BODY COMPOSITION REVIEW

Body composition changes in pregnancy: measurement, predictors and outcomes

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Prevalence of overweight and obesity has risen in the United States over the past few decades. Concurrent with this rise in obesity has been an increase in pregravid body mass index and gestational weight gain affecting maternal body composition changes in pregnancy. During pregnancy, many of the assumptions inherent in body composition estimation are violated, particularly the hydration of fat-free mass, and available methods are unable to disentangle maternal composition from fetus and supporting tissues; therefore, estimates of maternal body composition during pregnancy are prone to error. Here we review commonly used and available methods for assessing body composition changes in pregnancy, including: (1) anthropometry, (2) total body water, (3) densitometry, (4) imaging, (5) dual-energy X-ray absorptiometry, (6) bioelectrical impedance and (7) ultrasound. Several of these methods can measure regional changes in adipose tissue; however, most of these methods provide only whole-body estimates of fat and fat-free mass. Consideration is given to factors that may influence changes in maternal body composition, as well as long-term maternal and offspring outcomes. Finally, we provide recommendations for future research in this area.

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INTRODUCTION

The body exhibits dynamic changes in composition during pregnancy to support the fetus as it develops from conceptus to live born infant. These changes are reflected in gestational weight gain (GWG), which includes gains in maternal and fetal fat mass (FM) and fat-free mass (FFM), as well as the placenta and amniotic fluid (Figure 1). The Institute of Medicine GWG guidelines by prepregnancy body mass index (BMI) aim to optimize maternal, fetal and infant health outcomes and further recommend that women achieve a healthy body weight before pregnancy.[1] Prevalence of overweight/obesity in women of childbearing age remains high and, moreover, over half of women recently have gained excessive weight in pregnancy with consequences for the mother and offspring.[2] With excess GWG, mothers are at increased risk of cesarean delivery[3] and may be at increased risk of abnormal glucose metabolism and pregnancy-induced hypertension.[4] Furthermore, offspring are at risk of high birth weight,[4] macrosomia,[4] large-for-gestational age,[3,4] impaired fetal growth[4] and preterm birth.[3,4] Postpartum, mothers with excessive GWG are at risk for weight retention,[4] subsequent obesity[4] and likely obesity-associated health consequences, including type 2 diabetes and cardiovascular disease thereafter, but evidence is limited in this area.[1,5,6] Offspring of mothers with excessive GWG have higher weight-for-age Z-scores and length-for-age Z-scores in infancy,[7] higher BMI Z-scores in childhood[8] and possibly a greater risk of obesity-associated sequelae.[5,9]

Cumulatively, these adverse health consequences from excessive GWG may pose an even greater threat to maternal and infant long-term health in resource-poor settings undergoing various phases of the nutrition transition.[10] The nutrition transition is marked by shifts in diet from traditional foods to a more Western-type diet along with decreasing physical activity that propagate obesity and nutrition-related non-communicable diseases, such as cardiovascular disease and diabetes.[11] As women of reproductive age in these settings may have been previously exposed to undernutrition and are now becoming overweight/obese, excessive GWG among mothers previously exposed to undernutrition may further lead toward heightened risk of maternal and offspring obesity and nutrition-related diseases; however, evidence is limited in this area.

Previously, various components of GWG, including total body water (TBW), FM and FFM—where TBW was estimated by deuterium dilution; and FM and FFM estimated with a four-compartment model (details later in this review)—were found to be positively correlated with total GWG;[12] but only FM gain was related to initial BMI values.[12] Higher initial BMI was associated with greater FM gains.[12] GWG and FM gains were correlated with fat retention postpartum, while TBW and FM gains were correlated with infant birth weight.[12] Although several studies have examined how GWG relates to maternal and infant health outcomes,[5,7,12,13] there is much less evidence related to the association between change in maternal body composition and maternal and infant short- and long-term health which may be due to measurement challenges in this population.

Measuring maternal body composition during gestation is challenged by available *in vivo* measuring methods that cannot differentiate between maternal and fetal depots[14] and approach the maternal–fetal dyad as a single unit. Moreover, some pregnancy-induced changes in body composition violate the assumptions that are the foundation of many of the commonly available measurement methods, and pregnancy-specific corrections (that often vary by gestational age) are needed. For example,

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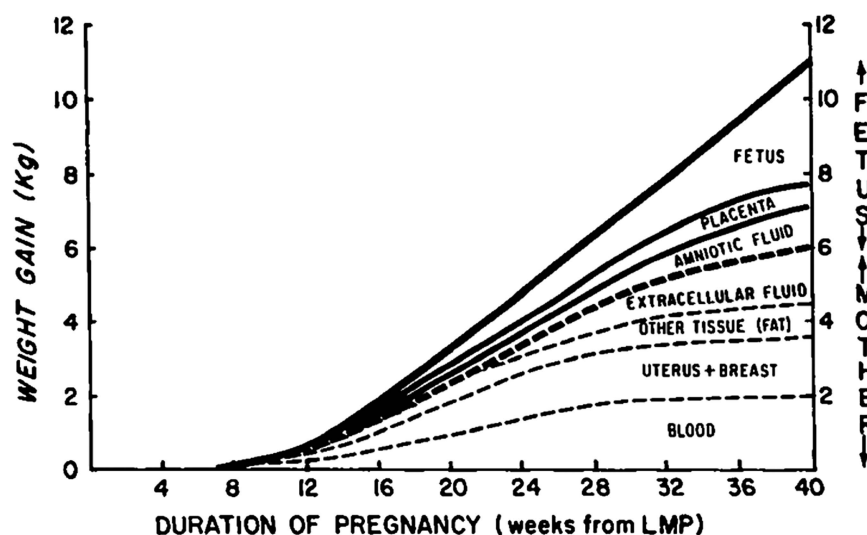E-mail: ew2435@columbia.edu

Figure 1. Pattern and components of average weight gain in pregnancy. LMP, last menstrual period. Source: Pitkin RM. Nutritional support in obstetrics and gynecology. *Clin Obstet Gynecol* 1976; **19**: 489–513. Reprinted.

TBW increases during pregnancy by about 5–8 liters[15–18] and the composition of lean tissue changes as pregnancy progresses, thereby invalidating a basic assumption that underlies many measurement techniques, that 73% of the adult's FFM compartment is water.[19–22] In reality, obtaining an accurate estimate of pregravid weight status and/or body composition immediately before or early in pregnancy is not feasible, thereby affecting the validity of body composition change estimates. The Institute of Medicine guidelines assume that women gain on average 0.5–2 kg in the first trimester according to their pregravid BMI in their recommendations for total GWG;[1] however, evidence suggests that the pattern of GWG in this period is highly variable. For example, total first trimester GWG was − 0.4 , 2.7 and 6.9 kg at the 10, 50 and 90th percentiles, respectively, in predominately non-Hispanic white women from the United States.[23] This GWG variability also may reflect changes in body composition; therefore, in order to accurately estimate change in composition, a measurement of pregravid body composition in close proximity to conception is essential.

Here we review the state of the literature with regard to how maternal body composition changes during pregnancy. Methods for measuring maternal body composition are reviewed. Strengths and limitations of each method are discussed. Previous research is summarized for each component of body composition, including changes in body weight or mass, FM, body water compartments and bone mineral density. An overview of specific factors influencing maternal body composition during pregnancy are discussed, including initial weight status, parity, race/ethnicity, genetics and pregnancy in adolescent period. Finally, we briefly review current evidence relating maternal body composition during pregnancy to maternal and infant long-term health and provide recommendations for future research in this area.

SEARCH STRATEGY

Sections on maternal body composition from the Institute of Medicine recommendations for GWG and several textbooks were consulted.[1,14,16,24–26] PubMed searches up to July 2013 with the terms 'body composition changes pregnancy' or 'body water changes pregnancy' or 'adipose tissue changes pregnancy' were conducted with limits of human studies and English language, identifying 507 articles, excluding duplicates. Additional PubMed searches were conducted by (1) adding key terms for each

assessment method and (2) identifying predictors and outcomes of body composition changes in pregnancy. Papers or abstracts were reviewed when the study (1) focused on changes in body composition across the course of pregnancy or from prepregnancy to postpartum; and (2) focused on predictors and outcomes of body composition changes. Further, reference lists of these papers were reviewed for additional relevant publications. Seminal papers related to the development and validation of assessment methods were also reviewed. Overall, the search process resulted in 87 sources that were synthesized and included in this review.

TECHNIQUES FOR MEASURING MATERNAL BODY COMPOSITION

Table 1 summarizes methods for estimating changes in body composition in pregnancy. Most methods theoretically divide the body into compartments from which an estimate of FM is derived. The two-compartment model divides the body into FM and FFM, while the three-compartment model further sub-divides the FFM compartment into water and a combination of mineral and protein. The four-compartment models further subdivide the FFM compartment into mineral, water and protein. The Institute of Medicine has indicated that these models are 'satisfactory' for estimating body composition changes in pregnancy, given that corrected values for hydration and density of FFM are applied, and for three- and four-compartment models that FFM hydration or density are measured.[1] Furthermore, the Food and Agriculture Organization, World Health Organization and the United Nations University have also issued a similar joint statement regarding 'acceptability' of these models if appropriate corrections are applied.[27] These corrections and measures will be discussed later in this review.

Anthropometry

Anthropometric measurements, particularly skinfold thicknesses (SFT) and mid-upper arm circumferences, have been used extensively to estimate changes in body composition in pregnancy. Typically FM changes are estimated using equations with body weight, SFT and often circumference measures. Although several equations to estimate FM using anthropometric measurements have been developed in non-pregnant women,[28–31] these equations overestimate fat changes in pregnancy when compared with estimates from a four-compartment model.[22] Paxton *et al.*[22]

Table 1. Summary of methods to measure body composition changes in pregnancy

Method	Participant complexity	Technical complexity	Source of Error	Compartment model	Regional distribution	Suitable in field settings
Anthropometry—skinfold thickness	Simple	Simple	Measurement error—requires technician expertise. Over the course of pregnancy, changes in (1) compressibility of skinfold thickness, (2) edema and (3) ability to measure certain regions. Equations to estimate total body fat available for only certain gestational ages	2	Yes	Y
Total body water (TBW)	Simple	Specialized instruments	Hydration of fat-free mass. Unable to disentangle the maternal–fetal unit	2/Multiple[a]	No	Y
Underwater weighing	Complex	Specialized instruments	Unable to disentangle the maternal–fetal unit	2/Multiple[a]	No	N
Air displacement plethysmography (ADP/BodPod)	Complex	Specialized instruments	Unable to disentangle the maternal–fetal unit	2/Multiple[a]	No	N
Magnetic resonance imaging (MRI)	Simple	Specialized instruments	Methods have not been developed specifically for pregnancy; therefore, the source of error is not fully understood	2	Yes	N
Bioelectrical impedance analysis (BIA)	Simple	Specialized, portable equipment depending on model	Has not been validated against reference methods in pregnancy. Unable to disentangle the maternal–fetal unit	2	Yes, but not validated	Y
Dual energy X-ray absorptiometry (DEXA)	Simple—for use in prenatal and postnatal	Specialized instrument	Not suitable during pregnancy due to radiation exposure. Bone mineral content estimates used for four-compartment models. Fat and fat-free mass estimates prone to error due to changes in the composition of lean tissue that may persist into the postpartum period	2/Multiple[a]	Yes, but not validated	N
Ultrasound	Simple	Specialized instrument, available in most hospital settings	Estimates regional adiposity, not total body composition. Has not been validated against reference methods in pregnancy		Yes, but not validated	N

[a]These methods are used for multi-component models in combination with other body composition measurements and body mass.

developed and validated equations for estimating fat change from 14 to 37 weeks of gestation and an equation to predict FM at 37 weeks[22] (Table 2). Similarly, Huston Presley et al.[32] developed and validated an equation for estimating FM at 30-week gestation derived from SFT measures and weight (Table 2). These equations, however, are for specific gestational ages and may not apply to other times in pregnancy. Thus use of SFT measurements themselves rather than estimates of fat and FFM are often preferred.

Skinfold measurements and circumferences have been widely used to estimate changes in subcutaneous fat, as well as arm muscle area and arm fat area (Table 2), indicators of muscle mass and FM, in pregnancy.[33–37] Several studies have described longitudinal changes in SFT in various populations of well-nourished and undernourished women.[25,33–36] Together, these reports suggest highly variable changes in SFT across measurement sites over the course of pregnancy. In well-nourished populations, one study reported decreases in SFT (triceps, thigh and subscapular) from prepregnancy to 6-week gestation.[36] This

report and others indicate increases in SFT across several sites up to 30–35 weeks[33,36] followed by few changes to 38 weeks (excluding mid-thigh skinfold that continues to increase[33]). Thereafter, rapid decreases occur postpartum that are likely attributable to changes in hydration following delivery rather than marked changes in subcutaneous adipose tissue. In marginally undernourished women, average triceps and subscapular SFT increased in the first and second trimester and decreased markedly in the third trimester, resulting in a net loss in skinfolds over the course of pregnancy.[34] Although SFT increases were predominate and associated with GWG, declines in triceps and subscapular SFT were also observed, particularly in women who began pregnancy with more subcutaneous fat.[34] In both well-nourished and undernourished women, arm fat area typically increases early in pregnancy and declines in the last trimester, while arm muscle area increases in this period.[25,33,35]

Estimates of body fat changes derived from skinfolds are prone to measurement error, especially during pregnancy.[38]

Table 2. Equations for estimating body fat in pregnancy

	Population
Anthropometric equations	
Paxton (1) fat change from 14 to 37 weeks:	White, black and Hispanic women in New
Fat change, kg = 0.77 (weight change, kg) + 0.07 (change in thigh skinfold thickness, mm) − 6.13.	York City, NY, USA
Paxton (1) body fat mass at term (37 weeks):	
Fat mass, kg = 0.40 (weight at week 37, kg) + 0.16 (biceps skinfold thickness at 37 wk, mm) − 0.15	
(thigh skinfold thickness at 37 weeks, mm) − 0.09 (wrist circumference at 37 weeks, mm) + 0.10	
(prepregnancy weight, kg) − 6.56 (2).	
Huston Presley (2) body fat mass at 30 weeks:	Predominantly white women in
Fat mass, kg = 0.33529 (weight, kg) + 0.65664 (triceps skinfold thickness, mm) − 0.4373	Cleveland, OH, USA
(subscapular skinfold thickness, mm) + 0.43461 (suprailliac skinfold thickness, mm) − 13.0538.	
Equations for deriving arm fat area (AFA) and arm muscle area (AMA) (3)	
AMA (cm^2) = [mid-upper arm circumference − (triceps skinfold × π)]^2/4π	
AFA (cm^2) = (mid-upper-arm circumference^2/4π − arm muscle area) (3)	
Equation for body composition from body density, total body water and body weight	
Siri (4, 5) equation for body composition:	
Fat mass, kg = [2.118 × (BV/body weight)] − (0.78 × TBW/body weight) − 1.354] × 100	

Abbreviations: BV, body volume (l); TBW, total body water (kg).

First, extensive technician training is necessary to obtain valid and reliable measures of SFT and anthropometry. Second, SFT is influenced by the compressibility of the subcutaneous adipose tissue layer that is affected by site, age, gender, recent weight changes and also pregnancy. There is some evidence that skinfolds compressibility increases in the first trimester and gradually increases thereafter in the second and third trimesters, which is believed to be attributable to the increases in hydration of extracellular components of connective tissues due to shifts in hormonal milieu.[39] This study was completed in a cohort of primaparous women in the 1960s; whether these reported compressibility changes across pregnancy vary by GWG, rate of weight gain or other factors is unknown, and more research on this subject in contemporary cohorts is needed. In contrast to previous findings, percentage of skinfold compression calculated from calipers and ultrasound measurements in pregnant adolescents was found to decrease between ~11- and ~30-week gestation in the trunk region, but no changes were observed in the limb regions.[40] It is important to note that these findings may not be generalizable to adult populations, as body composition changes are different in adolescent pregnancy compared with adult women,[41] and whether skinfold compressibility is different in adolescent pregnancy compared with adult pregnancy has not been reported.[41] Moreover, as pregnancy progresses it becomes difficult to obtain skinfold measurements from the trunk region.[42] Edema may also affect the ability to obtain accurate measurements, especially in the leg region. Finally, equations have not been developed for estimating body composition changes in FM and FFM throughout pregnancy from SFT measures. Applying equations from non-pregnant populations to estimate FM and FFM may not be appropriate, particularly in resource-poor settings.

TBW

During pregnancy, TBW changes are highly variable. Several studies have reported TBW accretion of approximately 5–8 l over the course of pregnancy.[15–18] However, in Swedish women TBW accretion of 6.6 l was reported by 32-week gestation,[43] which is somewhat higher than previously reported taking into account the timing of this measurement relative to delivery, and therefore may indicate greater TBW accretion in pregnancy compared with previous estimates in this population.

TBW is typically measured using the dilution principle with isotope-labeled water labeled with deuterium (^2H_2O) or Oxygen 18 (^{18}O), which provides an estimate of TBW in the combined maternal and fetal unit. Before administering the labeled water, a physiological baseline sample of serum, urine or saliva is collected. A precisely weighed dose of labeled water is then ingested orally or administered subcutaneously. Two methods are utilized to determine TBW by dilution: plateau and back extrapolation. With the plateau method, a second physiological sample is obtained after an equilibration period; extended in pregnancy to 4 h for oral dosing and 3 h for subcutaneous dosing to ensure equilibrium,[44] as extracellular water compartments are expanded. With back extrapolation, physiological samples are collected at several intervals up to 14 days after dose administration, and TBW is calculated by back extrapolation to the time of dose.

Body composition estimates can be determined from TBW coupled with measurements of body weight and density; yet, inherent in this estimate is the assumption of the hydration of FFM, calculated as the ratio of TBW to FFM, to be approximately 0. 73.[45] FFM hydration changes in pregnancy leading to errors in body fat estimates.[43] Moreover, FFM hydration variability also changes during the course of pregnancy with greater variability early in pregnancy (14 weeks) compared with variability at 32 weeks,[43] suggesting the two-compartment model is less accurate in individuals in early pregnancy due to heightened biological variability of the hydration of FFM. Several studies have predicted[19,21,46] or estimated[20,43] hydration factors which indicate that the hydration of FFM generally increases as pregnancy progresses and subsequently decreases postpartum, and correction factors are available for varying gestational ages (Table 3). These were developed in predominantly normal BMI populations from United States or Europe who were of White, Black or Hispanic origins (if reported). Because of variation in FFM hydration in severe obesity and in racially and ethnically diverse samples, these hydration factors may not apply to all populations; thus additional research is needed in this area. Another consideration is the proportion of gain in FFM relative to pregravid FFM; Van Raaij et al.[19] suggested that the gain in FFM relative to prepregnancy FFM may influence the hydration of FFM which would therefore result in errors based on hydration factors calculated for a reference woman. However, based on their estimates for a range of ratios for gain in FFM relative to prepregnant value, this is unlikely to result in a substantial error, as the body fat estimates from their derivations for those with extreme ratios only differed slightly from estimates of the reference women (0.3–0.6 kg),[25] and thus the authors suggest that these hydration ratios may be appropriate for most pregnant women.[19]

Table 3. Hydration and densities of fat-free mass from prepregnancy to postpartum[a,b]

	Prepregnancy	Weeks			Postpartum	Density component	Population
		10–14	~20	30–32	35–40			

Hydration (%)

Longitudinal studies

	Prepregnancy	10–14	~20	30–32	35–40	Postpartum	Density component	Population
van Raaij et al.[19 c]								
No/only leg edema		0.725	0.732	0.740	0.750			Derived by van Raaij et al.[19] from data on chemical analysis of six adult humans (five male, one female), BMI not reported[84]
Edema		0.725	0.734	0.748	0.765			
Fidanza et al.[21 c]	0.738	0.738		0.752	0.761			Derived from reference body[85] (based on three male cadavers): mean BMI: 20.9 kg/m^2
Lof et al.[43]	0.718	0.723	0.747	0.747		0.732		Swedish women (n = 19), pregravid BMI: 24.2 kg/m^2
Paxton et al.[22]		0.738			0.757			US women (n = 200): 55% Hispanic; 21% non-Hispanic White; 25% non-Hispanic Black; pregravid BMI: underweight (< 19.8): 10.5%; normal (19.8–26.0): 61.5%; overweight (>26–29.0): 14.5%; obese (>29): 13.5%
Sohlström and Forsum[42 d]	0.669 ± 3.3[e]					0.697 ± 5.0[e]		Swedish women (n = 16); pregravid BMI: 23.7 kg/m^2
Hopkinson et al.[48]				0.76 ± 0.02		0.75 ± 0.02		US women (n = 56); pregravid BMI: 22.8 kg/m^2
Cross-sectional studies								
Prentice et al.[46]					0.768			British women (n = 8); pregravid BMI: 23.1 kg/m^2
Catalano et al.[20]				0.762				Predominately white US women (n = 20); pregravid BMI: 25.7 kg/m^2

Density (g/cm^3)

	Prepregnancy	10–14	~20	30–32	35–40	Postpartum	Density component	Population
Paxton et al.[22 f]		1.100			1.091		Maternal and fetal	Estimates based on the Selinger four-compartment model;[86] population details above
Fidanza et al.[21 c]	1.100	1.100	1.097	1.092	1.087		Maternal and fetal	Derived from reference body (based on three male cadavers) and based on Hytten's report:[25] mean BMI: 20.9 kg/m^2
Hopkinson et al.[48 g]					1.087 ± 0.006	1.094 ± 0.007	Calculated maternal	Estimates based on the Fuller four-compartment model corrected according to the estimates by van Raaij et al. at 36 weeks;[19] US women (n = 56); pregravid BMI: 22.8 kg/m^2

Density (g/l) of fat-free mass gain

	Prepregnancy	10–14	~20	30–32	35–40	Postpartum	Density component	Population
van Raaij et al.[19 c,f]								
No/only leg edema		1.022	1.027	1.032	1.030		Maternal and fetal	Estimates derived from Hytten, population details not reported
Edema		1.022	1.020	1.023	1.019			

[a]Hydration factor for fat-free mass calculated as total body water/ fat-free mass. [b]Values reported are mean ± s.d. [c]Estimates derived from Hytten's estimates of composition of tissues.[25] [d]Fat-free mass estimated with magnetic resonance imaging (MRI). [e]Because fat-free mass was estimated with MRI, these values are based on different assumptions and are not comparable with the other values in the table. [f]Density estimated with underwater weighing and estimated using the Goldman and Buskirk equation.[87] [g]Derived from equations from Van Raaij et al. (1988) developed according to the Hytten's estimates of composition of tissues.[25]

Although TBW measurements using stable isotope methods are considered safe in pregnancy, women may not want to ingest the stable isotope, and the method may be difficult to perform in settings without access to refrigeration. Other indirect methods of measuring body water in pregnancy have not been developed or validated against reference methods across a range of gestational ages (for example, TBW estimates from bioelectrical impedance analysis (BIA) or bioimpedance spectroscopy (BIS)); while BIS TBW estimates were comparable to deuterium estimates at 14 weeks, BIS TBW estimates were significantly lower than deuterium at 32 weeks, indicating that a revised model is needed for this period.[47] Moreover, the correction factors for TBW estimates needed to derive body composition estimates may need to be population specific (normal weight, overweight, obese).

Densitometry

Body density can be estimated using hydrodensitometry (HD), otherwise known as underwater weighing, or air-displacement plethysmography (ADP) from which estimates of body composition of the combined, maternal–fetal unit can be derived; these methods are unable to assess body density of the pregnant women independent of the fetus and supporting tissues. Body density (DB) is estimated from the ratio of body mass (M) to volume (V) (DB = M/V), from which estimates of FM and FFM can be derived incorporating assumed respective densities for fat (DF) (0.900 g/cm^3) and FFM (DFFM) (variable, see Table 3): 1/DB = FM/DF+FFM/DFFM.

Estimation of body components with these methods is affected by the shifts in the density and composition of FFM over the course of pregnancy. Initially FFM increments are predominately maternal tissues, while in later pregnancy FFM changes are predominately fetal tissues of lower density.[24] As such, FFM density is decreased in late pregnancy relative to a non-pregnancy state; estimates of body composition during this time that do not account for this decrease underestimate FFM and overestimate FM. Studies have been conducted in an effort to obtain a better estimate of the density of maternal and/or the maternal–fetal unit FFM across the course of pregnancy. FFM density values have also been estimated for various gestational ages (Table 3).[19,21] These values may not be applicable to all populations and research to

understand if body density values vary by maternal age, race/ethnicity and size is warranted.

HD uses Archimedes' principle to estimate body density, where due to buoyancy the weight of a body immersed in fluid is equal to the weight of displaced fluid: body volume = (weight$_{AIR}$ − weight$_{WATER}$)/density$_{WATER}$. Several studies have utilized HD, which has primarily been incorporated into four-compartment model estimates of body composition.[12,15,48] More recently ADP has become more popular to estimate body composition and density, but use in pregnancy has been limited. ADP is based on Boyle's law, where air compressed will decrease in volume proportional to increasing pressure at a constant temperature. ADP is measured with the BodPod (Cosmed, Concord, CA, USA), a device with two chambers, one where the subject sits of approximately 450 l and a reference chamber of approximately 300 l, and a moving diaphragm between the chambers that produces contrasting small volume and pressure changes in each chamber.[49,50] Based on these changes coupled with measurement and correction for lung volume (estimated through a breathing exercise), body volume and composition (FM and FFM) are estimated. Subjects need to wear skintight clothing, such as a tight-fitting swimsuit or undergarments, to minimize the amount of trapped air in hair or clothes that would result in an overestimate of body volume.

HD and ADP are non-invasive methods to obtain body density of the maternal–fetal unit; however, these methods are not suitable for field research and require specialized equipment. Although HD has been used extensively in pregnancy, it may be difficult for pregnant women to be submerged in water, particularly later in pregnancy. Thus ADP may be the preferred body volume and density method in pregnancy for measuring the combined maternal–fetal unit due to its ease. However, as the system has not been validated in persons weighting >250 kg, obese pregnant women whose body weight exceeds this limit at any point in pregnancy, even if the system can accommodate their body size, should not be measured.

Imaging

Imaging methods, including computed tomography and magnetic resonance imaging (MRI) and three-dimensional photonic scanning (3DPS), can be utilized to estimate body composition; however, 3DPS and MRI are still in the exploratory stages for pregnancy, while computed tomography is contraindicated due to radiation exposure and has not been utilized to evaluate changes from prepregnancy to postpartum. As such, this discussion will focus on 3DPS and MRI.

MRI is the only method available for in vivo measurement of adipose tissue, skeletal muscle and organ mass that can estimate changes in mass and distribution over the course of pregnancy; however, density and hydration cannot be measured with MRI. There are no known risks to the use of MRI at low field strengths (for example, 1.5 Tesla) but its safety during the first trimester has not been sufficiently evaluated.[51] There are no published studies to date that have used MRI to estimate changes in maternal body composition during pregnancy. One study used MRI before pregnancy and again 5–10 days postpartum in 15 Swedish women.[52] On average, women gained 7.4 kg from prepregnancy to 1-week postpartum in total body adipose tissue.[52] This included a 5.4 l gain in whole body adipose tissue of which gains were primarily subcutaneous 4.1 l gain in subcutaneous tissues and 1.3 l in non-subcutaneous tissues. There was marked variation between women in terms of the overall changes and regional distribution of the adipose tissue; moreover, a net loss in tissue volume was observed in a few women.[52] Although this study provides much insight regarding gains in subcutaneous and overall body fat in pregnancy, the time period before conception was not reported. If this period was extended beyond a few weeks, error may have

been introduced to the estimates of changes in body composition; however, obtaining estimates immediately before conception is typically not feasible for most researchers.

In vivo validation of MRI estimates is not feasible; therefore, studies have compared MRI estimates obtained before or after pregnancy with other body composition assessment methods.[42,53] In 25 healthy Swedish women, the difference between the percentage of fat estimates from HD and MRI was $1.4 \pm 2.9\%$, which did not vary by percentage body fat ($r = 0.39$, $P > 0.05$).[53] In 11–16 women, MRI estimates of percentage of fat measured before and after pregnancy were significantly lower than estimates from skinfolds and body water dilution.[42] Although MRI research is currently the most cutting-edge method available for use in pregnancy, there are several limitations, including cost of the MRI test, technician expertise, unsuitable for field-based settings and time required for the test and analysis. Moreover, pregnant women may not want to be exposed to a magnetic field. Finally, overweight and obese women may have difficultly fitting in the MRI device, particularly later in pregnancy.

3DPS has been validated for measuring body volumes,[54,55] circumferences, length and percentage of fat in adults;[55] however, 3DPS has not been validated to estimate dimensions and composition in pregnancy. Two cross-sectional studies have examined changes in body shape in relation to parity.[56,57] In British women, parity was associated with increased waist and thigh girths in women aged < 41 years; but in older women this association was not observed, suggesting that effects of parity on body dimensions are attenuated over time.[58] Somewhat similar regional trends were observed in Thai women aged < 41 years, in whom parity was associated with greater waist and arm girth but lower calf girth.[57] In contrast to the findings in British women, an association was observed between parity and increased arm girths, but reduced hip, and calf girths in older Thai women, which is likely attributable to the differences in socioeconomic status, activity and diets between these populations.[57]

Ultrasound

Several cross-sectional[59] and longitudinal[40,60] studies have used ultrasound measurements in pregnancy to measure maternal regional subcutaneous and visceral fat; however, standardized protocols for body fat assessment with ultrasound have not been developed. Thus it may be challenging to reliably and validly track adipose tissue changes over the course of pregnancy, particularly as the compressibility of tissue changes (see skinfolds section), thereby influencing ultrasound estimates. In adult men ($n = 124$), ultrasound and SFT estimates of subcutaneous fat at triceps, biceps, subscapular, waist, suprailliac, thigh and calf sites were significantly negatively correlated ($r = -0.48$ to -0.75, $P < 0.001$) with HD-derived estimates of body density.[61] In non-pregnant females ($n = 50$), ultrasound-derived intra-abdominal thickness was correlated ($r = 0.67$, $P < 0.001$) with computed tomography estimates of visceral fat.[62] Although both of these studies had significant correlations, the coefficients were indicative of mediocre or poor prediction, which is likely attributable to the various factors influencing the compressibility of the skin at the ultrasound site even in non-pregnant adults. In pregnancy, ultrasound has not been validated against a suitable reference method, such as MRI. However, because ultrasound is widely available in hospital-based settings, further research is needed to develop standard protocols for measurement and analysis if validity and reliability is demonstrated.

BIA

BIA is an inexpensive, rapid and non-invasive method for estimating body composition. BIA is based on the assumptions and relationships regarding electrical properties of various biological tissues at varying frequencies. BIA devices use an alternating current with very low amperage that uses the water content of the body as a

conductor. The impedance, or opposition, of the electrical flow by tissues allows for estimation of TBW from which estimates of fat and FFM can be derived.

Several factors compromise the validity and ability to validate BIA in pregnancy. First, estimates of TBW are influenced by the ratio of intracellular (ICW) to extracellular water (ECW),[63] which changes markedly throughout pregnancy compared with a non-pregnant state[64] and is likely to vary between women and by gestational age. BIA devices currently estimate this ratio with manufacturer-developed regression equations; no comparisons of BIA ECW/ICW estimates to reference methods have been reported. Previously, BIS (an approach similar to BIA that measures impedance at varying frequencies) estimates of ICW, ECW and TBW at 14 weeks and ICW at 32 weeks were similar to reference methods (sodium bromide and deuterium dilution), while ECW and TBW estimates were lower than reference values at 32 weeks.[47] The authors report that the model utilizing wrist-to-ankle BIS was developed in non-pregnant populations and may not be suitable for pregnancy, where greater water is located in the trunk region compared with non-pregnant populations, and therefore suggest development of a new model for BIS for assessment of body water in pregnancy.[47] Therefore, it is unclear whether it is even feasible to validate BIA in pregnancy owing to the between-women variability of changes in TBW concurrent with changes in composition.

Dual-energy x-ray absorptiometry (DXA)

DXA is unsuitable in pregnancy due to radiation exposure; however, DXA is used before and after pregnancy to measure bone mineral content (BMC), which is one of the components in four-compartment model estimation of body composition,[12,17,48] and can also be used for estimates of fat and FFM. Use of DXA estimates of BMC for four-compartment estimates of fat and FFM assumes no changes across the course of pregnancy and no changes from delivery to time of measurement. However, several studies have reported conflicting evidence of either no significant changes[65–69] or small changes[70–73] in BMC at specific skeletal sites or total body BMC. Another study reported declines at several sites and in whole-body bone mineral area density (bone mineral content adjusted for area of the skeleton scanned) in pregnancy.[74] Together this indicates that further research is needed in this area. In the event that BMC values change during pregnancy, correction factors would need to be developed.

Several assumptions underlie DXA estimates of body composition for soft tissue: (1) a constant attenuation of the fat and lean tissue, (2) body thickness does not influence measurements, and (3) the fat content of the area analyzed is comparable to the fat content of the non-analyzed areas; and for BMC estimates: (1) small changes in hydration of FFM, and (2) body thickness do not affect estimates. Given the marked changes in body water in pregnancy, at parturition and postdelivery, DXA measurements are typically conducted a few weeks (range: 2–6 weeks[17,48,75]) after delivery to allow for some normalization of body water values. It is unclear, however, whether BMC changes between delivery and this period, particularly for lactating mothers, or whether varying subject thickness influences BMC values in postpartum women. Although DXA has been suggested for measuring total fat and FFM from prepregnancy to postpartum, as well as changes in regional lean and FM,[64] we caution the use of DXA in the immediate postpartum period for estimating fat, FFM or lean mass due to the influences of ongoing changes in body water and hydration of FFM that likely violate the assumptions inherent in these estimates.

SUMMARY OF BODY COMPOSITION CHANGES IN PREGNANCY

Overall maternal body composition changes markedly across the course of pregnancy to support the growing fetus and prepare the mother for lactation. Here we summarize the results from several reports of four-compartment estimates of body composition changes in multi-ethnic women from metropolitan areas in the United States (Table 4). Overall, these women exhibited somewhat similar gains in weight, fat and body water across pregnancy, and subsequent decline in values postpartum. Whether women in other countries and socioeconomic settings or women with overweight/obesity/underweight prepregnancy BMI or excessive/inadequate GWG experience similar changes in body composition over the course of pregnancy and postpartum is unclear and warrants further research.

OVERVIEW OF PREDICTORS OF BODY COMPOSITION CHANGES IN PREGNANCY

Several factors, including initial size, parity, race and socio-economic status, have been established as predictors of GWG;[1]

Table 4. Summary of four-compartment estimates of body composition across pregnancy

			Weeks			
		Prepregnancy	8–14	26	36–40	2–6 Postpartum
Hopkinson et al.[1,48]						
n = 56	Body weight, kg	60.7 ± 9.1			74.6 ± 10.1	66.3 ± 9.8
Houston area	FM, kg				22.8 ± 7.1	22.0 ± 7.3
0.6 mean parity	TBW, kg				39.3 ± 3.9	33.2 ± 3.8
Multi-ethnic: predominately White						
Kopp-Hoolihan et al.[2,17]						
n = 9	Body weight, kg	64.7 ± 7.8	64.9 ± 8.4	72.1 ± 9.4	75.9 ± 9.6	68.0 ± 8.9
San Francisco Bay area	FM, kg	46.3 ± 6.2	46.7 ± 6.5	49.7 ± 5.8	52.8 ± 5.3	46.7 ± 5.1
Primi/multiparous	FFM, kg	20.2 ± 4.7	20.3 ± 4.7	24.4 ± 4.4	24.3 ± 5.6	22.0 ± 4.6
Race/ethnicity not reported	TBW, kg	33.5 ± 4.5	33.9 ± 4.8	36.5 ± 4.1	39.1 ± 3.9	33.8 ± 3.7
Lederman et al.[3,75]						
n = 196	Body weight, kg	63.3 ± 12.9	65.3 ± 12.9		76.8 ± 12.6	
New York area	FM, kg		21.4 ± 9.04		24.8 ± 8.58	
0.8 mean parity	TBW, l		32.4 ± 4.7		39.4 ± 5.15	
Multi-ethnic: Black, White, Hispanic, and non-Hispanic						

Abbreviations: FM, fat mass; FFM, fat-free mass; TBW, total body weight. Values reported are mean ± s.d.

however, whether these factors independently predict overall body composition changes across pregnancy is unclear due to limited studies in this area. Here, we briefly review predictors of these changes, including initial maternal size, parity, socio-economic factors and adolescent pregnancy. Initial maternal size, measured typically by prepregnancy BMI, is associated with regional[36,76] and total body changes in fat but not TBW.[15] Heavier women show smaller changes in SFT, whereas underweight women show larger changes.[33,36] Primiparous women showed larger changes in skinfolds, compared with multiparous women.[33,36] Compared with girls who had stopped growing or mature women, adolescent pregnancy among growing girls was associated with continued increases in arm fat area and no changes in subscapular SFT after 28-week gestation, suggesting that energy reserves were being conserved.[77] There is some evidence of associations between higher socioeconomic status and regional changes in body composition;[35] however, few studies have reported associations between socioeconomic status and overall changes in composition. Wealth, occupation, education, as well as, maternal age and parity predicted changes in mid-upper arm circumferences, arm muscle area or arm fat area in generally healthy HIV+ Malawian women, while seasonal exposure to famine modified some of these associations.[35] Some but not all maternal and offspring obesity-related genetic variants are associated with GWG,[78,79] but it is unknown whether these variants are associated with the composition of GWG. Although racial differences in regional fat distribution have been reported,[80] these reports have not included pregnancy and it is unknown whether body composition changes during pregnancy differ by race/ethnicity.

OUTCOMES OF MATERNAL BODY COMPOSITION CHANGES IN PREGNANCY

Although there is a growing body of research focusing on perinatal, offspring and maternal outcomes of GWG,[4] there is a dearth of information on the short- and long-term outcomes of body composition changes during pregnancy on offspring and maternal outcomes and also whether these associations vary by initial BMI and body composition (FM, FFM). This is largely attributable to challenges in measuring body composition during pregnancy. The composition of GWG has been identified as a predictor of postpartum weight and fat retention, as well as the pattern of adipose tissue accretion in parous versus nulliparous women. In 63 women from the Houston area, greater FM gains in pregnancy was associated with higher weight and fat retention at 27 weeks postpartum.[12] Moreover, childbearing was associated with greater visceral adipose tissue accumulation, independent of overall body fat changes.[81] Several studies have established that the overall composition of weight gain, specifically gains in body water and/or lean mass, are associated with greater offspring birth weight,[12,75,82] whereas gains in fat are not associated with birth weight.[12,18,75] Because of the limited studies with robust body composition estimates in pregnancy that have measurements beyond the first year of life, it is unclear whether the composition of GWG is associated with later maternal and offspring FM and obesity-associated sequelae.

RESEARCH GAPS IN BODY COMPOSITION ASSESSMENT IN PREGNANCY

Due to the dearth of literature in this area, we were unable to do a systematic review or meta-analysis on this subject. Few studies have been conducted in contemporary cohorts of multi-ethnic populations of varying initial size (for example, underweight, overweight or obese) and socioeconomic status. It is unclear whether racial and ethnic differences in body composition observed in women of reproductive age also apply to changes in body composition in pregnancy.[80] Although several methods are considered 'satisfactory'[1] or 'acceptable'[27] to assess changes in body composition in pregnancy, all well-established methods of overall body composition are unable to disentangle the maternal––fetal unit, which is an important goal for future research in this area; differentiating some components (for example, adipose tissue, skeletal muscle mass) may be feasible with MRI. It is clear that validation of methods that are non-invasive and readily accessible in clinical settings such as BIA and ultrasound appear warranted. If possible, validation of BIA is needed so that revised BIA equations and/or correction factors can be developed that account for changes in TBW and the FFM hydration in pregnancy. Ultrasound methodology needs to be standardized for use in clinical practice. Although several equations are available for estimating fat and lean mass in pregnancy, further development of equations that account for predictors of body composition that may vary across gestational age is needed. Finally, studies that examine determinants and outcomes of body composition changes in pregnancy are needed in order to guide future interventions and public health policies to optimize maternal health in pregnancy and maternal and offspring health postpartum.

CONCLUSIONS

Maternal body composition changes in pregnancy are associated with maternal and infant health outcomes in the immediate postpartum period and thereafter. Although there is a body of research regarding predictors and outcomes of GWG, these studies are unable to disentangle the components of weight gain (FM versus FFM) and how these components influence both maternal and offspring health. This may be due, in part, to the challenges of measuring maternal body composition in pregnancy due to the dynamic shifts in this period and also the lack of available methods to differentiate maternal and fetal components. The most commonly used method to measure maternal body composition changes in pregnancy is anthropometry (SFT and mid-upper arm circumferences). Although BIA has been used, it does not provide a measure of maternal body composition that is independent of the fetus and supporting tissues. The gold-standard four-compartment model currently provides the most robust estimates of body composition and changes in pregnancy but is unable to disentangle maternal and fetal tissues. Emerging methods that yet require validation and standardized methodology include MRI and ultrasound. Future research should focus on improving estimation of body composition changes and understanding predictors or modifiers of these changes, particularly prepregnancy BMI and body composition, across the duration of pregnancy in resource-rich and resource-poor settings with the ultimate goal of improving maternal and offspring health in pregnancy and thereafter.

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