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Session 1: Nutritional assessment**

**New techniques in nutritional assessment: body composition methods**

M. Elia<sup>1</sup>\* and L. C. Ward<sup>2</sup>

<sup>1</sup>*Dunn Clinical Nutrition Centre, Hills Road, Cambridge CB2 2DH, UK*

<sup>2</sup>*Department of Biochemistry, University of Queensland, Brisbane, Queensland 4072, Australia*

New techniques in air-displacement plethysmography seem to have overcome many of the previous problems of poor reproducibility and validity. These have made body-density measurements available to a larger range of individuals, including children, elderly and sick patients who often have difficulties in being submerged underwater in hydrodensitometry systems. The BOD POD air-displacement system (BOD POD body composition system; Life Measurement Instruments, Concord, CA, USA) is more precise than hydrodensitometry, is simple and rapid to operate (approximately 1 min measurements) and the results agree closely with those of hydrodensitometry (e.g.  $\pm 3.4\%$  for estimation of body fat). Body line scanners employing the principles of three-dimensional photography are potentially able to measure the surface area and volume of the body and its segments even more rapidly (approximately 10 s), but the validity of the measurements needs to be established. Advances in i.r. spectroscopy and mathematical modelling for calculating the area under the curve have improved precision for measuring enrichment of  $^2\text{H}_2\text{O}$  in studies of water dilution (CV 0.1–0.9% within the range of 400–1000  $\mu\text{l/l}$ ) in saliva, plasma and urine. The technique is rapid and compares closely with mass spectrometry (bias 1 (SD 2) %). Advances in bedside bioelectrical-impedance techniques are making possible potential measurements of skinfold thicknesses and limb muscle mass electronically. Preliminary results suggest that the electronic method is more reproducible (intra- and inter-individual reproducibility for measuring skinfold thicknesses) and associated with less bias (+12%), than anthropometry (+40%). In addition to these selected examples, the 'mobility' or transfer of reference methods between centres has made the distinction between reference and bedside or field techniques less distinct than in the past.

**Body-composition techniques: Air-displacement plethysmography: Body-volume techniques: Bioelectrical-impedance techniques: Body-water measurement**

Assessment of body composition is an important aspect of public health and clinical nutrition, but the methods used depend on whether the aim is to screen for the presence of under- or overnutrition, or to establish accurate measurements of body constituents (fat, protein, mineral, water and mass of specific tissues such as muscle), as in detailed metabolic studies of protein–energy metabolism. Although reference methods are not used routinely in clinical practice,

they have two particular functions. First, they can be used to calibrate simpler instruments that can be readily used by the bedside and in the field. Second, they may be used to assess the effects of specific therapeutic regimens on body structure and lead to general recommendations about specific regimens (Hill, 1992). Thus, some selected advances in reference body composition techniques relevant to clinical nutrition are discussed first.

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\*Corresponding author: Dr M. Elia, fax +44 (0) 1223 413763.

## Reference methods

### Assessing body volume

Hydrodensitometry was used in 1942 by Albert Behnke (Behnke *et al.* 1942) to assess body volume, and used to calculate body density (density = weight/volume). Hydrodensitometry, which has been used as a reference method for about 50 years, is tedious and requires operator expertise and subject compliance. This is because the subject has to be totally immersed under water whilst the volume of lung air is assessed using a gas-dilution technique. The technique is not suitable for sick patients, small children, and those frightened of water. Furthermore, measurements may be difficult to undertake in anxious or very obese individuals.

Over the last four decades attempts have been made to overcome the limitations of hydrodensitometry by using gas-air-displacement systems (Fomon *et al.* 1963; Gnaedinger *et al.* 1963; Taylor *et al.* 1985; Gundlach & Visscher, 1986) or acoustic plethysmography (Valerio Jimenez *et al.* 1993) to measure body volume. They have not found routine use, partly because of technical problems associated with poor reproducibility and validity, and partly because the design of equipment was unsuitable for routine use. However, a new air-displacement system has recently become available (BOD POD body composition system; Life Measurement Instruments, Concord, CA, USA) which seems to overcome many of the previous problems (Dempster & Aitkens, 1995; McCrory *et al.* 1995).

The device consists of two adjacent chambers (approximately 450 litres in the front and approximately 300 litres behind) separated by a diaphragm which is moved (approximately 350 ml) by a volume-perturbing element to produce pressure fluctuations (about  $\pm 10$  mm water). Measurements of these pressure fluctuations are made with and without the subject in the anterior chamber, and used to calculate body volume.

Body volume (litres) = body volume (raw value; litres),  
 – surface area artifact (litres),  
 + 40 % thoracic gas volume (litres),

where the surface area artifact is  $k$  (litres/cm<sup>2</sup>)  $\times$  body surface area (cm<sup>2</sup>); body surface area (Dubois formula,

Dubois & Dubois, 1916; cm<sup>2</sup>) = 71.84. Weight<sup>0.425</sup> (kg)  $\times$  height<sup>0.725</sup> (cm) and the thoracic gas volume are either measured or predicted from standard equations based on height or age (Crapo *et al.* 1992; McCrory *et al.* 1998) Both these variables are essentially correction factors which are necessary because air within the thoracic cavity and air near the skin surface are maintained close to isothermal conditions (physiological body temperature). Under such isothermal conditions, gas is more compressible than under adiabatic conditions. Small volume perturbations relative to total volume produce pressure changes that are 40 % less than under adiabatic conditions (hence the value of 40 % in the previously stated equation). The constant ( $k$ ) for the surface area artifact has been established by testing plastic films and Al foil ( $4.67 \times 10^{-5}$  litres/cm<sup>2</sup>). Since hair and clothing show apparent negative volume effects, the measurements are made with closely-fitting swimming trunks and a swimming cap. Each measurement takes only about 1 min to perform, while the subject sits in a chamber with a clear Perspex window and breathes normally. The technique can be readily applied to children, the obese, the elderly, and even sick patients.

Apart from the practical advantages over hydrodensitometry, the BOD POD body composition system has good precision, which is better than that obtained by hydrodensitometry (Table 1), and less errors associated with incorrect measurements or predictions of thoracic gas volume (only 40 % of the error is incorporated into the previously stated equation). Agreement between hydrodensitometry and air-displacement plethysmography is summarized in Table 2. Approximately half the difference between methods (SD of the difference) can be explained by methodological imprecision.

### Total body water

Total body water is also used to assess body composition, since the hydration fraction of lean body mass is relatively fixed (approximately 0.73 for healthy subjects or patients without fluid disturbances). Although much of the early water-dilution work was carried out using <sup>3</sup>H<sub>2</sub>O, which can be readily measured using a scintillation counter, ethical

**Table 1.** Precision (1 SD) of air-displacement plethysmography (BOD POD body composition system; Life Measurement Instruments, Concord, CA, USA) and hydrodensitometry for assessing body volume and body fat

	<i>n</i>	Air-displacement plethysmography			Hydrodensitometry			Reference
		Volume (litres)	Fat		Volume (litres)	Fat		
			% body wt	kg		% body wt	kg	
Adults*	68	0.08	0.4	-0.32	0.10	0.5	-0.39	McCrory <i>et al.</i> (1995)
Adults†	10	0.10	0.7	0.43	0.21	1.8	1.04	O Dewit, NJ Fuller, M Elia and CJK Wells (unpublished results)
Children†	18	0.10	1.5	0.53	0.17	2.6	0.89	Dewit <i>et al.</i> (1998)

–, Approximately.

\* In this study duplicate sets of measurements were carried out. In each set, BOD POD volume measurements were repeated until they were within  $\pm 0.2$  % of each other (only two measurements usually needed), and hydrodensitometry was repeated until underwater weights were within 50g of each other (usually four to eight trials). Subject characteristics were (weight and height respectively): 64.3 (SD 10.5) kg and 1.65 (SD 0.07) m for women (*n* 26), 87.9 (SD 12.5) kg and 1.80 (SD 0.05) m for men (*n* 42).

† Duplicate measurements, occasionally triplicate, for BOD POD to satisfy requirements of the machine: two body volume values within 0.15 litres of each other. Subject characteristics were (weight and height respectively): 62.1 (SD 6.5) kg and 1.71 (SD 0.08) m for adults, 33.4 (SD 7.5) kg and 1.40 (SD 0.06) m for children.

**Table 2.** Percentage body fat determined by air-displacement plethysmography and hydrodensitometry (Mean values and standard deviations)

	n	Air-displacement plethysmography (BOD POD*)		Hydrodensitometry		Bias		Reference
		Mean	SD	Mean	SD	Mean	SD	
Adults†	68	25.2	6.6	25.4	6.6	-0.2	1.8	McCrorry <i>et al.</i> (1995)
Adults‡	10	20.2	9.6	23.5	8.8	-3.3	2.3	O Dewit, NJ Fuller, M Elia and CJK Wells (unpublished results)
Children‡	18	21.3	7.8	20.4	9.0	0.8	5.7	Dewit <i>et al.</i> (1998)

\* BOD POD body composition system; Life Measurement Instruments, Concord, CA, USA.

† In this study duplicate sets of measurements were carried out. In each set BOD POD volume measurements were repeated until they were within  $\pm 0.2\%$  of each other (only two measurements usually needed), and hydrodensitometry was repeated until underwater weights were within 50g of each other (usually four to eight trials). Subject characteristics were (weight and height respectively): 64.3 (SD 10.5) kg and 1.65 (SD 0.07) m for women (*n* 26), 87.9 (SD 12.5) kg and 1.80 (SD 0.05) m for men (*n* 42).

‡ Duplicate measurements, occasionally triplicate, for BOD POD to satisfy requirements of the machine: two body volumes within 0.15 litres of each other. Subject characteristics were (weight and height respectively): 62.1 (SD 6.5) kg and 1.71 (SD 0.08) m for adults, 33.4 (SD 7.5) kg and 1.40 (SD 0.06) m for children. When the SD of the difference between methods is expressed in kg fat rather than percentage fat, the results for adults and children are similar (1.5 v. 2.0 kg respectively).

considerations restrict its use in women of child-bearing age and young children. Thus, measurements are now usually undertaken with stable isotopes, mainly  $^2\text{H}_2\text{O}$ . However, measurement of  $^2\text{H}_2\text{O}$  by mass spectrometry involves the use of expensive equipment, which is not widely available, and requires operator expertise. Furthermore, the preparative procedures mean that there is usually a substantial delay in analysis, which precludes the use of the technique in a routine clinical setting.

Another method for determining  $^2\text{H}$  in water is i.r. spectroscopy, which has been advanced by the application of Fourier transform techniques (Lukaski & Johnson, 1985), and mathematical modelling techniques which can measure the area under the curve with greater precision (Bluck & Coward, 1997). In the measurement of  $^2\text{H}_2\text{O}$  the i.r. spectrophotometer compares pre- and post-dose  $^2\text{H}_2\text{O}$  enrichment in physiological fluids (plasma, saliva and urine). The signal due to the  $^2\text{H}-\text{O}$  bond is superimposed on a large band due to water. Shifts in baseline positioning between pre- and post-dose samples can cause problems. A mathematical approach that takes into account the whole of the relevant peak (rather than a single point, typically 25 000 nm, in the standard measurement of  $^2\text{H}_2\text{O}$ ) has advantages in baseline positioning. Using this approach the precision of the measurement can be improved several-fold (Table 3). Results for plasma, saliva and urine are comparable with each other and with those obtained by mass spectrometry (1.6 (SD 1) %). The method is rapid, e.g. sixty-four repeat scans on a

sample, with five measurements per scan, can be obtained within 2.5 min.

#### Volume by scanning techniques

Magnetic-resonance imaging, computerized axial tomography and dual-energy X-ray absorptiometry have been used to provide volume measurements of the body and its segments, but they are not normally used for this purpose. Other approaches include the use of acoustic techniques, electromagnetic techniques, and light, i.r. and laser scanning techniques.

Advances in three-dimensional optic techniques over the last two decades have led to the development of instruments that can measure surface area, circumference and volume of the body and its segments with increasing accuracy (Ng *et al.* 1994). An example of an instrument that uses three-dimensional 'optic' techniques is the body line scanner developed by Hamamatsu (Hamamatsu City, Japan), originally for the clothes industry. It takes approximately 10 s to scan the body using six pairs of sensor heads to illuminate the body and scan body lines. Investigations into the potential application of this and a variety of other scanners in the field of orthotics anthropometry, imaging and body composition are being pursued by several groups, particularly with respect to software development and instrument validation against classic reference techniques.

The photo-topographic system for the quantification of changes in breast volume during lactation can be used to illustrate a general theoretical principle (Cox *et al.* 1996). In the Shape C measurement system (Alexander & Ng, 1987) a parallel pattern of stripes is projected onto the breast and the distortion of the pattern by the curvature of the breast is monitored by a camera. Measurement takes only a few seconds. The captured image is then converted into a topographic map. A set of *x*, *y*, *z* co-ordinates of individual points on the image may then be calculated providing a three-dimensional surface of the breast. Integration of the region under the surface provides an estimate of relative breast volume. Although changes in volume of the breast of as little as 2 % may be determined, the potential of the method for measuring volumes of body regions other than the breast (e.g. limbs) has yet to be realized.

**Table 3.** A comparison of the CV (*n* 5; separate samples) obtained using two different methods for measuring the area under the  $^2\text{H}_2\text{O}$  peak (Based on G Jennings, L Bluck, A Wright and M Elia, unpublished results)

(Values based on eight scans per reading and five measurements per scan)

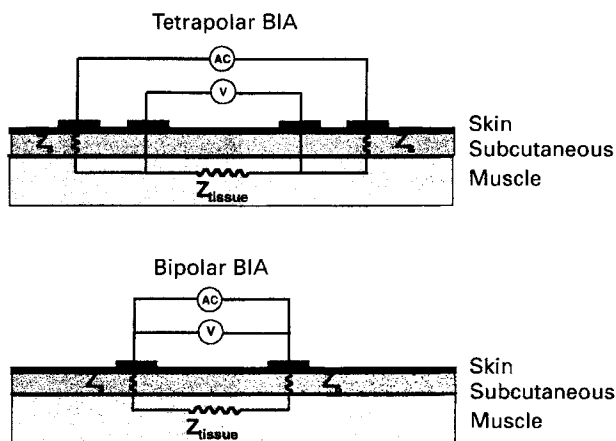
$^2\text{H}_2\text{O}$ standard ( $\mu\text{l/l}$ )	CV (%)	
	Traditional method	Improved method
1000	3.68	0.35
800	6.17	0.39
400	3.01	0.87
200	4.98	1.41

### Bedside methods: new developments in bioelectrical impedance

Bioelectrical-impedance analysis has been widely used to assess body composition of the whole body, but relatively little attention has been given to the assessment of the composition of particular parts of the body. Recent developments in electrical-impedance techniques have made it possible to assess muscle and adipose tissue mass in limbs (Brown *et al.* 1988), to measure skinfold thicknesses (Ward *et al.* 1998), to assess the blood volume (Siconolfi *et al.* 1996), and even the presence of tooth decay (Longbottom *et al.* 1996). Here only two developments involving muscle and fat mass will be described.

#### The electronic skinfold caliper

Conventional bioelectrical-impedance techniques measure the impedance of the body or body segment along their longitudinal axes using a tetrapolar electrode arrangement (Fig. 1). A novel method for measuring the impedance of skin and subcutaneous adipose tissue has been developed in which both tetrapolar and bipolar impedance measurements are made. In the bipolar arrangement the inner electrodes act both as the electrodes that send the current (outer electrodes in the tetrapolar arrangement) and as receiving electrodes. The difference between the two impedance measurements is considered to represent the combined impedance of skin + subcutaneous tissue at two sites (Fig. 1). The technique can be modified so as to measure impedance of skin + subcutaneous adipose tissue at a single site (Ward *et al.* 1998). If the resistivities of skin + subcutaneous adipose tissue are known, then it is possible to calculate the skinfold thickness (mainly due to adipose tissue). We have used this technique to compare the results of skinfold



**Fig. 1.** Conventional tetrapolar bioelectrical-impedance (BIA) arrangement for measuring impedance along the length of limb. If the outer two electrodes (electrodes sending current) are superimposed onto the inner electrodes (receiving electrodes) then a bipolar BIA arrangement exists with the same electrodes acting as receiving and sending electrodes. The difference in impedance measurements between the tetrapolar and bipolar arrangement reflects the impedance of skin and subcutaneous fat (see p. 36). AC, alternating current;  $Z_s$ ,  $Z_{\text{tissue}}$ , impedance in skin and subcutaneous fat and in muscle respectively.

thicknesses obtained by anthropometry at four sites (Table 4). The best correlation coefficient was with the biceps skinfold thickness ( $r$  0.94; SE of estimate 4.3 %).

These two methods correlated similarly with measurements of body fat obtained by a reference four-compartment model of body composition (Fuller *et al.* 1992). However, both the intra- and inter-observer coefficient of validation were better with the impedance technique (approximately half the value obtained by the skinfold caliper; Ward *et al.* 1998), in keeping with observations on the reproducibility of different methods in the whole body (Fuller *et al.* 1991). Thus, the impedance technique may be of value in studies involving multiple observers. It may also be of value in studies involving very obese subjects in whom measurement of skinfold thicknesses by anthropometry may be difficult or impossible. However, further studies are required using more precise and accurate measurements of skin + subcutaneous adipose tissue.

#### Measurement of limb muscle and adipose tissue by bioimpedance

The principle of this bedside technique is based on the resistance ( $R$ ) offered by a conductor of length  $L$ , cross-sectional area  $A$ , and resistivity  $\rho$ , where:

$$R = \rho \frac{L}{A} \quad \text{or} \quad \frac{1}{R} = \frac{A}{\rho L}$$

For a uniform section of a limb the following equation can be derived, assuming that it consists of electrical resistors (muscle ( $m$ ), skin ( $s$ ), bone ( $b$ ), adipose tissue ( $f$ ) and neurovascular bundle ( $n$ ) in parallel; (Brown *et al.* 1988):

$$\frac{L}{R} = \frac{Am}{\rho m} + \frac{Af}{\rho f} + \frac{An}{\rho n} + \frac{As}{\rho s} + \frac{Ab}{\rho b}$$

This equation can be rearranged and simplified because of the small effects of bone (very high resistivity), neurovascular bundle (small cross-sectional area) and skin, to give the following approximate equation for the cross-sectional area of muscle:

$$Am = \left( \frac{L}{R} - \frac{A}{\rho f} \right) \left( \frac{\rho m \times \rho f}{\rho f - \rho m} \right)$$

$L$  is the resistance between receiving electrodes (tetrapolar arrangement) and  $R$  is the measured resistance between them.  $A$  is the cross-sectional area calculated by anthropometry. Results of this technique are shown in Table 5 in which measurements of the thigh (inter-electrode distance 200 mm) and calf (inter-electrode distance 100 mm) are compared with those obtained by magnetic-resonance imaging over the same region. Anthropometry overestimated thigh muscle mass by a mean of 40 %, whilst the impedance technique overestimated it by only 12 % (corresponding values for calf are +18 % and -5 %). The standard deviation of the difference was similar when the anthropometric and bioimpedance results were compared with the magnetic-resonance imaging measurements (approximately 0.5 litres for the thigh, and approximately 0.08 litres for the calf). Amongst the reasons for the discrepancy between the magnetic-resonance imaging and impedance techniques are the non-uniform cross-sectional areas of the limbs and their constituent tissues, and uncertainty about

**Table 4.** Correlation of skinfold thickness (anthropometry at four sites) with impedance of skin + subcutaneous adipose tissue (bioelectrical-impedance technique using tetrapolar and bipolar impedance measurement) (Based on Ward *et al.* 1998)

Site	Skinfold (mm)	Impedance (ohm)	<i>r</i>	SE of estimate		Statistical significance of correlation <i>P</i> <
				ohms	%	
Biceps	4.8–19.0	145–258	0.94	8.6	4.3	0.001
Triceps	7.1–26.0	158–255	0.57	21.0	10.4	0.01
Suprailiac	7.0–30.0	126–244	0.80	15.9	8.7	0.001
Subscapular	6.6–37.0	105–203	0.82	12.7	8.1	0.001
Sum of skinfolds	33.0–110.5	573–914	0.85	41.3	5.5	0.001

the resistivity of muscle, which is different when the current flows along the muscle fibres than when it is flowing diagonally or across muscle fibres (Geddes & Baker, 1967). However, accurate anthropometric measurements (i.e. skinfold measurements) may be very difficult in some individuals, especially the obese, and assumptions about the circularity of muscle within the limb are not valid.

#### *Measurement of limb composition using high-frequency energy absorption*

The principle of this method is that the absorption of high-frequency energy from a coil around a limb is absorbed by tissues proportional to their electrolyte content. Thus, assuming that the distribution of electrolytes between intra- and extracellular fluid is fixed, and that fat and bone are essentially electrolyte free (in solution), then absorption of energy will be an index of limb musculature. Portable-battery-powered high-frequency energy absorption instruments have been developed (Michaelsen *et al.* 1993) operating at frequencies in the range 15–40 MHz. The instruments have been validated using *in vitro* test models (saline (NaCl) solutions) and in man. In the latter studies high-frequency energy absorption estimates of the musculature of the calf and thigh, expressed relative to total limb volume, were highly correlated with similar estimates obtained by magnetic-resonance imaging. The CV for the method was 6–7 %. Further development of the technique is required, notably investigation of the effects of varying electrolyte status, but it holds great promise as a simple bedside technique.

#### **Mobility of reference methods**

Pilot studies have been exploring possibilities of using reference body composition methods in the field in an attempt to

obtain more accurate data on large numbers of individuals. Even large equipment such as dual-energy X-ray absorptiometry machines can become 'mobile' and be transferred from centre to centre for large-scale studies. This development is attractive, not only because dual-energy X-ray absorptiometry provides objective information about the mass of fat and fat-free tissues, but also because it provides information about the distribution of fat (an independent predictor of cardiovascular disease) and bone mineral (of value to osteoporosis studies) within individual body segments. The BOD POD air-displacement system can also be transferred from centre to centre. In addition, the improved i.r. method for measuring enrichment of <sup>2</sup>H<sub>2</sub>O can be readily used close to the 'bedside', where the clinician makes day-to-day decisions about fluid therapy. One of the most rapid reference methods is the body line scanner (10 s for data acquisition), and therefore it is potentially attractive for use in large-scale field studies. However, first there is a need to establish more information about its validity and reliability.

#### **Conclusion**

Technological advances are increasingly being utilized in a range of body composition techniques (Pierson, 1998), making measurements more accurate and rapid, and more acceptable to individuals in both health and disease. They have also made possible new body composition measurements, such as those in individual body segments. In the last decade developments in 'bedside' or 'field' methods have generally occurred less rapidly than reference methods. However, since some of these reference methods can be transferred from one investigation centre to another (including field centres), the distinction between 'reference' methods and 'bedside' or 'field' methods is becoming less clear than in the past.

**Table 5.** Comparison of methods for estimating muscle and adipose tissue volumes (litres) in the thigh (200 mm length) and calf (100 mm length) (Based on Fuller *et al.* 1998). (Mean values and standard deviations)

	Magnetic-resonance imaging		Bioelectrical impedance		Anthropometry	
	Mean	SD	Mean	SD	Mean	SD
Thigh: Muscle	2.30	0.59	2.59	0.65	3.22	0.63
Adipose tissue	1.68	0.79	1.41	0.61	0.95	0.42
Calf: Muscle	0.60	0.14	0.57	0.13	0.71	0.20
Adipose tissue	0.26	0.12	0.36	0.15	0.24	0.01

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