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Mini-Review

The beneficial effects of body fat and adipose tissue in humans*

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Body fat and adipose tissue are considered to have beneficial effects when they promote or protect the present and future function. These effects do not occur at absolute amounts or percentages of the body weight but rather they are context specific. Body fat stores are the major energy stores of the body and are important determinants of survival in starvation or undernutrition. Reproduction features highly as a biological function. Humans are alone in having major sex-specific fat stores and patterns of fat distribution[1] and these have been linked with the onset and maintenance of menstruation, with mate selection and sexual signalling, and with favourable pregnancy and lactation outcomes. To survive and reproduce good physical and psychological health are advantageous attributes. Work metabolism, bone health and, possibly immune function and energy balance itself, are related in functionally beneficial ways to fat content and distribution.

Keywords: body fat; survival; reproduction; mate selection; work capacity; bone health

Introduction

In addressing and dealing with the problems caused by overweight and obesity, we tend to lose sight of the fact that the human body evolved with a capacity to store dietary energy as fat and that this ability has had a selective advantage. The Association for the Study of Obesity Workshop on 'Good Fat, Bad Fat'—clinical and metabolic aspects of adipose tissue distribution in November 1996 provided an opportunity for a reminder of some beneficial aspects of body fat and fatness. Body fat and adipose tissue are considered to have beneficial effects when they promote or protect present and future function. These effects do not occur at absolute amounts or percentages of the body weight but rather they are context specific. What in one set of circumstances may be beneficial may be dysfunctional in others.

Human fat contents

Energy is the key to life and, as intermittent feeders, we require stores of energy and mechanisms to accumulate and release these stores in the short and long term. Fat, here taken to be triacylglyceride, is quantitatively the most important form of stored energy and is found in adipose tissue (AT). There is a sexual dimorphism in fat content and distribution. Typical fat contents are 10 and 15 kg, 15 and 27% of body weight, as in the Reference Man and Woman of Albert Behnke.[2] These are not averages or desirable amounts but rather models based on average dimensions to be used as comparators for other data. These amounts have been separated into essential and storage fat; 3 and 12% of body weight in men and 9 and 15% in women, respectively. Essential fat is that in bone marrow, heart, lungs, liver, kidneys, intestines, muscles and lipid-rich tissue of the central nervous system with roles other than energy storage. It includes other fats in addition to triacylglycerides, such as phospholipids. In the model of Reference Woman, the essential fat also includes sex specific fat, primarily in the mammary glands, the pelvic region and the thighs. There is no general agreement of the quantities of these and whether they are strictly essential or a storage reserve for the energy demands of pregnancy and lactation. Katch and colleagues[3] have suggested subdividing storage fat so that there are three fat components in women, essential (4%), sex-specific reserve storage (5%) and expendable storage (15%), on average.

The sexual dimorphism in adult fat distribution is particularly marked. Men have a central pattern of deposition, mainly on the trunk and abdomen. In

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women deposition is, characteristically, on the buttocks and thighs. The sex-specific amounts and distribution, particularly the regional adiposity in the abdominal and gluteo-femoral regions, are caused, in a large part, by the sex hormones. Testosterone may facilitate deposition in the former and utilisation in the latter and the reverse for oestrogen. According to Martin and Daniel[4] the effects are more related to the oestrogen/androgen balance than to oestrogen alone. They consider that the suggestion that sex hormones have a major role in sex differences has not been proved. The enzyme lipoprotein lipase (LPL) facilitates fat uptake and storage in adipose tissue. Its level is high in the adipose tissue at the hip, thigh and breast in women and in the abdomen in men. Variations in LPL levels may contribute to differences in fat distributions between the sexes, between individuals of the same sex, between ethnic groups, during pregnancy and in middle age.

The responses of adipose tissue to metabolic and nutritional change vary at different sites. Truncal deposits appear to be the primary energy stores. Even at the same subcutaneous site superficial layers seem less responsive perhaps because they have more of a structural role.[5]

Survival

Energy stores and energy flux

Typical healthy young men and women with body fat stores of 15 and 25% of body weight, some 10 and 15 kg of fat, have fat energy stores of 370 and 555 MJ, respectively. At an energy expenditure of 6 MJ/d, these would provide sufficient energy for 60–90 d. There is also energy available from body protein but only half of the protein, containing some 100 MJ, can be mobilised without becoming life threatening. The arithmetic seems simple and compelling. The larger the fat stores when entering a period of starvation or chronic energy deficiency, the longer the survival period or the less threatening it is. At death, body weight loss may be as much as 50% by which time all fat stores will be depleted. The differential survival rates of males and females under conditions of dietary energy stress are well known from studies in war-time Europe and elsewhere and attest to the importance of energy stores in starvation.[6–10]

The arithmetic is not, however, uncomplicated because of the adaptations to negative energy balance that occur. Weight, fat and energy are not lost at a constant rate throughout a period of undernutrition or starvation. Firstly, a smaller body size lowers the energy requirement. Secondly, volitional physical activity falls, further lowering the energy requirement. There may also be a reduction in metabolic rate per unit of non-osseous lean tissue. Thus, on a constant, initially inadequate energy intake, the rate of weight and fat loss decreases exponentially.

Views on the lowest body mass index (BMI) compatible with life have seen downward revisions in recent years. James *et al*[11] proposed a BMI of 12 as the absolute lower limit compatible with life. Henry[8] in a more detailed review endorsed this proposal but thought an apparent sex difference of 13 in males and 11 in females warranted further investigation. It is now clear from data collected in famine victims that values as low as 10 are compatible with life with specialised care.[10,12]

A second effect of body fat on survival, in addition to the size of the energy stores, is that the types of responses to energy deficits are related to the initial level of energy stores in the body, at least in studies of more than four weeks duration.[13] The nitrogen (N) or protein loss during starvation or undernutrition is less in individuals with high fat contents than those of low fat contents and less in females than in males. It is postulated to be constant in an individual during both storage and mobilisation until the preterminal phase of starvation.[14] It appears as though the thin are eking out their fat stores in a protective response but the greater N or protein losses appears maladaptive.

Hazards of thinness

There has been considerable debate over the health risks of low weight and BMI in young adults and the middle-aged. The U or J-shaped relationships between mortality or probability of death and low weight or BMI have been interpreted as the effect of the inclusion of smokers and the already ill causing the left-hand tails. A recent meta-analysis by Troiano *et al*[15] considered the 19 major prospective cohort studies that met strict inclusion criteria. They concluded that increased mortality persisted at moderately low BMI in white men after smoking or existing disease were accounted for. It was comparable to that observed at extreme overweight. The limited data on women indicated that there was little relationship between BMI and mortality in non-smokers over a 10 y period beginning 50 y of age. The 16 y follow-up of 115 000 30–55 y old US women in the Nurses' Health Study[16] also showed no increase in mortality in leaner women who had never smoked. Is this sex difference in mortality experience evidence of a fat content effect? It certainly demonstrates the hazards of thinness in men. The American Health Foundation's Expert Panel on Healthy Weight,[17] in a departure from other weight recommendations, eschewed publishing upper and lower limits of weight to avoid people losing more than may be necessary to achieve improved health.

Dietary restriction is well known to increase longevity in laboratory animals. Initially, the mechanism was thought to be that excess fat caused premature death. Now it appears that in dietary restricted animals longevity and body fat content are positively correlated.[18] This observation does not fit easily with any of the three current hypotheses of the mechanism by which dietary restriction increases longevity.

Lower limit of body fat in healthy men

Humans can survive with tiny amounts of body fat as can be seen in body builders and wrestlers, who both have normal or increased amounts of skeletal muscle, and in anorectics and famine victims. Friedl and colleagues[9] addressed the question of what is the lower limit of body fat in healthy adults by studying 55 young men undergoing strenuous US Army leadership training with food deficits. There was a 5 MJ/d energy deficit over eight weeks, leading to 16% weight loss. This level of food restriction approached the voluntarily tolerable limit for these highly motivated men. Body composition was measured by DEXA technology, thought to be less affected by changing compositions, although DEXA did overestimate gravimetrically determined body weight by 2–3 kg at six and eight weeks. When minimum body fat percentages of 4–6% were reached, some 2.5–4 kg of fat, increasing amounts of lean tissue were sacrificed. This was demonstrated by continuing decreases in waist, hip and thigh circumferences when body fat was low and had stopped falling. This minimum range compares well with the data at the end of the Minnesota study of 5.3% body fat, allowing for changing fat-free mass composition, and Behnke's Reference man with 3% or 2.1 kg of essential fat. Any encroachment into this impairs normal physiological function or capacity for endurance exercise. Although low energy levels may never be a cause of death they are a major contributory factor in the breakdown of adaptation and maintenance of homeostasis and the impairment of physiological function. Energy stores, particularly fat stores, protect function.

The role of body fat in insulation and survival in cold air or water

A classical environmental physiology dictum is that subcutaneous and deep body fat are major components determining the rate of internal heat transfer during water immersion. The benefits of body fat in the maintenance of core temperature during cold water immersion have been amply and consistently verified.[19] In addition to the insulative effects, women derive considerable hydrodynamic benefits from their greater fat content, which increases buoyancy, and the greater distribution of fat on the legs, making them more horizontal in the water with less drag. The record time for swimming the English Channel was held by a woman between 1978 and 1994.

Body fat, particularly subcutaneous fat, also provides significant protection during cold air exposure. However, Inuits (Eskimos) that followed a traditional way of life before acculturation had low skinfold thicknesses and Korean diving women who made a living by regularly diving in cold water had less subcutaneous fat than other Korean women and much less than American women.[20] Pond[21] has found that polar bears have proportions of fat situated subcutaneously not significantly different to those of temperate zone and tropical carnivores. This suggests that other physiological mechanisms such as vasoconstriction or counter-current circulation maybe as important as insulation in heat retention. Alternatively, the role of non-active, minimally perfused skeletal muscle acting as an insulator needs to be considered. The most commonly observed adjustment by circumpolar residents is a blunted shivering response.[22]

Reproduction

In evolutionary terms, survival itself is of little consequence. It is only advantageous for reproduction and for protecting the genes of the next generation. It has been suggested that because human reproduction is such an energy demanding process where the chances of a successful outcome are low mechanisms may have evolved to restrict reproduction at the outset.

Fertility

As is well known, Frisch and co-workers[23] suggested a critical body weight of 46–47 kg for menarche in American and European girls, later translated to 17% body fat for menarche and 22% for regular menstrual cycles.[24] Many objections have been raised about these limits and the treatment of the data in arriving at them, particularly the assessment of % fat from height and weight, and the hypothesis has been modified and extended. Famine and anorexia nervosa are known to affect reproductive function but attempts to apply the hypothesis to more moderate nutritional challenges have not been successful, except for physically active individuals particularly endurance runner and ballet dancers. Difficulties remain, such as observations that the % fat of menstruating and non-menstruating runners have been found to be similar[25] and many individuals do not behave according to the thresholds. The proposed amounts of stored energy required are very large compared with other species where pregnancy, often involving multiple births, and lactation are more energetically expensive. Brownell *et al*[26] suggested that regional fat loss rather than total fat loss may trigger amenorrhea. Deletion of fat on hips, thighs and buttocks, which provide much of the energy for pregnancy and lactation, may disrupt reproductive function. DeRidder *et al*[27] found that weight matched girls with lower waist-to-hip ratios (WHR) had early pubertal endocrine activity than those with higher WHR.

Frisch[28,29] has suggested a number of ways in which adipose tissue may regulate female reproduction through the hypothalamic-pituitary-ovarian axis. Firstly, adipose tissue of the breast and abdomen is a significant extra-gonadal source of oestrogen, accounting for a third of the circulating oestrogen in pre-menopausal women. Secondly, fatness seems to influence the direction of oestrogen metabolism to more potent forms in the obese or less potent forms in the lean. Thirdly, those obese women and young girls who are relatively fatter have a diminished capacity for oestrogen to bind to serum sex hormone-binding globulin (SHBG), leading to higher concentrations of the free form. SHBG also regulates the availability of oestradiol to the brain and other target tissues. Finally, the adipose tissue of obese women is known to store oestrogens. The question remains as to whether these effects influence ovarian function.

Many other factors are now being implicated in the regulation of the hypothalamic-pituitary-ovarian axis and most workers consider physical and psychological stress leading to increased adrenal corticosteroid and catecholamine excretions, energy drain, and nutritional inadequacies to be equally if not more important than low adipose tissue masses. There is a complex interplay of many factors on menstrual function. It could be that low fat levels reflect the discipline of dietary restriction and training rather than having a causative effect. Attention is switching away from athletes, with physiques that could have a bias towards lower ovarian activity, and the presence or absence of menstruation towards the more subtle effects of hormone levels, such as the shortened luteal phase of the cycle, the appearance of anovulatory cycles and, in particular, the down-regulation of the hypothalamic gonadotrophin pulse generator.[30]

Human mate selection: the role of shape preferences

Darwinian theory has not been applied successfully to human affairs. The previous attempts by Herbert Spencer at the end of the 19th century, the application of neo-Darwinism to the social sciences in the 1920s and the efforts of sociobiology in the 1970s failed, perhaps because of the emphasis on rigid behaviours rather than inbuilt behavioural predispositions highly attuned to environmental factors. The latest attempt at application is occurring under the name of 'evolutionary psychology'. One example is in the area of human mate selection. Men and women select mating partners who will enhance their reproductive success, according to evolutionary theories of human mate selection. For women, this may be high status men who control resources. For men, reproductive success may be increased by choosing a woman with the characteristics of being fecund and a good mother. Singh[31] states that a fundamental assumption of all evolutionary theories of human mate selection is that physical attractiveness is largely a reflection of reliable cues to a woman's reproductive success. The assumption is that men assign great significance to good looks and this is said to be a cross-cultural universal. It is said to be easy to identify high status men but fecundity is not overt and more difficult to identify. In the absence of direct signals of ovulation or fertility in humans, in contrast to the non-human primates, indirect cues are said to be used.

Singh[31] asserts that the female hour-glass body shape distinguishes menstruating from pre-menarchal, pregnant and post-menopausal women and WHR is the best indirect index of this. He showed that rankings of the attributes of 'healthy', 'youthful-looking women', 'attractive and sexy', and 'desire and capacity for having children' were highest in the lowest WHR shapes presented to rankers, irrespective of the shapes being of underweight (BMI = 15), normal (BMI = 20) or overweight (BMI = 25). Fatness and, surprisingly, thinness were perceived as unattractive. Singh[32] found no evidence that young black men and women in the USA behaved differently by regarding overweight female figures as desirable and attractive. Physicians of both sexes also assigned higher rankings of health, reproductive capability, and attractiveness, to normal weight, low WHR female outlines.[32] For a trait to be considered adaptive it must be transgenerationally stable and Singh reported ratings of attractiveness and other attributes to be similar in all age groups.[31]

It is necessary to establish a link between attributes of attractiveness and physiological mechanisms regulating components of fitness such as health, fecundity, successful pregnancy and nursing. Body fat and its distribution may provide the link, with the high levels of circulating oestrogen in women producing a lower WHR. Singh[31] notes that in the work of De Ridder[27] on weight matched girls, those with lower WHR had early pubertal endocrine activity and married women with higher WHR and lower BMI are reported to have more difficulty getting pregnant and to have the first birth at later age.[34] Also, in a Dutch prospective study on artificial insemination, a 0.1 unit increase in WHR led to a 30% decrease in probability of conception, after controlling for many interfering variables.[35]

The conclusion from Singh's studies on Western populations is that body fat and its distribution plays a crucial role in judgements of female attractiveness, health, youthfulness, and reproductive potential. The suggestion is not that shape as evinced by WHR is the only factor in mate selection but one involved in the initial stages, 'a first wide pass filter'. At another level, cultural factors come into play, as exemplified by the different socio-economic status and obesity relationships in the First and Third Worlds.

How does Singh's theory of the role of shape preferences in human mate selection fit in with the supposed secular changes in definitions and preferences of attractiveness, particularly the shift from the hour glass shape to the tubular? Studies of Playboy centrefolds[36] and Miss America competitors[37] suggest that the hour glass shape, and the WHR in particular, have been maintained, even though body weights and bust sizes of participants have decreased. Currently, the curvy shape is regaining popularity as a glamorous attribute. It is quite possible that it is features that are rare or difficult to achieve that are sought. The history of fashion shows us that during times of scarcity skirts with plenty of material were fashionable. In times of plenty, skirts are short and narrow. Likewise, body fat is socially desirable and esteemed in times or areas of shortage.[38] Whether thinness or fatness is difficult to achieve the attraction of the proportionally wider hip than waist remains.

Waists and buttocks are uniquely human features, not shared by the great apes. The evolution of human bipedal locomotion has been associated with changes to the mechanisms of pelvis and femur. The buttocks arise from the rotation of the sacrum and pelvis and the development of the gluteus maximus for bipedal posture. The waist has its origins in the short ilium, the development of the lumbar vertebrae and the lumbar curve of the spine and the subcutaneous adipose tissue on the gluteal facial. Pond[39] has speculated that the WHR effect could be a vestigial form of selection for correct pelvis shape, in that it signalled the erect posture of the female early hominid and her ability to give birth to large-brained offspring. The locomotory influences on body shape also allows male attractiveness to have a role in mate selection. Whereas men imaging women admire a muscular chest, arms and shoulders, they actually nominate the buttocks as the most attractive part of a man.[40] Do these signal endurance capacity and hunting prowess?

Pregnancy and lactation

There are a number of sex and regional differences in adipose tissue content and metabolism.[41] The sexes differ most noticeably in their gluteofemoral fat content. The gluteofemoral fat cells are bigger than other subcutaneous adipose tissue cells. They have increased lipoprotein lipase levels, a rate limit on fat uptake, compared with mammary and abdominal cells, and a lower lipolytic activity due to more alpha than beta adrenergic activity. Therefore, they tend to accumulate fat. This pattern is accentuated during pregnancy but disappears during lactation. As a consequence, gluteofemoral fat deposits are regarded as deposits to meet the energy demands of lactation. After the menopause, these regional differences disappear although this can be reversed with hormone replacement therapy.

Pregnancy

Fat stores are beneficial for successful pregnancy outcome. Low maternal weight before pregnancy and poor weight gain during pregnancy are known to result in an increased prevalence of low birthweight infants.[42] van der Spuy *et al*[43] studied the outcome of pregnancy and undernutrition in 1212 spontaneously ovulating women and in 41 women in whom ovulation had been induced to treat anovulatory infertility. They found that in spontaneously ovulating women those with a BMI less than 19 ($n=179$) had nearly double the expected rate of low birth weight babies (less than the 10th percentile of reference data). Birth weight was corrected for sex, parity, gestational age and maternal height. Women in whom ovulation was induced had higher risk of low birth weight babies (25% of births) increasing to 54% if they were underweight. van der Spuy[43] concluded that the most suitable treatment for infertility secondary to weight related amenorrhea is dietary rather than induction of ovulation.

Lactation

Lactation is an energetically expensive process and the fat stores laid down in pregnancy are often regarded as stores for lactation. In women in the UK, however, the sources of energy for milk production have been found to be from increased energy intake (62%), from decreased physical activity (35%) and from decreased BMR (3%).[44] There may also be a reduction in diet-induced thermogenesis. In women in developing countries, there may be less scope for increasing energy intakes and decreasing activity and fat stores may be more important to them. Prentice *et al*[45] reviewed the world literature of 41 databases to test whether relationships existed between low BMI and breast milk quantity and quality. Milk production was not affected by low BMI nor was composition with the possible exception of milk fat levels. Human lactation performance therefore appears very robust and unaffected by low energy stores. To achieve this, energy intakes must be raised so this robustness may not persist in famine or near famine conditions and fat energy stores will prove beneficial.

Some metabolic aspects

Many metabolic aspects of adipose tissue are discussed fully in other reviews arising from the ASO Workshop on 'Good Fat, Bad Fat'. Because of the interest in obesity, most attention has been focused on the large adipose tissue depots and their relation to health. However, there are suggested roles for some of the smaller discreet adipose tissue deposits in protecting and promoting function. One such unique type is brown adipose tissue.

Brown adipose tissue (BAT)

BAT, like many other tissues can oxidise a variety of substrates but it is unique in that oxidation can be uncoupled from oxidative phosphorylation, that is substrate energy can be transduced directly to heat. Uncoupling is under the control of the sympathetic nervous system which also has a co-ordinating role by increasing lipolysis and blood flow with the effect of transporting more oxygen to and heat from the tissue. This has two possible advantageous outcomes, in maintaining body temperature in the cold and in regulating body energy content, as proposed by Rothwell and Stock.[46] Such regulatory adipose tissue should be regarded as protective adipose tissue but its significance in adult humans is uncertain.

Immune function

Pond has proposed a role for adipose tissue in the function of the immune system, noting that many features of mammalian adipose tissue cannot be explained as adaptations to energy storage, thermal insulation or protection.[47] Adipose tissue and the cellular immune systems are partitioned into numerous small entities with major differences in the capacities for interaction. Pond concludes that immediate, controllable access to lipolytic products of appropriate composition is probably much more important for local interaction with lymphoid cells in nodes than access to large quantities of lipids. Investigation of these small local deposits may prove a more fruitful approach.

On the other hand, Stallone[48] reviewed the meagre evidence relating immune function to fatness and concluded that obesity is associated with impairments in host defence mechanisms and that certain types of weight reduction strategies produce further alterations in immune responsiveness. He too concluded that more work was needed.

Fat and physical performance

There is a widespread impression that body fat is always detrimental to physical performance. There is a strong negative relationship between body fat and performance in most activities, such as running, gymnastics, figure skating and ballet, but this is not so in long distance swimming. Also, it has been known since the 1930s that high fat diets impair endurance performance.[49] However, the fat in adipose tissue, and the smaller amounts but equally important intra-muscular fat, play important roles in the metabolism of exercise, a role that may be blocked by inappropriate carbohydrate consumption with a consequent impairment of work capacity.

The factor limiting work capacity in hard work, at 75% VO_2 max, or 40–60 kJ/min, is muscle glycogen stores. Greater utilisation of fat conserves the muscle glycogen and prolongs work time. It is in this way, that caffeine may have ergogenic effects in high intensity endurance exercise. Most of the energy for low intensity fasting exercise such as walking is derived from plasma fatty acids from body fat, the concentration of which increases as exercise proceeds.[50] However, fat uptake by muscle is rate limited by lipoprotein lipase and as exercise intensity increases up to 65% of maximal oxygen uptake, intra-muscular fat stores make an important contribution. At 85% of maximal oxygen uptake and above, muscle glycogen and plasma glucose are the dominant substrates. Trained individuals have lower exercise respiratory exchange ratios (RER) indicating increased fat uptakes and greater fat use, particularly intramuscular fat, thus sparing muscle glycogen.[51] Fat in the metabolic mixture, particularly in hard work, is beneficial.

There are reports that women, with their greater adipose tissue masses, have lower RERs in exercise than men[52] and in this respect they resemble trained individuals. However, because of the great heterogeneity of protocols adopted and subjects investigated there is still some doubt about sex differences in substrate utilisation during exercise.[53] Costill *et al*[54] found similar RERs in endurance runners of both sexes at 70% VO_2 max after 60 min exercise. Thus, the differences between sexes diminishes as the level of cardiorespiratory fitness is increased to that of highly trained individuals.[53]

In the context of a discussion of beneficial effects of fat, the question arises whether the sex differences in responses to exercise are related to fat content? The increased utilisation of fat in women compared with men exercising at 60–75% VO_2 max, was found not to be proportional to fat weight, suggesting it is not a direct effect.[55]

Women are reported to have more Type 1 muscle fibres than men.[41] Their fibre diameters are smaller, particularly those of fast twitch fibres, giving rise to larger Type 1 fractional volume. This could contribute to a higher potential for oxidative metabolism per unit muscle in women. In addition, a sex difference in the adrenergic regulation of lipid mobilisation has been described.[56] In men, both beta and alpha adrenergic receptors in adipose tissue are activated. In women, only beta receptors are activated.

Bone health

Hip fractures are a major public health problem in many parts of the world, involving high rates of hospital bed occupancy and reduced quality of life for the sufferers. Fracture risk depends on attributes of bone, such as bone mineral density, the trabecular (inner lacey bone) integrity and microfracture healing, and the propensity to falls.

It is well established that bone mass is positively associated with body weight. There has been debate as to whether the effects were due to adipose tissue or lean tissue or both. A recent international multicentre study of the influence of adipose and lean mass on bone mineral content has provided evidence for differences in their relative influences at the major fracture sites.[57] One thousand and six hundred early postmenopausal women less than 130% ideal weight from four areas in US and Europe were recruited using population based strategies. The bone sites investigated included the hip, the femoral neck, the trochanter, spine and radius. Bone mineral content (BMC) was measured by Hologic DEXA. The results were expressed as percent differences over the interquartile ranges of weight, lean and adipose tissue, determined by regression analysis controlling for several interfering variables.

Body weight had strong associations at all skeletal sites examined with BMC differences of 4–6% per interquartile range. These seem small but they are clinically significant. For longitudinal studies, 5% differences in BMC have been shown to correspond to 17–24% changed fracture risk. In clinical trials, the differential risk is double. The associations of BMC with the fat and lean components were more variable, lean 2–7%, fat 4–6% but low fat mass or low lean mass could both adversely affect the major fracture sites. The bones with the greatest differences in fracture rates according to fat mass were the most highly trabecular sites. The associations were similar in direction and comparable in magnitude at each geographic location.

The mechanisms whereby fat and lean masses influence bone mineral content may involve both hormonal effects and physical loading. Conversion of adrenal androgen to oestrogen occurs in adipose tissue, androgen conversion being the most important source of endogenous oestrogen in post menopausal women. Low fat masses could therefore result in low bone masses. The spine and distal radius are two of the sites most affected, suggesting a whole body effect. Lean mass makes up most of the body weight and it may influence bone by a loading effect and by the mechanical stresses of activity and muscle tension. The hip and neck and shaft of femur were most influenced by lean mass, suggesting independent regional effects.

The results of Hla *et al*[57] agree with those of Compston *et al*,[58] Sowers *et al*[59] and Edelstein and Barrett-Connor.[60] Reid *et al*[61] thought fat mass more important than lean and neither oestrone production or physical loading could explain the effect while Sowers *et al*[59] concluded that higher fat mass is only protective with higher lean mass.

The down-side of higher fat and lean masses is that higher body weights will result in increased forces across the joints which, with systemic factors, may predispose to osteo-arthritis. There is a 4–5 fold increase in risk of osteo-arthritis with $BMI > 30$ compared to < 25.[62] The effect may be less at the hip than the knee because the forces generated by excess weight there are lower. However, obesity is also related to osteo-arthritis in non-weight bearing joints, such as the hand.

The protective effects of fat has been considered in terms of functional protection but adipose tissue can have a strictly mechanical protecting effect too. Thick layers of subcutaneous adipose tissue afford protection to the limbs and internal organs from falls, blows and other physical trauma. Adipose tissue deposits within the orbits of the eye and on the palms and soles also appear to have important protective functions as they are much less affected by starvation than other sites.

The risk of hip fracture from a fall is known to be lower with higher BMI. Lauritzen[63] in his review of the pathogenic mechanisms leading to hip fracture identifies the soft tissue covering the hip as an important determinant of hip fracture. Women with hip fractures have a lower body weight compared with controls, and they may also have less soft tissue covering the hip, even when adjusted for BMI, indicating a more android body habitus. Experimental studies show that the passive energy absorption in soft tissue covering the hip may influence the risk of hip fracture and be an important determinant of hip fracture perhaps even more important than bone strength. Lauritzen developed and tested external hip protectors in an open randomised nursing home study. The rate of hip fracture was reduced by 50%, corresponding to 9 out of 247 residents saved from sustaining a hip fracture, a valuable outcome.

A human biologist's end note

Obesity is an extensive and increasing problem in most parts of the world. The human body is a machine of extraordinary design but why are there so many flaws in design that lead to disease? Why has natural selection not selected for genes that, for instance, control energy intake and/or expenditure better? One obvious answer could be that a limit to fat stores has never had an advantage in reproductive fitness in the past. But the body is best seen as a series of compromises. Most medical research seeks proximate explanations to problems, the 'what' and 'how'. Evolutionary explanations, the 'why' have been neglected, perhaps because of the dangers of teleology, ascribing purpose to natural phenomena. The approach of Darwinian medicine is going some way to offering explanations in terms of unrecognised benefits to such apparently disadvantageous responses as fever and pregnancy sickness.[64] Equally, however, natural selection does not create every adaptation that would be valuable, for example monkeys with prehensile tails evolved in South America but not Africa. From the evidence presented, in biological terms, in a variety of conditions, much of the body fat of humans can be considered to be beneficial fat.

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