Assessing Early Growth and Adiposity: Report from an EarlyNutrition Academy Workshop

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on behalf of the EarlyNutrition Academy

Abstract
This report provides a summary of a workshop organised by the European Commission-funded EarlyNutrition Project and the EarlyNutrition Academy. Accurate and reliable methods to assess body composition are needed in research on prenatal and early post-natal influences of nutrition on later health because common surrogate measures of maternal and offspring adiposity (body fat content), such as body mass index (BMI), have relatively poor predictive power for the risk of later disease. The key goals of the workshop were to discuss approaches to assess growth and body composition from pregnancy to adolescence, to summarise conclusions and to prepare a framework for research in the EarlyNutrition Project. The participants concluded that there is a pressing need to harmonise the methodologies for assessing body composition, recognising that each has advantages and limitations. Essential core measurements across studies assessing early growth and body composition were identified, including weight, length, BMI, waist and mid-upper arm circumference, subscapular and triceps skinfold thicknesses, and bioelectrical impedance analysis. In research settings with access to more sophisticated technologies, additional methods could include dual-energy X-ray absorptiometry, peripheral quantitative computed tomography, ultrasound assessment of regional body fat, magnetic resonance imaging (MRI), air displacement plethysmography (ADP), and deuterium dilution. These provide richer data to answer research questions in greater depth but also increase costs. Where overall whole-body composition is the primary outcome measure, ADP or tracer dilution should be used whenever possible. Where regional distribution of body fat is of greater interest, an imaging technique such as MRI is preferred.

Introduction
This paper reports on the principal conclusions of a research workshop on the assessment of growth and body composition organised by the EarlyNutrition Project and...
the EarlyNutrition Academy (ENA). The EarlyNutrition Project (www.project-earlynutrition.eu) is a large-scale research project running from 2012 to 2017 with funding from the European Commission’s 7th Framework Programme (FP7). This multi-disciplinary collaboration, which focuses on developmental influences on obesity and associated disorders, brings together international leaders in key areas of the developmental programming field located in 12 European countries, the USA and Australia [1]. Work packages include randomised intervention trials in pregnancy and infancy, as well as cohort studies of women before and during pregnancy and their children, which all assess growth and body composition in the mothers and offspring. In addition, the research programme incorporates mechanistic studies in animals, metabolic characterisation of the processes underlying programming and research in placental biology. ENA (www.early-nutrition.org) is a non-profit organisation that was developed in collaboration with several European Commission-supported research projects, including the EarlyNutrition Project, EARNEST, NUTRIMENTHE and EURRECA. The aims are to foster nutrition research, particularly relating to nutrition in women of childbearing age, infants and children, to facilitate research collaboration and to disseminate scientific knowledge in this area of research, in part through organisation of research workshops and position papers [2–5]. Under the auspices of the EarlyNutrition Project and ENA, a workshop was organised in March 2012 that gathered together a multidisciplinary team of experts in the assessment of growth and body composition. The goals of the workshop were to:

- review and critically discuss suitable approaches to assess growth, body composition and adiposity, from pregnancy through to childhood and adolescence,
- summarise conclusions and unresolved challenges in body composition research, and
- prepare a framework for research to be incorporated in the EarlyNutrition Project.

This paper presents a summary of this workshop.

**Background**

Overweight and obesity are major health problems worldwide both in children and adults [6]. There is increasing recognition that the progenitors of adult obesity lie in infancy or even in prenatal life [7, 8], and childhood obesity itself confers the risk of adult obesity and the associated co-morbidities of related disorders including type 2 diabetes and cardiovascular disease.

**Body Composition Predicts Risk**

In adults, body composition is considered a better predictor of health outcome than body weight [9]. Likewise, in children and adolescents, percentage body fat is closely related to chronic disease risk factors, as exemplified in the US National Health and Nutrition Surveys (NHANES III and IV) including data from over 12,000 children and adolescents [10]. Higher percentages of body fat (>20% in boys and >30% in girls) were associated with cardiovascular disease risk factors (higher blood pressure, lipids and lipoproteins, glucose, insulin and circulating C-reactive protein) and percentage body fat thresholds with a low and a high risk of the metabolic syndrome have been proposed [9]. The optimal body mass index (BMI) percentiles associated with the low-risk percentage body fat threshold were the 83rd and 80th in boys and girls, respectively, while the percentiles associated with the higher risk threshold were the 92nd and 90th, respectively [10]. BMI and percentage body fat derived from skinfolds showed reasonable agreement when used to classify adiposity in children.

Catalano et al. [11] have shown high neonatal body fat content measured by dual-energy X-ray absorptiometry (DXA) to be significantly associated with increased body fat at age 9 years (fig. 1). In turn, pre-gravid maternal obesity, as indicated by pre-gravid BMI, has a significant correlation with neonatal measures of fat mass (FM) or per-
percentage body fat, and with FM in later childhood and adulthood [12, 13]. The effect appears to be a more important risk factor for increased neonatal adiposity by about twofold than maternal diabetes [14]. Women that are obese at the beginning of pregnancy have fatter and heavier children [15] and there is also evidence for an association between excessive weight gain in pregnancy and increased adiposity in the neonate and child [16]. It is not certain, however, whether these associations reflect a direct relationship between maternal and neonatal FM as few studies have addressed the relationships between the size or distribution of maternal fat depots and offspring fat-free mass (FFM) and FM. Likewise, it is not known if the independent relationships between maternal obesity and excessive gestational weight gain and childhood adiposity reflect direct effects of maternal ‘fatness’ or more subtle influences of maternal obesity or related dietary factors on pathways of energy balance in the child. There is thus a need for more research into the relationships of maternal fat depot size and distribution with neonatal and childhood FM and related health outcomes. Importantly, an ability to assess the distribution of FM early in pregnancy or to identify reliable surrogate plasma biomarkers may aid in the prediction of adverse pregnancy outcome.

These effects are not limited to children born in the developed countries. The outcomes of the Pune Maternal Nutrition Study have also demonstrated that maternal influences on infant body composition and growth rate during early life are predictive of later outcomes. For example, lower maternal vitamin B<sub>12</sub> status and smaller mid-upper arm circumference at 6 months of age predicted higher insulin resistance at age 6 years [17].

Although providing strong evidence that maternal nutritional status influences fetal and neonatal body composition, the data which underpin the relationships described are frequently based on surrogate methods for the assessment of body composition. BMI provides a convenient but not entirely accurate estimate of body composition, a problem further compounded in pregnant women by the products of conception and changes in maternal total body water (TBW) and FM to the extent that BMI becomes a useless measure of maternal adiposity after the first trimester. There is increasing recognition that commonly used indices of fatness such as BMI do not adequately capture changes in body composition or adipose tissue distribution that accompany changes in overall adiposity. BMI is correlated with body FM in infants and young children but has relatively poor predictive power for later health and disease risks. This has highlighted the need for accurate and reliable methods to assess body composition from birth through infancy to adolescence and into adulthood.

Problems of Measurement of Body Composition in Neonates and Infants

Although a large number of methods has been developed or adapted for the measurement of body composition, the assessment of body composition in infants and children presents particular challenges. Both practical and ethical constraints restrict the methods available and their evaluation. In general, methods which involve a significant radiation hazard, e.g. whole-body computed tomography (CT), or are invasive, e.g. tracer dilution techniques that involve repeated blood sampling, are precluded; equally, methods that can safely be undertaken in children [such as total body potassium (40K) counting] may not be practical for routine use outside specialist centres. Some techniques that held great promise, e.g. total body electrical conductivity, are no longer possible since the required instrumentation is not currently manufactured. The remaining techniques, principally anthropometry, bioelectrical impedance analysis (BIA), DXA, magnetic resonance imaging (MRI), ultrasound, air displacement plethysmography (ADP), peripheral quantitative CT (pQCT), tracer dilution with non-radioactive tracers and saliva or urine sampling, all have intrinsic advantages and disadvantages. Some are more complex than others, cost varies substantially, subject convenience differs markedly, and the accuracy and precision varies considerably [18] (table 1). In general, there is an inverse relationship between many of these attributes; low-cost, simple-to-use techniques frequently exhibit the lowest accuracy and precision. The task facing researchers is to balance feasibility of technique against cost and accuracy. It is also necessary to define clearly the outcome desired, recognising that this may not be the same at all stages of childhood – neonate, infant, pre-school and school age, and adolescence.

What Is a ‘Good’ Method?

Measurement methods may be either indirect, BMI being a good example when used to predict body fat, or direct, e.g. the determination of TBW by tracer dilution which can then be used in an indirect estimation of body fat. Irrespective of whether a technique is direct
or indirect, the method must be shown to be valid by comparison to a reference or ‘gold standard’ method. Methods may also be cross validated against each other in order to assess interchangeability and allow comparison of results obtained using different techniques. Validation assesses whether a method of measurement produces the correct or true result. Unfortunately, in body composition analysis the ‘true’ value is rarely known, although it might be possible to validate aspects of any given method, for example the density of fat necessary for densitometric methods of body composition analysis such as PEA POD. Cross validation assesses whether one method produces the same result as another. In the body composition field, most published ‘validation’ studies are actually cross validation studies. The cautionary note sounded by Parker et al. [19] is worthy of repetition here ‘As noted in our paper, the literature is dominated by many studies in which methods of unknown validity are compared against other methods of unknown validity. These studies, although common, are not particularly helpful in that they cannot establish validity of body composition methods, because they do not include a criterion method (multi-component model).’ Cross validation may be against an accepted reference method, another field method or between population groups. Ideally, cross validation should always be against a reference method. The consensus of what constitutes a reference method has changed over time as technological advances have opened up opportunities that were previously not possible; notably, the four-component model of body composition

weight = fat mass + water + protein + minerals,

is the generally accepted reference method [20], but only became possible with the advent of DXA to quantify bone mineral content.

There is also a need to cross validate in different populations. This is particularly important in a paediatric setting where the density, mineralisation and potassium concentration of the FFM is lower in children than adults and changes progressively as a child matures from infancy to adulthood. Conversely, the water content of the FFM (hydration fraction) is ≥10% higher in preterm infants than in term 3-month-old infants. Accounting for these variables with appropriate validation is particularly important for highly predictive methods such as those using measurements of impedance. While it is crucially important that all methods adopt standardised protocols for their implementation, this is sadly lacking in the body composition arena. Organisations such as the International Atomic Energy Authority are taking a lead here.

It is not always appreciated that cross validation studies can assess only whether the different methods produce the same result. This does not necessarily mean that a ‘true’ result is provided. Similarly, it is not sufficient to demonstrate a high correlation between results obtained by different methods and to assume that this means that the methods are in agreement or concordant. Appropriate statistical analytic techniques are required. Some journals (e.g. the BMJ group) have admirably taken a lead in requiring that all method comparison stud-

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Portability</th>
<th>Ease of use</th>
<th>Time involved</th>
<th>Patient convenience</th>
<th>Safety</th>
<th>Operator skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance</td>
<td>low to high</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>DXA</td>
<td>high</td>
<td>none to medium</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Isotope dilution</td>
<td>medium</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>medium to high</td>
<td>medium to high</td>
<td>low</td>
</tr>
<tr>
<td>ADP (e.g. PEA POD, BOD POD)</td>
<td>very low</td>
<td>low</td>
<td>low to medium</td>
<td>medium</td>
<td>low</td>
<td>medium to high</td>
<td>medium</td>
</tr>
<tr>
<td>Imaging (e.g. ultrasound, MRI)</td>
<td>medium to very high</td>
<td>none</td>
<td>low to medium</td>
<td>medium to high</td>
<td>medium</td>
<td>medium</td>
<td>very high</td>
</tr>
<tr>
<td>Anthropometry</td>
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<td>high</td>
<td>high</td>
<td>medium</td>
<td>high</td>
<td>high</td>
<td>medium</td>
</tr>
</tbody>
</table>

Table 1. Advantages and disadvantages of commonly used technologies for the assessment of body composition

Early-Life Body Composition Assessment

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ies meet acceptable statistical guidelines [‘Statistical advice for contributors’ http://group.bmj.com/products/journals/instructions-for-authors/statadvice.pdf].

**Body Composition Methods Suitable for Paediatric Use**

Presentations at the ENA workshop covered a wide range of technologies that consortium members were using for body composition assessment. These ranged from classical anthropometric techniques through to sophisticated 3D fetal ultrasound.

**Anthropometry**

Anthropometry remains an important aspect of many studies of infant and childhood growth and for monitoring adiposity during pregnancy. Extensive use is being made of anthropometry in the European Childhood Obesity Project study and the Southampton Women’s Survey (SWS). In both studies, standardisation and attention to details were applied in the development of standard operating procedures.

The European Childhood Obesity study [21–23] is an intervention study comparing growth in two groups of children that were fed during the 1st year of life with one of two types of formula feeds for infants differing in protein content while preserving energy content. Children exclusively breastfed for at least 3 months are followed as a comparison group. The study is conducted in 11 study sites of 5 European countries. Extensive anthropometric data are collected at inclusion and 3, 6, 12 and 24 months, half yearly until 6 years of age and at the ages of 7.5, 8, 8.5 and 11 years using highly standardised protocols. Particular attention is paid to standardisation and quality control in anthropometric measurements as it has been recognised that it is essential to minimise measurement error and enhance reliability and precision. Considerable efforts have to be undertaken to attain these goals with a main focus on practical teaching and training of anthropometrists. The Childhood Obesity Project study also implements novel statistical approaches to the evaluation of growth data [24–26].

The SWS has been designed to gain insight into perinatal body composition and developmental programming [27]. Over 12,500 non-pregnant women aged 20–34 years living in the city of Southampton have been interviewed, with measurements of pre- and post-natal growth in 3,160 first singleton live births. In the EarlyNutrition project, the children will be studied at the age of 10–11 years. Anthropometric measurements are based on the methods outlined in the *Anthropometric Standardisation Reference Manual* [28], which is now out of print, but the recently published *Handbook of Growth and Growth Monitoring in Health and Disease* [29] represents a suitable alternative.

**Ultrasound**

Ultrasound is a technique that bears a low risk, is easy to perform and provides information on localised fat deposition. 2D ultrasound is routinely used in pregnancy to detect congenital anomalies and to assess fetal growth, but obtaining satisfactory images is technically challenging in obese pregnant women, even with the use of tissue harmonic imaging. Obese women are at increased risk of spontaneous abortion and of fetal congenital abnormalities and, later in gestation, the fetus is at increased risk of macrosomia, with implications for later metabolic risk as a result of fetal programming.

Ultrasound is being used in several major studies on pre- and post-natal nutrition to assess growth and body composition. The SWS has utilised a systematic algorithm that combines detailed menstrual data for accurate estimation of gestational age with ultrasound scan data to determine fetal growth trajectories. Deriving standard deviation scores from the ‘clouds’ or clusters of size measurements at specific gestational ages has posed statistical challenges, and studies in the SWS have shown the potential for systematic biases to be introduced when using some approaches. Using Royston’s [30] method has, however, provided an appropriate model for characterising size and growth velocity in utero.

The SWS has also provided the opportunity to investigate the utility of 3D ultrasound in the investigation of maternal influences on fetal body composition, and volumes of the fetal femur, thigh muscle and thigh subcutaneous fat/skin using 3D ultrasound at 34 weeks gestation have been measured. The findings suggest that 3D ultrasound can provide useful measurements of fetal body composition in late gestation. Fetal femur volume was most strongly associated with the mother’s height, fetal thigh muscle volume with the mother’s arm muscle area, and fetal subcutaneous fat/skin volume with the mother’s sum of skinfold thicknesses.

Later in life, ultrasound is extremely useful in assessing localised or regional fat depots. The Generation R Study Group at the Erasmus Medical Centre has developed a method to assess different measures of abdominal visceral fat by ultrasound in children. Visceral and pre-peritoneal fat thickness and area were well correlated [0.58 (p <
Early-Life Body Composition Assessment

BIA works by passing a small electrical current through the body and measuring the impedance to the current. By assuming that the impedance is proportional to the volume of water in the body, it is possible to use BIA to estimate TBW by using a validated prediction equation. Prediction equations are typically based on the impedance index, $\text{height}^2/R$, where $R$ is the resistance or impedance [33]. The impedance index predicts TBW reasonably well, provided appropriate equations are used [34]. Once TBW has been estimated, FFM and FM can be estimated using the two component model as described below (see measurement of TBW by tracer dilution). The advantages of BIA are that it is a relatively inexpensive and non-invasive way of assessing body composition that is well tolerated by patients and can be performed rapidly and easily at the bedside, without the need for bulky equipment. A disadvantage of BIA is the requirement for population-specific equations for the prediction of TBW, coupled with the need for a hydration coefficient (proportion of the FFM that is water) for FFM that is appropriate for use in the population being studied. Another disadvantage of BIA is that its ability to estimate body composition in terms of FFM and FM will be affected by changes in the subject’s hydration status, with FFM being overestimated in oedematous or overhydrated individuals – this is a particular issue in preterm infants who, by comparison with older children or adults, have a high body water content.

BIA has generally been shown to predict accurately TBW in pregnancy, particularly when using equations specific for pregnant women which incorporate additional anthropometry to allow for the changes in body geometry associated with pregnancy [35–38]. Studies in preterm and term infants have shown it to predict TBW accurately [39–41]. However, the rapid fluxes in TBW in preterm and newborn infants mean that its ability to accurately predict body composition in terms of FFM and FM is limited. Several studies have shown that it offers no advantage over standard anthropometry (weight and height) in estimating body composition in infants in the first few weeks or months of life, and even beyond this is subject to significant error [42, 43]. BIA has been shown to correlate highly with measures of TBW obtained using deuterium dilution, and equations have been derived to enable prediction of TBW in children and adolescents. The addition of BIA improved prediction of TBW compared to using anthropometry alone.

One problem that remains to be overcome in order for BIA to be used more widely is the current variety of equipment, approaches and choice of prediction equations for each study population. Standardisation is required to ensure that investigators using this method are using the same approaches in terms of instrumentation, electrode positioning and data analysis, allowing better harmonisation between investigators and comparison between different research groups. Again the International Atomic Energy Authority is taking a lead here [44].

**Air Displacement Plethysmography**

The PEA POD infant body composition tracking system (Life Measurement, Concord, Calif., USA) uses ADP and has been developed to measure the percentage body fat of infants [45]. The system is an air displacement plethysmograph in which the naked infant is placed in a closed chamber and air displacement is measured using pressure and volume changes. Body density is derived from measured body mass and the calculated body volume. Measurements of percentage body fat made using the PEA POD have been shown to vary considerably depending on the gestational age at delivery and gender of the infant [46], an observation supported by a carcass analysis validation study using piglets [47]. The method...
has been used successfully to measure body composition in full-term healthy infants at 1 and 12 weeks of age [48]. PEA POD measurement takes only a few minutes to complete but the equipment is not portable and can only measure the body composition in infants with a body weight between 1 and 8 kg. The available data from a limited number of studies evaluating the performance of the method in comparison with other techniques or standards support the conclusion that this method is accurate, reliable and produces reproducible results [49]. A modified version of the adult BOD POD ADP instrument has recently been validated for use in infants and children aged 6–48 months [50].

**Magnetic Resonance Imaging**

Quantity and distribution of adiposity in neonates can be studied using MRI. However, image analysis algorithms distinguishing specific fat compartments are lacking. The GUSTO cohort study (http://gusto.sg/about/gustoinfo.html) has sought to develop a comprehensive analysis programme for segmentation and quantification of abdominal fat in Asian neonates, although this should be applicable to other ethnicities. Analysis methods for MRI data (T1-weighted; 1.5-tesla scanner) collected within 21 days of delivery from an initial group of 387 neonates ≥34 weeks gestation and weight ≥2 kg have been developed. Abdominal fat tissue from the level of the diaphragm to the sacrum was divided into superficial subcutaneous, deep subcutaneous and internal. Volumes of fat tissue (ml) are determined using an in-house MATLAB package comprising automatic processing (watershed transform of local standard deviation, initial identification of superficial subcutaneous and internal compartments) and manual routines. Using these routines, MRI can be used to measure specific fat depots in birth cohort studies. Analysis of neonatal fat depots in the GUSTO cohort is in progress and should provide valuable insights into developmental influences on early-life fat distribution, and their role in metabolic risk observed later in life.

**Tracer Dilution**

Measurement of TBW by stable isotope dilution has long been utilised to estimate body composition since it has been demonstrated that a fixed fraction of lean body mass is composed of water. This method relies on the two-component model that divides body weight into FM and FFM (lean body). Deuterium dilution can be used to measure TBW by administering a dose of water labelled with deuterium, and, following equilibration, deuterium enrichment of body water is measured in samples of urine or saliva [51, 52], thereby enabling calculation of lean mass and then, by subtraction, FM. The two-component method is subject to some error due to variation in the composition of FFM. The four-component method of body composition divides body weight into fat, water, mineral and protein. It allows for several assumed constants that are critical for improved accuracy of the two-component model. Improvement in the estimates of FFM by deuterium dilution in infants and children has been provided by the generation of new equations that take into consideration age and gender-specific variation constants used to convert measured body constituents into FFM in the two-component models [21]. The use and generation of new equations have been evaluated in several studies [53–56] and these provide useful reference data.

Multi-component models are the most accurate to estimate body composition but due to complexity, cost and ease of use, they are not practical in most settings. Tracer dilution is easy to carry out, acceptable for all ages and requires minimal subject cooperation. It may be ideal for infants and toddlers due to compliance issues with other methods. It is relatively cost effective and can be performed in a non-laboratory setting. The limitations include the need for a biological sample, lack of data on fat distribution and the need for normal hydration. The importance of well-trained staff to instruct parents and administer the dose of deuterium is essential for use in infants and young children. Accuracy in measurement of the dose delivered and collection of samples is necessary to provide the best estimate for body fatness. In healthy subjects, estimation of body fatness using deuterium dilution is relatively accurate and compares well against the ‘gold standard’ four-component model.

**Dual-Energy X-Ray Absorptiometry**

In addition to providing gold standard measurements of bone mineral content, DXA provides an alternative approach to the estimation of both fat and lean mass. The total X-ray dose for neonatal whole-body scans is approximately equivalent to around 1- to 2-day background radiation. Specific paediatric software is required and movement artefact is a potential limitation in infants and children; by swaddling in a standard towel, good quality DXA measurements have, however, been achieved in over 1,000 infants taking part in the SWS [27, 57]. The accuracy of DXA for the assessment of body composition in small animals has been demonstrated in piglets [58]. DXA has been shown to have good reliability for body
composition assessment in newborns and has been suggested as reference technique [59]. While DXA measurements of ‘lean’ cannot distinguish between the mass of internal organs, newer machines and software are increasingly able to focus on specific body regions.

Peripheral Quantitative Computed Tomography

The assessment of bone density and geometry has become more and more popular in paediatric research and clinical practice. Around 90% of bone mass is built up during childhood and adolescence, and the impact of these first 2 decades of life on bone health and risk for osteoporosis is well accepted. There is increasing interest to use pQCT for bone assessment in children and adolescents [60]. This technique can be applied to measure the meta- and diaphysis of long bones (radius, tibia or femur) and only requires a low radiation dose [61, 62]. Despite important advantages over DXA, pQCT is less frequently used. While pQCT determines true 3D volumetric bone mineral density, DXA only measures bone mineral content and bone area. Therefore, DXA tends to underestimate bone mineral density in stunted patients and overestimates it in subjects with tall stature [63]. pQCT can also assess the muscle area at the diaphysis. Muscle density is also measured by pQCT, which is important in terms of adiposity-related changes in muscle composition. Data on healthy children and adolescents measured by pQCT are available [64, 65].

Despite these advantages, there are still drawbacks that confine the use of pQCT. The site of measurement is limited to radius, tibia or femur. There is a paucity of evidence on the comparability of different devices including software, added to which there is no consensus on the optimal site of measurement, and the placement of the reference line is missing [66].

In conclusion, pQCT is able to provide important and precise information not only on bone mass but also on bone geometry and its development during childhood and adolescence. However, clinicians and researchers have to consider carefully the challenges and limitations of this technique, and should report all results adequately. Further research is needed to establish valid reference data, to demonstrate the strengths and limitations of different devices, and to give evidence for a rational and consistent analysis protocol.

Consensus Statement on Assessing Early Growth and Adiposity and Research Needs

There is an over-riding need to harmonise methodologies for the assessment of body composition. All methods have their own advantages and disadvantages (table 2). Needs may vary for different study designs. In a validation study, accuracy is paramount. In intervention studies, precision is more important where comparisons are to be made, while in cohort studies a key requirement is that methods are reliable and repeatable over time. The choice of the method is also governed by feasibility and cost constraints. Nevertheless, a number of essential core measurements across studies can be identified (table 3). These relatively low-cost technologies, applicable across all age groups, may provide limited but nonetheless essential information. They are suitable for routine use and it is recommended that they are undertaken in all studies focused on growth and body composition outcomes.

In a research setting, where access to more sophisticated technologies is possible, the scope of available methods broadens (table 3). Use of one or more of these

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Table 2. Core body composition measurements recommended for studies of early growth

<table>
<thead>
<tr>
<th>Measurement</th>
<th>FM</th>
<th>Lean mass</th>
<th>Fat distribution</th>
<th>Cost</th>
<th>Training</th>
<th>Feasibility</th>
<th>All ages</th>
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<tr>
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<td>N/A</td>
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<td>$</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Length</td>
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<td>N/A</td>
<td>N/A</td>
<td>$</td>
<td>+</td>
<td>+++</td>
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</tr>
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<td>BMI</td>
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<td>++</td>
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<td>$</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Waist circumference</td>
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<tr>
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<td>$</td>
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<td>++</td>
<td>$$</td>
<td>+++</td>
<td>++</td>
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<tr>
<td>TR</td>
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<tr>
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</tr>
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</table>

MUAC = Mid-upper arm circumference; SS/TR = subscapular/triceps skinfold thicknesses; $ = low USD; $$ = moderate USD.
methods provides richer data to answer deeper research questions. Inevitably, there are increased costs associated with their use. It was recommended that, where overall whole-body composition is the primary outcome measure, ADP or tracer dilution be used whenever possible. Where regional distribution of body fat is of greater interest, an imaging technique such as MRI is to be preferred.

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**Disclosure Statement**

L.C.W. has consulted ImpediMed Ltd. K.M.G. has acted as a consultant to Abbott Nutrition and Nestle Nutrition, and has received reimbursement for speaking at an Abbott Nutrition Conference on Pregnancy Nutrition and Later Health Outcomes and at a Nestle Nutrition Institute Workshop. L.P. has received reimbursements for speaking at an Abbott Nutrition Conference on Pregnancy Nutrition and at a Danone Round Table on Prevention of Obesity. K.M.G., L.P. and B.K. participate in a European Commission-funded research consortium with scientific collaboration with Abbott Nutrition, Beneo and Danone Research. None of these commercial entities had any involvement in the conception, execution or preparation of this paper.

**Table 3. Body composition techniques for use in a research setting**

<table>
<thead>
<tr>
<th></th>
<th>FM Lean mass</th>
<th>Fat distribution</th>
<th>Bone mass/density</th>
<th>Liver volume</th>
<th>Costs</th>
<th>Training</th>
<th>Feasibility</th>
<th>All ages</th>
</tr>
</thead>
<tbody>
<tr>
<td>DXA</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>N/A</td>
<td>$$ $$</td>
<td>++</td>
<td>+++</td>
<td>$(+)</td>
</tr>
<tr>
<td>pQCT</td>
<td>N/A</td>
<td>+</td>
<td>N/A</td>
<td>++</td>
<td>N/A</td>
<td>$$ $$</td>
<td>+++</td>
<td>N/A</td>
</tr>
<tr>
<td>CT</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>(+)</td>
<td>+</td>
<td>$$ $$</td>
<td>+++</td>
<td>N/A</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>N/A</td>
<td>N/A</td>
<td>++</td>
<td>N/A</td>
<td>+</td>
<td>$$ $$</td>
<td>++ ++</td>
<td>N/A</td>
</tr>
<tr>
<td>MRI</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>N/A</td>
<td>+++</td>
<td>$$ $$</td>
<td>+++</td>
<td>(+)</td>
</tr>
<tr>
<td>ADP (BOD POD)</td>
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<td>+++</td>
<td>N/A</td>
<td>N/A</td>
<td>$+$</td>
<td>+</td>
<td>++ ++</td>
<td>++ (+)</td>
</tr>
<tr>
<td>Deuterium dilution</td>
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<td>+++</td>
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<td>N/A</td>
<td>$+$</td>
<td>+</td>
<td>++ ++</td>
<td>++ (+)</td>
</tr>
</tbody>
</table>

$ = Moderate USD; $$ = high USD.

**References**


