Module 3.2

Body Composition

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Learning Objectives:

- To learn how appropriate body composition is essential for optimal health;
- To learn the importance of the components of body composition;
- To learn what influences body composition;
- To learn how body composition can be measured and to learn how reliable these measurements are.

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Key messages:

- The integrity of body cell mass (BCM) crucially determines health, including muscle function and immune response;
- Inflammatory activity and lack of nutritional intake decrease BCM;
- Fat mass (FM) and fat-free mass (FFM) can be measured relatively easily;
- In a healthy state, FFM is related to BCM;
- In starvation and stress/starvation the ratio of body cell mass to extracellular mass (BCM/ECM) decreases, which makes FFM a less reliable indicator of nutritional status;
- In vivo body composition measurements are always indirect, based on one or more assumptions concerning the nature of the body components FM and FFM;
- Some methods are doubly indirect (validated against indirect methods) and therefore based on more assumptions;
- Apart from the BIVA approach, the basis for all methods of body composition analysis is the measurement of body weight using a calibrated scale.

1. Why is body composition important?

Body composition describes the body compartments such as fat mass (FM), fat-free mass (FFM), muscle mass or bone mineral mass in percentage terms depending on the body composition model used (see **Fig. 3**).

It has long been acknowledged that body composition is linked to health. An increase in FM is associated with various metabolic consequences such as insulin resistance, metabolic syndrome and with cardiovascular disease, as well as with certain tumour types. Moreover, fat distribution, and visceral fat in particular, are the most important risk factors for cardiovascular disease-related mortality.

A decrease in muscle mass on the other hand, as seen in age-associated sarcopenia or in physical inactivity, is related to reduced functional capacity, loss of autonomy and is considered a risk factor for falls and related fractures. Furthermore, reduced muscle mass has metabolic implications, as lower muscle mass relative to body size correlates with decreased insulin sensitivity even in healthy subjects without diabetes or sarcopenia.

Prolonged reduced nutritional intake invariably leads to tissue loss. In the healthy fasting state, the body can limit net protein catabolism, so the greatest loss is of fat, although all tissues, except the central nervous system, diminish in size. Therefore, the ability to generate a host response to trauma/stress is relatively well preserved during the first phases of weight loss, but when weight loss becomes severe (more than 15%) the host response becomes weaker and of shorter duration.

In disease, body composition can be altered via a range of mechanisms. Certain rare endocrine disorders, such as Cushing's Syndrome or acromegaly, are correlated with distinct changes in body composition. But more importantly, any severe acute or chronic disease can impair body composition due to catabolic effects, and this is associated with deleterious effects on outcomes (1). It is well known, for example, that chronic inflammatory activity leads to tissue loss which is reflected in decreased body cell mass.

Changes in body composition may occur independently from changes in weight or body mass index (BMI) which makes it clear that weight or BMI alone are not reliable markers of body composition. While short-term changes in weight usually reflect changes in fluid compartments, long-term changes also reflect changes in tissue mass. However, they do not indicate which tissue is affected. Body composition analysis has therefore gained attention in disease prevention and health promotion, as well as in medical practice (2, 3). Lately, body composition has also increasingly been recognized to have an impact on treatment success. For example, low FFM has been found to be a predictor of chemotherapy-related side effects since it correlates closely with the distribution volume of hydrophilic chemotherapy agents (4).

2. Lipids, proteins, carbohydrates and their compartments

FM consists of 80% adipose tissue and 20% water. The amount of fat differs considerably due to varying degrees of obesity and may even become the largest compartment in the body in an obese patient. Apart from stored fat, lipids are essential components of membranes, hormones and the central nervous system. The FFM (i.e. the non-fat component of the body) constitutes the main structural (muscle and bone) and functional (visceral organ mass) component of the human body. The main element of FFM is water (72%) whereas protein constitutes approximately 21% and bone minerals 7% **(Table 1).** Proteins are a part of the structure of every cell in the body, but have numerous other functions as well, such as in storage or transport, as enzymes and hormones, and they play a crucial role in the immune system as immunoglobulins and antibodies. Carbohydrates are mainly stored in the body as glycogen in the liver and in muscle. Their amount depends largely on body size, previously ingested quantity of carbohydrates, as well as physical activity and muscle mass (athletes may store up to twice as much as the regular 500 g).

Table 1: Reference Man: Gross Organ Size* (g)

Weight	70,000	
Skeletal muscle	28,000	
Adipose tissue	15,000	(fat 12,000)
Skeleton	10,000	[cortical bone 4,000; tra- becular bone 1,000; mar- row 3,000; cartilage 1,100; periarticular tissue 900]
Skin	4,900	1000075
Liver	1,800	
Brain	1,400	
Heart	330	
Kidneys	310	

*From International Committee on Radiation Protection: Report of the Task Group on Reference Man for Purposes of Radiation Protection. Oxford, Pergamon Press, 1975.

Several models have been developed for body composition analysis, ranging from the twocompartment model, which only distinguishes between fat mass and fat-free mass, to the four-compartment model (FM, total body water (TBW), bone mineral mass, and protein), and other models describing body composition on an atomic, molecular or tissue level (see **Fig. 1)**.



Fig.1. The five levels of body composition

Wang et al Am J Clin Nutr. 1992 Jul;56(1) Abbrev. ECF and ECS: extracellular fluid and solid

In the two-compartment model, body weight can be considered to consist of FM and FFM. In the frequently used three-compartment model, FFM further consists of BCM and ECM. BCM is the living, actively metabolizing part of the organism, consisting mainly of muscle and organ mass and thus its size and integrity is crucial for health and the ability to cope

with noxious exogenous influences. In nutritional therapy, the goal should always be to maintain or increase BCM.

In a healthy state, the ratio between ECM and BCM is fairly fixed. Consequently, if FFM is measured (for instance by measuring TBW) BCM can be estimated.

Body composition changes markedly during development of the neonate and through to old age: while FM increases with age, muscle mass and TBW both decrease (Table 2).

	Male				Female					
Age	H ₂ O (%)	ECF/H ₂ O	K (meq/kg)	N (%)	Density (g/ml)	H2O (%)	ECF/H2O	K (meq/kg)	N (%)	Density (g/ml)
Fetus 24 week Fetus 32 week	89* 86*		40* 46*							
Birth	81	0.61	49	2.4	1.063	81	0.61	49	2.4	1.064
5 year	77	0.46	64	2.96	1.078	78	0.48	62	2.88	1.073
10 year	75	0.43	67	3.1	1.085	77	0.45	64	2.99	1.075
18.5 year	73.6	0.38		3.24	1.093					
Young adult	73		68.1		1.10	73		64.2		1.10
				K/N (meq/g)					K/N (meq/g)	
Young adult†		0.44 0.42‡		1.88			0.48		1.73	
Old adult†		0.50 0.48‡		1.78			0.52		1.65	

 Table 2. Composition of FFM in different age groups*

*Table adapted from Shils, Young, Modern Nutrition in Health and Disease, Lea & Febiger, Philadelphia. Data collected from Ziegler et al, Growth 1976 40: 329-341; Formon et al, Am J Clin Nutr 1982 35: 1169-1175; Haschke Acta Paed. Scand. (Suppl.) 1983 307: 1-23; Cohn et al, Am J Clin Nutr 1984 40: 255-259; Borkan et al, Hum. Biol. 1977 49: 495-514.

3. Changes in body composition in starvation and disease/starvation

In pure starvation, i.e. without the presence of further disease, the body limits protein catabolism, so FFM is relatively spared and losses of nitrogen may be as low as 5-8 g of nitrogen/24 h. This amounts to 120-200 g of wet muscle which yields 130-200 kcal. Energy is largely derived from adipose tissue which therefore shrinks at a rate of roughly 200 g of adipose tissue/24 h yielding 1400 kcal assuming that actual energy expenditure is approximately 1600 kcal. In starvation accompanied by inflammatory activity, however, nitrogen losses may increase to 15 or 20 g/24 h amounting to 360-480 g of wet muscle/24 h and yielding 400-500 kcal. The largest part of energy expenditure still has to be covered by lipids, leading to a similar loss of 200 g/24 h as during pure starvation, assuming that energy expenditure will be slightly raised to approximately 1800 kcal/24 h. Both in starvation and in starvation combined with inflammatory activity, glycogen will no longer contribute to cover energy needs after a few days. A small amount of new glucose will therefore be produced and (partially) oxidized contributing to a minor extent to energy production; this, however, is an energetically inefficient process.

In the catabolic state, the solid component of FFM will decrease as calculated, but due to compensatory fluid retention, FFM volume will not decrease proportionally (Fig. 2 and Fig. 3). ECM will increase disproportionally whereas BCM will diminish (Fig. 4), thus the ratio between these two compartments (ECM/BCM ratio) increases more severely than in pure starvation.

Therefore, FFM, calculated by measuring TBW will not adequately reflect BCM in disease related malnutrition. Consequently, the validity of FFM as an indicator of nutritional status decreases as severity of illness increases. On the other hand, the increasing ratio of ECM to BCM is a more sensitive marker of malnutrition.



Fig.2. Calculated tissue composition in weight loss and weight gain associated with partial starvation

Data from Keys and co-workers: A Keys et al The Biology of Human Starvation. Vol.1. Minneapolis, University of Minnesota Press, 1950: Chapter 20.



Fig.3. Body composition of adult male subjects with varying degrees of nutritional compromise

The height of each compartment is referred to the kilogram scale on the left. The numbers within the compartments are percent body weight. Thus, the muscle cell mass of the severely compromised group amounts to 10.2 kg (29.1 minus 19.0 kg) which is 23.8% of body weight. Body cell mass is presented both as the sum of visceral and muscle cell mass, as well as the sum of intercellular water and cell solids. M. Barac-Nieto et al, Am J Clin Nutr 1978 31: 23-40

4. How to measure body composition?

4.1. Simple methods

4.1.1. Anthropometry

Body weight is an important basic parameter, which is, unfortunately, still not routinely measured in clinical practice. It is important to measure weights on scales that have been thoroughly calibrated and to use the same scales over time as there is a large variability between different scales.

Body mass index (BMI) is expressed as body weight/height squared (kg/m2).

- 20-25 normal weight
 - > 30 < 40 obese

BMI

- > 40 morbid obesity
- < 18.5 underweight
- < 22 underweight in old age due to loss of height

Low as well as high BMI values are accompanied by increased morbidity and mortality. The BMI does not, however, reliably indicate the distribution between lean mass and adipose tissue as there is no linear relationship between BMI and body compartments. Individuals with low BMI may have an increased FFM; on the other hand, individuals with a high BMI may have a disproportionately low FFM (as in sarcopenic obesity) placing them at increased risk of not overcoming disease or trauma successfully.

Anthropometric measurements of circumferences or skin folds represent a simple, noninvasive and inexpensive way to assess nutritional status. Anthropometric measurements were originally developed for use in evaluating undernourished children in the field in the early 1960s, and were introduced into the hospital setting in the 1970s. While midarm circumference (MAC) has been shown to reflect muscle mass, triceps skin fold thickness (TSF) is considered to be an indicator of upper arm subcutaneous fat. Although the measurements appear relatively easy, considerable skill is required to obtain reliable results. The precision of body compartment prediction is, moreover, less than adequate. Also, the substantial coefficient of variation for individual measurements makes it unsuitable for monitoring changes over a short period of time.

4.1.2. Functional tests

Body composition is mainly measured to estimate the ability of the organism to react sufficiently to disease/trauma. In contrast, function is not routinely addressed as a component of nutritional assessment. Three types of function determine quality of life, in this case, the ability to generate an adequate defence against disease/trauma: muscle strength, immune function and cognitive function.

Direct electrical stimulation e.g. of the adductor pollicis muscle measures contraction, force and relaxation, allowing tracing of force frequency curves. While it is considered the superior procedure with regard to objectivity, it is invasive and not suitable for clinical routine.

Among the measurements of voluntary muscle strength (e.g. hand grip, knee extension or hip flexion strength and peak expiratory flow), hand grip strength by dynamometry is the most frequently used bedside method for clinical purposes. Impaired grip strength is a predictor of increased postoperative complications, increased length of hospitalization, higher re-hospitalisation rate and decreased physical status. Moreover, it is an excellent predictor of short and even long-term mortality (5). For the interpretation of single values, however, reference values must be consulted.

Immune function was measured in the 1980s by testing skin reactivity to an array of antigens. The results of this largely reflect severity of disease, and as such give a crude yes or no answer to the question as to whether immune function is compromised. It does not furnish a quantitative measure of immune function. Lymphocyte counts generally indicate the degree of illness but have also been suggested to reflect malnutrition (moderate between 900 and 1500 cells/mm³; severe below 900 cells/mm³).

Cognitive function tests exist for various populations (elderly, patients with liver disease), but are not routinely used in clinical practice. This may be subject to future studies.

4.1.3. Creatinine excretion rate

The urinary excretion of creatinine reflects muscle mass to some extent, being high in muscular weight lifters and low in depleted patients. The creatinine excretion over 24 hours is used to calculate a creatinine height index (CHI):

CHI (%) = measured 24 h urinary Creatinine x 100 ideal 24 h urinary creatinine for height*

* obtained from standard tables

A deficit of 5-15% may be classified as mild, 15-30% moderate and >30% as severe malnutrition.

One limitation that affects the validity of this method is the substantial intraindividual variability in daily urinary creatinine excretion (11-30%). The accuracy of the measurement can be increased if no meat is ingested, but this makes it unsuitable in clinical practice. Furthermore, the duration of the urine collection is crucial.

4.1.4. Nitrogen balance

Nitrogen balance is mainly a research tool since under clinical conditions nitrogen intake is nearly always overestimated and losses in urine, stools, skin, wounds etc. are underestimated. It suffers also from the difficulty from how to estimate the contribution of red cell, plasma or albumin infusion to nitrogen intake. Nitrogen should be measured using the Kjeldahl technique or the combustion technique for total nitrogen because extrapolation from 24 h urinary urea excretion may not be representative of nitrogen under normal circumstances, this fraction varies with malnutrition and illness. Nonetheless, large changes in urinary urea excretion may be a useful indication of changes in net protein catabolism and it is a simple method to use (e.g., in the intensive care unit), provided that urine collection is complete. Very low serum urea concentrations may be found in starvation with low protein turnover as well as in patients receiving liberal amounts of fluid leading to high urine production, and those with severe liver disease who are unable to synthesise it.

4.1.5. Bioelectrical impedance (vector) analysis (BIA and BIVA)

BIA is a simple, inexpensive and non-invasive method for estimating body composition suitable for routine bed-side measurement of body composition. It measures the opposition (=impedance) of body tissues to the flow of a small alternating current of 800 μ A. The current flows through all conducting material in the path between the source and the sensor electrode. While tissues containing large amounts of water and electrolytes are good conductors, FM, air and bone are poor conductive materials. Under stable conditions the conductivity of a body segment is directly proportional to the amount of electrolyterich fluids. At low frequencies the current flows through the extracellular space, providing

an estimate of extracellular water (ECW) but at higher frequencies, the current is able to penetrate cell membranes providing an estimate of TBW. BIA has good reliability and reproducibility which makes it a good tool for repeated measurements.

However, BIA is an indirect method and has to be validated against reference methods of assessing body composition. This implies that the equations developed to describe body composition are only valid for subjects who closely match the reference population used in the original derivation. Moreover, for the calculation of body composition, some assumptions are required: homogenous composition, fixed cross-sectional area and consistent distribution of current density, as well as constant hydration. In healthy subjects who have no fluid imbalance, no body shape abnormalities and who are within a certain BMI range (16-34 kg/m²), BIA offers reliable information on body composition, provided that suitable (i.e. age-, sex- and population-specific) equations for the calculation of body compartments are applied. However, these conditions are frequently violated in sick and hospitalized patients since disturbed hydration or altered distribution of extra- and intracellular water are often present, as for example in cirrhosis, renal failure, cardiac insufficiency and obesity. Various disease-specific equations with considerable variation in the estimated body compartments have accordingly been developed.

Compartment	Calculation
Total body water (TBW)	H ² /R50-100kHz
Extracellular water (ECW)	H²/R1-5kHz
Intracellular water (ICW)	TBW – ECW
Fat-free mass (FFM)	TBW/0.73
Fat mass	body weight - FFM
Body cell mass (BCM)	FFM x phase angle x k
Extracellular mass (ECM)	FFM - BCM

Table 3: Exemplary deduction of body compartments from impedance measurements. *

H: Height of the conductor = body height. R: Resistance. Xc: Reactance, 0.73 = hydration

In the last two decades, the use of raw impedance parameters rather than the results of the standard equations has increased in clinical practice. They provide information on hydration status, body cell mass and cell integrity without algorithm-inherent errors or requiring assumptions such as constant tissue hydration. Moreover, they have proven to be of high prognostic value (6).

Impedance is a function of two components: resistance (R) and reactance (Xc). Resistance is the pure opposition of a biological conductor to the flow of an alternating current through intra- and extracellular ionic solutions, whereas reactance is the resistive effect produced by the tissue interfaces, non-ionic tissues and cell membranes. The phase angle (a) reflects the contributions between resistance and reactance (arc tangent of the ratio of capacitance to resistance converted to degrees). The phase angle has been shown to be a superior predictor of impaired clinical outcome and mortality in a variety of benign and malignant diseases; however, the interpretation in clinical practice requires age-, sex-, and BMI-stratified reference values (7).

Another approach is the Bioelectrical Impedance Vector Analysis (BIVA) which uses the plot of resistance and reactance normalized over height as a bivariate vector in the RXc graph. The position and length of the vector provides information about hydration status as well as BCM and cell integrity (**see Fig. 4a**). The impedance parameters can be z-scored and compared to reference values (i.e. reference tolerance ellipses) allowing immediate assessment of the patient (**Fig. 4b**). Both malnutrition and obesity are clearly

reflected in the BIVA, making this approach an attractive bedside method for identifying and monitoring patients' nutritional status.



Fig.4a. Different positions of the vector in the RX Graph indicate different types of body composition

A horizontal migration of the vector due to low or high reactance indicates decrease or increase in dielectric mass (membranes and tissue interfaces) of soft tissues. The length of the vector indicates hydration status from fluid overload (decreased resistance, short vector) to exsiccosis (increased resistance, longer vector).





4.2. Sophisticated methods

4.2.1. Dual Energy X-ray Absorptiometry (DEXA)

DEXA is a sophisticated but indirect method which allows measurement of the volume of FM, FFM and bone mineral mass/density (i.e. the three compartment model). The method uses two levels of X-ray energy and separates the components based on different attenuation of the X-ray energy in a tissue-specific manner. DEXA is relatively inexpensive and is increasingly used in clinical research. However, it is associated with some radiation exposure which makes it unsuitable for repeated routine measurements of body composition in clinical practice.

4.2.2. Magnetic Resonance Imaging (MRI) and Computed Tomography (CT)

Body composition can also be assessed by using cross-sectional imaging techniques, such as MRI and CT. In contrast to CT and X-rays, MRI does not need ionizing radiation but uses magnetic field gradients and radio frequency fields to align the magnetization of specific atomic nuclei (mainly protons) in the body. This produces a rotating magnetic field which can be detected by a scanner. MRI and CT allow not only the quantification of FM and FFM, but also the assessment of the regional fat distribution and estimation of skeletal muscle. To date, they are the most precise methods for assessing body composition and are thus considered methods of choice for the calibration and validation of new methods or equations (8). Due, however, to the higher costs, availability, time and effort, as well as radiation in case of CT, they are mainly used in research.

4.2.3. Dilution methods

Tracer dilution methods are based on the principle that the volume of a compartment can be defined as the ratio of the dose of an administered tracer to its concentration in that body compartment within a defined time. The tracer is administered and allowed to distribute within the compartment over a certain amount of time. The tracer is then collected from body fluid and the dilution measured. The degree of dilution of the tracer administered is a measure of the size of the compartment of interest. For TBW a tracer dose of labeled water (usually deuterium) is given orally and two body fluid samples are collected: one predose sample to determine baseline levels and the second sample after an equilibration time of 2–3 h. Estimation of TBW by dilution methods is considered the gold standard. Bromide is used for ECW since it mainly distributes extracellularly. Once TBW and ECW are estimated, subtraction of ECW from TBW yields intracellular water (ICW). One should take into account that the sicker the patient is, the more bromide will appear intracellularly, making the method less reliable in disease.

4.2.4. Underwater Weighing (UWW) and Air Displacement Plethysmography (ADP)

Developed early, UWW is still often referred to as a gold standard for body composition measurements, although it is only a two-compartment model. It is based on the measurement of body density (densitometry). The participant is completely submerged in water and, with the subject's weight and the volume of displaced water, whole body density can be estimated. Since specific density of FM and FFM is known, their respective volumes can then be calculated. While constant density of FM can safely be assumed, FFM is a very heterogeneous compartment and some variation in density may occur in disease. Another limitation is the correction for residual lung volume, which - if approximated with equations - introduces an error of up to 4% in the FM volume. Due to its cumbersome nature, UWW is not suitable for patients. Lately, ADP has started to replace UWW. Here, the subject is not immersed in water but in a closed air-filled chamber and the change in

volume can be measured in a second reference chamber. ADP uses the inverse relationship between pressure and volume to derive body volume for a subject. This procedure is more suitable for patients but the same limitations as for UWW otherwise apply.

4.2.5. Total body Potassium

Total body potassium counting captures gamma rays from the naturally occurring potassium isotope (40 K). The technique adequately reflects the metabolically active cell mass, provided the intracellular concentration of potassium is constant. This might not be the case in disease and generally the sicker a patient is, the lower intracellular K⁺ will be.

4.2.6. In vivo Neutron Activation Analysis (IVNAA)

This technique allows estimation of whole body Na, Cl, N, Ca, and P. It is considered the gold standard for whole body protein (via estimation of N). However, this technique requires sophisticated equipment, is very expensive and will thus remain reserved for research purposes.

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