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BODY COMPOSITION

The assessment of nutritional status involves an understanding of the energy stores of the body. In developing countries, lack of food supply leads to wasting, whilst in developed countries obesity and cardiovascular disease are also important causes of illness. The prevention and management of these disorders requires techniques for measuring the extent of these changes in individuals and populations.

Elemental Composition of the Human Body

The human body is composed of many different elements. The International Commission on Radiation Protection (1975) compiled a list of the multitude of elements found in the body of the adult male. These data were based on the chemical analysis of human organs by several investigators, and represents the best estimate of total body content based on a wide review of the literature. Thirty-six elements have been listed as being present in the human body. Approximately eighteen to twenty of these elements have been shown to have a physiological function. Many factors will determine the amounts of a particular element in the body. Not only the health of the individual at the time of death, but also environmental exposure to an element, will contribute to individual differences. For example, exposure to compounds containing lead or mercury, or exposure to radiation fall-out leading to accumulation of caesium and strontium. Gender, age and size are also important determinants of the amount of differential elements in the body. Major element content is better correlated with lean weight than with total bodyweight, since adipose tissue is largely composed of neutral fat. Major element variation is relatively small for individuals of a given body size.

Models of Body Composition

Investigation into body composition began in the nineteenth century. Chemical analyses of fetus and adult cadavers were followed by the development of concepts of different functioning body compartments. In 1906, Adolf Magnus-Levy coined the term 'fat-free' mass (see Forbes, 1987). This was further refined in 1937, by Hastings and Eichelberger (see Forbes, 1987) who recognized that neutral fat does not bind water, nitrogen or electrolytes. It is now accepted practice in various body composition models to express body analyses in fat-free and fat mass terms. Several such models have been developed in order to better define and measure the different compartments that make up total body mass or weight.

The *two-compartment model* of body composition defines a lean compartment consisting of body cells and their surrounding extracellular water, plus the skeleton and connective tissue. Of course, the lean mass contains some lipid in the form of cell membranes, and is thus not truly fat-free. *See* ¡1002¡, ¡1003¡, ¡1038¡, ¡1280¡, ¡1341¡

In the healthy individual, the lean mass has a relatively constant composition, with a water content of 72–74%, an average density of 1·1 g cm^{-3} at 37°C, a potassium content of 60–70 mmol kg^{-1} in men and 50–60 mmol kg^{-1} in women, and a protein content of 20%.

The fat compartment varies considerably in healthy individuals, but it has a relatively constant density of 0·9 g cm^{-3} at 37°C, and a very small water and potassium content.

The *four-compartment model* which has been developed as techniques have become more sophisticated, involves measuring subcategories of the fat-free mass, i.e. protein content, skeletal mass and total body water, as well as the fat mass.

Glycogen stores and micronutrients (1–2% of bodyweight) are not included in this body composition model and need to be assessed separately where feasible.

Gender and Age Differences in Body Composition

Fetal growth rate reaches a maximum during the latter stages of pregnancy. Much of this growth is due to an increase in fat-free weight, consisting of water and protein as components of cell growth. Skeletal muscle contains about the same proportion of total body nitrogen, potassium and water in the newborn.

Growth velocity falls during infancy and childhood, reaching a nadir at about four years of age. A slow increase follows, culminating in the adolescent growth spurt. During this time there are differential rates of growth of different organs.

There is a small sex difference in lean body mass (LBM) throughout infancy and childhood, but in the adolescent period the rate of increase in growth to adult levels of the LBM in males is approximately twice as much as in females. The male adolescent increase in LBM is also of longer duration. This is a function of

hormonal action which continues to be an important determinant of body composition throughout life, together with genetic, nutritional and activity influences.

Adult men have a greater LBM and less body fat then adult women. Women have approximately two thirds the LBM of their male counterparts. whilst also having a greater relative fat mass. In young adults, the gender difference in LBM is greater then the difference in stature and in bodyweight.

There is much less variability between LBM values in individuals matched for age and height, compared with the variability in body fat.

The skeletal mass continues to grow until the late third decade. In women, there is an oestrogen-withdrawal-related decline in bone density over the period of the menopause. *See* ¡1303¡

In old age, there is a decline in LBM, with a shift in body water towards the extracellular phase. Bone mass declines further in both sexes. Body fat content shows more variability than LBM, but generally increases with age, and accounts for most of the variance in weight.

Methods of Measuring Body Composition (see Table 1)

Fat Compartment

Methods of measuring body composition in the fat compartment include anthropometry, bioelectrical impedance, heavy water (D_2O) dilution, and whole-body densitometry.

Anthropometry

Anthropometric techniques are readily portable and inexpensive. The equipment required includes a tape measure, height stick, scales and skin-fold callipers. Various formulae have been developed which allow the rapid calculation of different aspects of body composition, including percentage fat derived from triceps skin fold (Table 2), and the following anthropometric equations:

1. Body mass index (BMI) or Quetelet's index can be readily calculated from height and weight data: BMI = (weight in kg)/(height in m)^2.
2. Arm muscle circumference = mid-upper-arm circumference − ($\pi \times$ triceps skin fold).
3. Waist:hip ratio = (waist circumference)/(hip circumference).

Body mass index has a good correlation with body fatness, as measured by other techniques, and correlates well with morbidity and mortality in the obese individual.

Table 1. Summary of body composition measurement techniques

Model	Technique
Two-compartment[a]	
Fat mass	Anthropometry
Lean mass	Impedance
Four-compartment[b]	
Fat mass	Underwater weighing
	DEXA
	CT scan, MRI
Body water	
Intracellular	TBW (IC water)
Extracellular	TBK
Total	Heavy water (D_2O)
Body protein	IVNAA nitrogen
Skeletal mass	DEXA

[a] The two-compartment techniques are portable and simple.
[b] The four-compartment techniques are laboratory-based and more invasive.
DEXA, dual-energy X ray absorptiometry; CT, computerized tomography; MRI, magnetic resonance imaging; TBW, total body water; IC, intracellular; TBK, total body potassium; D_2O, deuterium oxide; IVNAA, *in vivo* neutron activation analysis.

Trunk circumferences define fat distribution. A waist:hip ratio >0·95 (males) and >0·85 (females) is consistent with abdominal obesity. As definitions of 'waist' and 'hip' have varied in the literature, it is important to have consistency in measurements in order to compare sets of data. The original Swedish observations of the risks and metabolic complications associated with abdominal obesity are reproducible whether the waist is taken as the smallest circumference or at the level of the umbilicus.

Skin fold thicknesses have been used to measure body fat. This method assumes that subcutaneous fat measurements represent total body fat. Various sites can be assessed and equations applied to derive body density and hence subcutaneous fat mass. Durnin and Womersley (1974) developed the regression equation using four skin folds (biceps, triceps, subscapular and suprailiac), gender and age. Equations have been developed using multiple or single skin fold sites.

Precision of skin fold measurement depends on the skill of the operator as well as the character of the subcutaneous fat. In general, the error is 5%, although this can be higher in the very obese individual.

Arm Muscle Circumference Measurement of the mid-arm circumference has been used to approximate total body protein stores. The triceps skin fold has been used as a measure of total body subcutaneous fat (Table 3).

The arm muscle circumference (or 'arm muscle and bone circumference') can be derived from the arm

Table 2. Percentage fat derived from triceps skin fold

Triceps skin fold (mm)	Relative fat mass (%)									
	Males (years)					Females (years)				
	17–19	20–29	30–39	40–49	50+	17–19	20–29	30–39	40–49	50+
5	8·0	10·0	18·0	16·5	18·5	12·5	9·5	13·0	15·5	16·0
7	11·5	13·5	20·0	20·0	23·0	16·5	14·0	17·0	20·0	20·5
9	14·5	16·0	22·0	23·0	26·0	19·5	18·0	20·5	23·0	24·5
11	17·0	18·0	23·5	25·5	29·0	22·0	21·0	23·0	26·0	27·5
13	19·0	19·5	24·5	27·7	31·0	24·5	23·5	25·5	28·0	30·0
15	20·5	21·0	25·5	29·5	33·0	26·0	25·5	27·5	30·0	32·5
17	22·0	22·5	26·5	31·0	35·0	28·0	27·5	29·0	32·0	34·0
19	23·5	23·5	27·0	32·5	36·0	29·0	29·5	30·5	33·5	36·0
21	25·0	24·5	28·0	33·5	37·5	30·5	31·0	32·0	35·0	37·5
23	26·0	25·5	28·5	35·0	39·0	31·5	32·5	33·5	36·0	39·0
25	27·0	26·5	29·0	36·0	40·0	33·0	33·5	34·5	37·5	40·5
27	28·0	27·0	30·0	37·0	41·0	34·0	35·0	35·5	38·5	41·5
29	29·0	28·0	30·5	38·0	42·0	35·0	36·0	36·5	39·5	43·0
31	30·0	29·0	31·0	38·5	43·0	35·5	37·0	37·5	40·5	44·0
33	30·5	29·5	31·0	39·5	44·0	36·5	38·0	38·5	41·5	45·0
35	31·0	30·0	32·0	40·0	45·0	37·5	39·0	39·5	42·5	46·0
37	32·0	30·5	32·0	41·0	45·5	38·0	40·0	40·0	43·0	47·0
39	32·5	31·0	32·5	41·5	46·5	38·5	41·0	41·0	44·0	47·0
40	33·0	31·5	33·0	42·0	47·0	39·0	41·5	41·0	44·5	48·0

Sources: Durnin and Wommersley (1974); unpublished data from the Body Composition Laboratory, Monash Medical Centre, Melbourne, Australia.

circumference and the triceps skin fold, and it gives a good indication of protein stores. This correlation holds true particularly in under-developed countries, where populations tend to have little subcutaneous fat, and it can be a useful tool in diagnosis and monitoring of progress in the management of protein–energy malnutrition.

Bioelectrical Impedance

Application of a constant, low-level alternating current to the body, can be used principally to determine total body water (TBW) and, by regression analysis from other techniques, to determine fat mass and fat-free mass. Both resistance and reactance are measured.

Water and electrolyte distribution determine electrical conductance in the living organism. Virtually all the water and electrolytes in the body are found within the fat-free (lean) mass which represents a low-resistance pathway. Fat and bone are poor conductors. Reactance is the opposition to the flow of electrical current caused by capacitance. The cell membrane, by maintaining an osmotic gradient between extra- and intracellular compartments, serves as a capacitor. Reactance is a measure of the quantity of cell membrane capacitance and may give an indication of the quantity of the intracellular cell mass. Whereas fat and water offer resistance to an electric current, only cell membranes have reactance.

The measurement of total body impedance (resistance and reactance) is a vector sum of resistance and reactance in the limbs and torso, with the limbs making the major contribution.

Use of this method has been validated in healthy populations as a determinant of TBW and deduced lean and fat mass. In disease states such as renal failure and dehydration, metabolic function may alter the compartmentation of TBW and bioelectrical impedance may be less useful and less reproducible, with the literature reporting conflicting results.

Heavy Water (D_2O) Dilution

Water is not present in stored triglyceride and occupies a relatively fixed fraction of the fat-free mass. Estimation of TBW can therefore be used as an index of body composition. Several isotopes have been used, but deuterium oxide (D_2O, the naturally occurring nonradioactive isotope of water, containing hydrogen protons with two neurons – heavy water – and present as 0·01% of naturally occurring water) is now beginning to be seen as the 'gold standard' for measurement of TBW.

The technique involves the administration of known quantity D_2O, an equilibrium period, and a sampling

period. It assumes that the D_2O has the same distribution volume as water and is exchanged by the body in a manner similar to water.

Sampling can be from either serum or saliva and whilst the analytical equipment is only suited to a laboratory, it enables collection of specimens in the field for later analysis.

A variety of analytical techniques have been used to measure D_2O, including mass spectrometry and Fourrier Transform infrared spectroscopy.

Whole-body densitometry

Whole-body densitometry is the 'gold standard' for the measuremenb of *body fat*. The technique assumes that the body is composed of two distinct compartments (fat and fat-free, each of a known or assumed density) and that the relative amount of each can be determined by measurement of the whole-body density.

Underwater weighing is the most widely used technique, based on Archimedes' principle which states that the volume of an object submerged in water is equal to the volume of water that the object displaced. The difference between the mass in air of the object and the mass in water of the object is corrected for the density of the water corresponding to the water temperature at the time of weighing, to derive the apparent body volume.

Body fat mass can then be calculated using one of the empirical equations describing the relationship between fat content and body density.

Valuable body composition data can be obtained using underwater weighing, although there are several inherent disadvantages. Subjects must be accustomed to swimming and submersion in water and must be medically fit enough to endure such procedures. These caveats to its use exclude use of this technique in many hospitalized patients. The apparatus required is substantial in size, and thus only suited for use in large institutions. In addition, variation in bone density owing to ethnicity, gender or ageing is not taken into account in the constant used for non-fat density.

Fat-Free Compartment

Methods of measuring body composition in the fat-free compartment include in vivo neutron activation analysis, total Body Potassium, and dual-energy X ray absorptiometry.

In Vivo *Neutron Activation Analysis*

In vivo neutron activation analysis (IVNAA) provides the only *in vivo* technique currently available to determine multielemental composition. Calcium, phosphorus, sodium and chloride content have been measured, but in current clinical practice only nitrogen is measured (from which total body protein is calculated).

Neutron activation involves delivery of a beam of neutrons to the subject. These neutrons are captured by the target atoms in the body, creating unstable istopes; in the case of protein, the isotope formed is nitrogen-15. The isotope reverts to a stable state by the emission of γ-rays of a characteristic energy, which can then be detected by the use of standard γ-spectrographic analysis. This method, targeting nitrogen, allows (1) the determination of total body nitrogen and, therefore, total body protein, which is the principal nitrogen-containing component of the body, and (2) the indirect determination of skeletal muscle mass, using the mathematical model derived by Burkinshaw *et al.* (1978).

Whilst IVNAA is a very useful tool for measurements of body composition, its development in only a few centres has limited the wider application of this methodology. In addition, concern has been expressed over the large expense of this technique. The American literature quotes costs as high as $400 000. Other units have been able to develop this methodology for less than $50 000.

Total Body Potassium

The naturally occurring radioactive isotope of potassium, ^{40}K, is present in a known, constant, very low percentage of total potassium. Since body potassium is essentially intracellular, and not present in stored fat, measurement of ^{40}K not only provides an estimate of total body potassium, but also allows estimation of body cell mass. If total body water is known (from deuterium dilution), extracellular water can be calculated.

The technique requires a highly shielded environment in which to detect the ^{40}K in the body, as ^{40}K also occurs in most environmental structures. In addition, the requirement for appropriate γ-ray detectors and corrections for factors such as body geometry make the technique expensive.

Dual-Energy X Ray Absorptiometry

Dual-energy X ray absorptiometry (DEXA) is a recent addition to the body composition analysis field. It was originally developed to measure regional and total body bone mineral content, but it is also capable of measuring fat mass. It is more sensitive than dual-photon absorptiometry, which it has now replaced, and exposes the subject to substantially lower radiation doses than total body calcium measured by neutron activation analysis.

The DEXA technique exposes the subject to low-energy X irradiation at two different energies. As there is differential absorption by tissues of different densities (bone, lean and fat tissues), values for bone mineral in the hip, spine, whole body or specialized regions, as well as values for fat or soft tissues, can be derived.

Table 3. Error of the methods

Method	Coefficient of variation (%)
Anthropometry	
Weight	< 1[a]
Height	< 1[a]
Skin folds	3–5[b]
Circumferences	~2[a]
Bioelectrical impedance	1–2[c]
Dual-energy X ray absorptiometry	
Bone density	1–2[d]
Fat, lean	3–4[e]
Deuterium dilution	1–2[a]
In vivo neutron activation analysis	
Total body protein	4[a]

[a] Unpublished data from the Body Composition Laboratory, Monash Medical Centre, Melbourne, Australia.
[b] Loman (1981).
[c] Lukaski *et al.* (1985).
[d] Mazess *et al.* (1989).
[e] Mazess *et al.* (1990).

It is a sensitive technique for determining bone mineral content and densities, and has become the 'gold standard' for clinical and research work in osteoporosis.

A recent development in measurement of regional bone mineral density is the use of ultrasound for measuring os calcis bone density. This technique appears to be promising for use in assessing foot stress fractures in subjects involved in extensive physical training.

Other Techniques

Other techniques for measuring body composition include computerized tomography (CT) scanning and magnetic resonance imaging (MRI). These techniques have been used for accurate measurement of various body compartments. Whilst their clinical and research use is limited by expense, availability and patient exposure to ionizing radiation, much helpful information has been obtained from the research groups who have utilized such technology.

Error of the Methods

Each of the methods for measuring body composition has intrinsic and biological errors. In general, these are very comparable to the errors of biochemical methods commonly performed in hospital laboratories (Table 3).

Effect of Disease Processes on Human Body Composition

Obesity

The fat compartment – expressed as mass or percentage fat – has importance as an expression of adiposity. The association between increased adiposity and morbidity is well documented. The incidence of diabetes, hypertension, ischaemic heart disease and gall bladder disease is increased at higher levels of adiposity. ***See*** ¡1294¡, ¡1295¡

Fat distribution is being increasingly recognized as a clinically relevant risk factor. Abdominal obesity, expressed as the waist:hip ratio, has been shown, independent of other factors, to represent an increased risk for morbidity and mortality. First described in the 1950s (Vague, 1956), this association has been verified and strengthened by intense research interest in the last decade. The correlation is not just an epidemiological one: many metabolic abnormalities, such as insulin resistance, are associated with this condition.

With increasing adiposity, it is usual to find an increase in lean mass. This occurs because of the increased skeletal muscle mass required to carry the increased fat mass.

In obese people who have undergone repeated near-starvation dieting, there may be marked wasting of skeletal muscle, even in the presence of adiposity. Similarly, muscle wasting, or even marasmus, can occur in the obese person who has concomitant severe illness. For example, a chronic alcoholic with a poor quality of food intake, and liver impairment may be osese (excess fat stores) and also have skeletal muscle wasting.

Undernutrition

In global terms, undernutrition remains one of the greatest determinants of health status. The most common expressions of undernutrition are commonly known as kwashiorkor and marasmus. Intermediate forms are commonly seen. In marasmus, there is a wasting of total body protein without expansion of the TBW compartment. In kwashiorkor, there is an expansion of the extracellular component of TBW, giving rise to peripheral oedema and ascites. Exactly why undernutrition results in these two different forms remains unclear. ***See*** ¡1237¡, ¡1256¡, ¡1259¡

Both forms are associated with a reduction in the capacity of the cell-mediated immune system of the body, giving rise to an increased risk of infection. Where food intake is reduced, it is likely that other nutrient deficiencies, such as iron, folate or vitamin A deficiency, will be present and may mask the extent of the underlying body composition changes.

In developing countries, these forms of undernutrition usually arise from the combination of inadequate food resources and chronic infection. In malnutrition

caused by inadequate food intake, many studies have shown an increase in the ratio of extracellular fluid (ECF) volume to TBW. Electrolyte abnormalities are common. Reduced levels of sodium, potassium and magnesium may be found. Protein stores, as measured by IVNAA and expressed as nitrogen index, are reduced.

In developed countries, these conditions are frequently seen in conjunction with malignancy, psychiatric conditions, organ failure and conditions in which self-feeding is difficult, e.g. stroke or arthritis. *See* ¡1257¡

The wasting seen in many malignancies, even when nutritional intake and absorption is apparently adequate, may be caused by cytokines such as cachectin and tumour necrosis factor.

Visceral size may be better preserved in cancer patients, suggesting that loss of muscle accounts for the major proportion of weight loss. This may be the result of a difference in metabolic rate between malignancy and anorexia; the rate is often increased in patients with malignancy, but reduced in anorexia nervosa. *See* ¡1019¡

In anorexia nervosa, many of the body composition changes seen are similar to those found in starved subjects. Total body nitrogen, total body potassium and blood volume are all reduced. Unlike primary starvation, ECF may be reduced by relatively greater amounts than the reduction in TBW owing to induced vomiting or purging. Interestingly, many patients with anorexia nervosa maintain normal levels of haemoglobin and serum albumin and rarely exhibit vitamin deficiencies or develop oedema.

Summary

An understanding of body composition and its measurement provides the clinician with further scientific data on which to base a nutritional assessment. Advances in this area are now available to provide accurate measurements which previously could only be estimated. Some of these techniques are easily applicable to office general practice or field studies, whilst others require more sophisticated equipment only available in specialized centres.

Body composition changes in health and disease help to explain the pathogenesis of illnesses which involve alteration in food intake or absorption and metabolic handling of macronutrients.

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