutrition in children.

Physical activity
Restricted energy intakes reduce levels of physical activity of infants and children. Prolonged reduction in physical activity due to sustained low energy intake may result in a reduction in the child's social interactions and exploration of its immediate environment which in turn may contribute to slower cognitive development, sub-optimal social performance and delayed motor development. Physical activity patterns are also altered in undernourished adults with more time spent on rest periods, longer time taken to complete tasks and encroachment on the time set apart for socially desirable activities.

Reproductive function
Successful reproduction is dependent upon adequate stores of energy in the body. Although severe undernutrition is associated with declines in fertility, whether marginal intakes in energy will reduce fertility is not certain. They may do so by delaying menarche. Pregnancy and lactation also impose high energy demands. Marginal intakes may lead to poor pregnancy outcomes such as low birth weight while severe restriction may result in spontaneous abortions and foetal growth retardation. Lactation however is more robust and resistant to energy deficiency.

Mortality
There is increasing evidence that mortality both in children and in adults increases with malnutrition. Emerging evidence supports the hypothesis that the effects of undernutrition in pregnancy leading to foetal growth retardation can predispose to early mortality both from chronic and infectious diseases.

Lower limits of energy intakes and requirements of adults and children: individual and population basis

Energy requirement is a function of two basic variables: physical health as expressed by body size (body weight) and physical activity. The existence of a range of body weights and a range of physical activity levels (economically necessary and socially as well as physiologically desirable) that are consistent with good health in individuals of any age or sex implies that there is a range of energy requirements for individuals in any population group. The existence of this range creates a problem in either arriving at what can be considered as the lower limit of energy intake (or requirement) or in identifying individuals whose energy intake may be considered to be inadequate and below their requirement.

The 1985 Expert Consultation (FAO/WHO/UNU, 1985) adopted not only the principle of relying on estimates of total energy expenditure (TEE) rather than energy intake to estimate energy requirements for adults but also

demonstrated how TEE expressed as a multiple of BMR can be used to determine the energy requirements of individuals and population groups.

These multiples of BMR are referred to as Physical Activity Levels (PALs) and are readily calculated by dividing TEE by BMR. Studies using doubly labelled water (DLW) to estimate TEE under special conditions can provide information on TEE at the lower (and upper) extremes of physical activity levels in adults and thus provide an indication of the lower (and upper) limits of energy intakes and hence requirements. A summary of studies of TEE using the DLW method (Black *et al*, 1996) and compilation of PALs for a review on energy requirement of adults (Shetty *et al*, 1996) suggest that the lower limit in non-ambulatory, chair/bed bound subjects apparently not exercising provides a mean PAL of 1.21 while an individual who mostly works seated with no option of moving around and little or no strenuous leisure activity has a PAL between 1.4–1.5. This is in contrast to the PAL value of 1.27 suggested by the Expert Consultation (FAO/WHO/UNU, 1985) as being the survival requirement. The Consultation suggested that the average daily energy requirement of adults classified as involved in light occupational activity should be based on PAL values of 1.55 and 1.56 for men and women respectively. These values do not account for the level of leisure time or non-occupational activities. The recommendation made for the United Kingdom (Department of Health, 1991), suggests a PAL value of 1.44 for both men and women when considering both occupational and non-occupational activities of an individual as light.

From a population point of view, the minimum (and average) per caput energy requirements are obtained as the weighted average of the lower limit (and average requirement), respectively, estimated for each age and sex group derived on the basis of the range of acceptable body weights and the range of acceptable activity levels (FAO, 1996). The body weights for adults for the average requirement is determined on the basis of the median of the acceptable range of weight for height (that is a BMI value of 22.0) and for activity on the basis of moderate activity levels (that is PAL values of 1.78 and 1.64 for men and women respectively). Hence, for a given height, the lower limit of the range of body weight for height is a BMI of 18.5 and the lower limit of activity level is a PAL value of 1.55 for men and 1.56 for women respectively. The same principle as used for adults applies for adolescents. For children however, the minimum body weight for estimating the lower limit of energy requirement is the median value of the weight for height range and the activity level considered equal to that of children in affluent societies plus an infection allowance for children up to 2 y of age. This is the basis by which the recent Sixth World Food Survey (FAO, 1996) has estimated global and regional prevalence of energy inadequacy.

Conclusions

The principal response to a lowering of energy intake in adults depends on the previous nutritional status of the individual. In well-nourished adults energy restriction leads to the utilisation of body tissue to meet energy needs and is also associated with a physiological response that may provide an element of metabolic efficiency. The reduction in body weight coupled with a small increase in efficiency will lower energy expenditure. Daily energy expenditure is lowered by a lower cost of physical activity largely contributed by the reduction in body weight but also by reduced voluntary activity. There is little evidence of any improvement in the mechanical efficiency of work.

The response to energy undernutrition seen in developing countries resulting from marginal intakes or deficient diets is compounded by other factors such as an increased risk of infections and a generalised environmental deprivation. The effects of undernutrition have to be examined from birth throughout the developmental phases into adulthood and are closely inter-linked with both the immediate effects of childhood malnutrition and the evolution of adult undernutrition later in life. The principal response is a reduction in body size, which persists into adulthood as short stature, low body weight and a reduced muscle mass and fat stores. There is little evidence of an increase in metabolic efficiency or an enhanced mechanical efficiency of work. Behavioural responses contribute to alterations in physical activity patterns and, along with the small body size, contribute much to reducing energy expenditure to meet the lower levels of intake. The compromised body size, altered physical activity patterns and reduced potential to carry out economically productive work have major costs — human and social — that the individual and society will have to bear.

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