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Changes in Visceral and Ectopic Adipose Tissue Stores Across Pregnancy and Their Relationship to Gestational Weight Gain

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ABSTRACT

Background: Excessive gestational weight gain has been associated with increased total body fat (TBF), metabolic syndrome, and abdominal obesity. However, little is known about the relationship of gestational weight gain with changes in metabolically active visceral or ectopic (hepatic and skeletal muscle) lipid stores.

Objectives: In a prospective study of 50 healthy, pregnant women, we assessed whether changes in weight were associated with changes in total, visceral, and ectopic lipid stores.

Methods: Participants (ages 19–39) were primarily White (84%). The mean preconception BMI was 25.8 kg/m^2 (SD, 4.5 kg/m^2; min-max, 17.1–35.9 kg/m^2). Measurements were completed at visits 1 and 2 at means of 16 and 34 weeks gestation, respectively, and included TBF using BOD POD; abdominal subcutaneous adipose tissue (SAT) and visceral adipose tissue (VAT) using MRI; and intrahepatic lipids (IHL), intramyocellular lipids (IMCL), and extramyocellular lipids (EMCL) using magnetic resonance spectroscopy. We used paired *t*-tests to examine changes in adipose tissue and Pearson's correlation to examine associations of adipose tissue changes and weight changes. We also examined whether changes in adipose tissue stores differed by preconception BMI (normal, overweight, and obese), using 1-way ANOVA.

Results: The TBF (mean change, +3.5 kg; 95% CI: 2.4–4.6 kg), SAT (mean change, +701 cm^3; 95% CI: 421–981 cm^3), VAT (mean change, +275 cm^3; 95% CI: 170–379 cm^3), and IHL (percentage water peak; median, +0.15; IQR = −0.01 to 0.32) values increased significantly; the IMCL and EMCL values did not change. Changes varied by BMI strata, with the least increase (or, for SAT, net loss) among women with obesity. Weight change was positively correlated with changes in TBF ($r = 0.83$; $P < 0.001$), SAT ($r = 0.74$; $P < 0.001$), and VAT ($r = 0.63$; $P < 0.001$) but not significantly correlated with changes in ectopic lipids (IHL, IMCL, and EMCL; $−0.14 < r < 0.26$).

Conclusions: Preferential deposition of adipose tissue to the viscera in pregnancy, as seen in our sample, could serve an important metabolic function; however, excessive deposition in this region could negatively affect maternal health. *J Nutr* 2022;152:1130–1137.

Introduction

In nonpregnant adults, visceral adiposity and ectopic fat are risk factors for type 2 diabetes and cardiovascular disease (1). Studies assessing central adiposity among women in the postpartum period suggest that pregnancy is associated with an increase in abdominal adipose tissue stores and specifically with an increase in abdominal visceral adipose tissue (VAT) (2). Excessive gestational weight gain is associated with increased

risks of metabolic syndrome and abdominal obesity (assessed by waist circumference) at 8 years postpartum (3). Understanding how gestational fat mass is distributed in normal pregnancy into abdominal and ectopic stores (muscle, liver) may provide insight into potential mediators of elevated maternal-fetal risks associated with maternal obesity and excessive gestational weight gain.

Previous studies have attempted to describe changes in VAT using serial abdominal ultrasound measures of preperitoneal

and visceral adipose tissue depths from early pregnancy to the early postpartum period (4, 5). However, ultrasound measures of VAT depths during pregnancy have not been validated against standard imaging techniques, such as MRI, and cannot be used in late pregnancy due to the enlarging uterus. A recent study utilizing whole-body MRI documented retained excess VAT up to 59 weeks postpartum compared to early pregnancy in mothers with preconception overweight or obesity (6), but this study was not able to include a later-pregnancy VAT measurement or determine amounts of ectopic lipid stores in liver [intrahepatic lipids (IHL)] and muscle [intramyocellular lipids (IMCL) and extramyocellular lipids (EMCL)].

The goal of the present study was to examine changes in abdominal subcutaneous adipose tissue (SAT), VAT, and ectopic lipid stores (IHL, IMCL, EMCL) during normal gestation in women spanning the preconception weight range from lean to obese using advanced imaging techniques, which would allow for measurement of these depots in both early and late pregnancy. We hypothesized that while visceral and ectopic adipose tissue stores would positively correlate with gestational weight gain, significant variations would nonetheless exist within different weight gain groupings, findings which could potentially serve as a reference for current and future studies of the relationship between maternal adiposity and maternal-fetal outcomes.

Methods

Study population

We conducted a prospective cohort study of healthy, pregnant women who were receiving care at Kaiser Permanente Northwest at the time of our recruitment window (November 2014 to April 2017). Patients were eligible if they were from 18–45 years of age; were less than 12 weeks pregnant with a singleton gestation; had a BMI between 18.5 kg/m^2 and 38 kg/m^2 at the time of enrollment; and were fluent English speakers. Patients were considered ineligible to participate if they met any of the following exlusion criteria: pregestational or gestational diabetes at the time of enrollment; contraindications to MRI study (e.g., claustrophobia, metal implants); a history of bariatric surgery or other medical conditions requiring specialized nutritional care; anemia; a current history of drug, tobacco, or alcohol use; a maternal rheumatologic or chronic inflammatory state; or chronic hypertension.

We used the Kaiser Permanente Northwest electronic medical record to identify members who met the study inclusion criteria. We mailed potentially eligible participants a recruitment letter and followed up by telephone a week later. During the phone call, study personnel performed additional eligibility screening. Women who were interested in participating were then scheduled for an explanatory visit, at which the study procedures were reviewed with the patient and written, informed consent was obtained. The study was performed in accordance with the Declaration of Helsinki and approved by the Kaiser Permanente Northwest (study ID #Pro00003993) and Oregon Healthy and Science University (study ID #10438) institutional review boards.

Body composition and distribution measures

Body composition and distribution measures were obtained in early pregnancy (visit 1; mean, 15.5 weeks of gestation; min-max, 12.9–16.9 weeks) and again in late pregnancy (visit 2; mean, 34.1 weeks; min-max, 31.6–37.7 weeks). Weight was measured at each visit using the same calibrated scale. Height was measured at the first study visit and was used for calculating BMI. Demographic variables and pregnancy history were obtained at enrollment. Both measured weights and a self-reported pregravid weight were extracted from the electronic medical record in order to calculate the preconception BMI. For women ($n = 9$) who did not have a weight measured between 3 months before to 6 weeks after pregnancy onset, we used the self-reported pregravid weight, which has been shown in prior analyses of data from our health-care system to have the high agreement with the measured weight (7).

Air displacement plethysmography.

We used air displacement plethysmography (BOD POD, COSMED USA, Inc.) at visits 1 and 2 to determine participants' fat-free mass, fat mass, and percentage body fat. Participants wore a bathing suit or spandex clothing and a swimming cap to minimize residual air from the body surface while they sat inside the BOD POD and air displaced by the body was measured. Raw body volume measurements were corrected for the thoracic gas volume using measured values when possible. The measured thoracic gas volume values were used at both early and late pregnancy for 40 of the participants (80%), predicted values were used at both time points for 4 (8%), and a combination of measured and predicted values were used for 6 (12%) (8). Results included total mass and body density. Fat-free mass and fat mass were estimated using van Raaij et al.'s (9) pregnancy equations to account for changes in the density of fat-free mass during pregnancy (10). Because there is variability in water accumulation during pregnancy and the van Raaij et al. (9) data only provide fat-free mass density values at 10-week intervals during gestation, we developed a regression equation that estimates fat-free mass as a function of gestational age, an approach that has been used by others to address this concern (8).

MRI.

As previously described, MRI data were collected at the Advanced Imaging Research Center at Oregon Health & Science University using a Siemens Prisma Fit 3T whole-body system (Siemens Healthineers) (11). The abdominal MRI protocol included up to 30 slices with 6-mm thickness spanning from the top of the liver to the L-4/5 intervertebral disk (upper and lower bounds, respectively) for the segmentation analysis for abdominal visceral and subcutaneous fat volumes. The actual number of slices between these landmarks varied between subjects, primarily due to height differences. Manually generated uterus/placenta and liver masks were created, as these 2 regions have high rates of false positives for classification as adipose tissue. Abdominal MRI volumes were segmented into 5 classes: unlabeled, SAT, VAT, muscle, and organ (including all other abdominal volume; **Supplemental Figure 1**; **Supplemental Methods**). Segmentation mask output from the automated pipeline (11) then underwent manual review slice-by-slice. This was followed by manual refinement by a single analyst (JQP) who utilized the 3D Slicer software package to ensure accuracy of VAT and SAT mask placements and consistency in measurements (Supplemental Methods).

Magnetic resonance spectroscopy.

Magnetic resonance spectroscopy (MRS) data were acquired during the same imaging session using the same magnetic resonance machine as used for the MRI described above. The IHL, IMCL, and EMCL

TABLE 1 Changes in weight and fat measures from early to late pregnancy[1]

Measure	Early pregnancy _n_	Early pregnancy Mean (SD)	Early to late pregnancy _N_	Change from early to late pregnancy Mean (95% CI)	_P_	Proportional change (%) Mean (SD)	Correlation of change in measure with weight change _r_	_P_
Weight, kg	50	72.6 (13.7)	50	10.7 (9.5–12.0)	<0.001	15 (6)	—	
BMI, kg/m^2	50	25.7 (3.9)	50	3.8 (3.4–4.2)	<0.001	15 (6)	—	
Body fat, %	50	34.5 (7.3)	50	− 0.18 (−1.1 to 0.79)	0.72	0 (10)	0.52	<0.001
Fat mass, kg	50	25.8 (9.3)	50	3.5 (2.4–4.6)	<0.001	16 (17)	0.83	<0.001
Fat-free mass, kg	50	46.8 (6.4)	50	7.2 (6.5–7.9)	<0.001	16 (5)	0.44	0.001
SAT volume, cm^3	50	4242 (2222)	46	701 (421–981)	<0.001	24 (26)	0.74	<0.001
VAT volume, cm^3	50	771 (574)	46	275 (170–379)	<0.001	56 (55)	0.63	<0.001
IHL, % water peak[2]	50	0.81 (1.3)	46	0.15 (−0.01 to 0.32)	0.001	51 (104)	0.21	0.16
IMCL, % water peak	44	1.4 (1.6)	41	0.21 (−0.08 to 0.49)	0.15	44 (91)	0.26	0.10
EMCL, % water peak	44	1.9 (0.8)	41	0.16 (−0.12 to 0.44)	0.25	20 (62)	− 0.14	0.37

[1]Abbreviations: EMCL, extramyocellular lipid; IHL, intrahepatic lipid; IMCL, intramyocellular lipid; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue.
[2]The change in IHL is reported as the median (IQR).

were measured using ^{1}H single-voxel MRS, following MRI. The MRS voxel was centered within the mid-soleus muscle with voxel volumes in the range of 4–7 cm^3. MRS voxels were positioned to avoid vascular structures and adipose tissue deposits. MRS data for the liver were obtained within the right lobe; voxel sizes ranged from 18 to 24 cm^3.

Muscle spectra were collected using a point resolved spectroscopy (PRESS) single-voxel spectroscopy sequence. MRS were acquired with and without water suppression, with water-suppressed spectra used for IMCL and EMCL fitting. Liver MRS also used a PRESS sequence, but with 3 averages, each separately acquired during a single 10-second breath hold. All spectral fits were inspected and rerun with additional constraints if the fitting contained errors. Water and fat signals were corrected for transverse relaxation effects. IHL, IMCL, and EMCL values are expressed as proportions of the primary lipid peak to water peak areas.

The Supplemental Methods describe reliability data for measures obtained by MRS (IHL, IMCL, and EMCL) and provides a comparison of manual segmentation alone compared with automated segmentation followed by manual refinement for SAT and VAT.

Statistical analyses

Data preparation and analyses were performed using SAS software version 9.4 (12). We calculated descriptive statistics for all variables and transformed those that showed extreme deviation from a normal distribution: for IHL, we performed a negative reciprocal root transformation; for IMCL and EMCL, we performed a natural log transformation. Paired _t_-tests were used to determine whether each variable changed from visit 1 to 2; we used the Wilcoxon signed-rank test to determine the change in IHL from visits 1 to 2.

To assess how changes in fat variables related to weight changes, we calculated Pearson correlation coefficients between changes in each fat variable (body fat, fat mass, fat-free mass, VAT, IMCL, EMCL, and SAT volumes) and change in weight from visits 1 to 2. For the correlation with changes in IHL, we calculated Spearman correlation coefficients, as the assumptions for calculating the Pearson correlation coefficient were not met.

As part of a secondary exploratory analysis, we also examined whether pregnancy-related changes in fat stores differed by preconception BMI using a 1-way ANOVA, with preconception BMI category as the independent variable and baseline and change between visits 1 and 2 as the dependent variables. The BMI categories were normal weight (18.5–24.9 kg/m^2), overweight (25.0–29.9 kg/m^2), and obese (≥30 kg/m^2). Two participants with a BMI in the normal range at study enrollment had a preconception BMI <18.5 kg/m^2 (underweight) and were categorized with the normal preconception weight group for analysis. A significant omnibus test was followed by Tukey adjusted post hoc contrasts to determine which pair(s) of categories differed. Because the change in IHL still violated the ANOVA assumptions even

after transformation, we used the parallel, nonparametric alternative (Kruskal–Wallis). All inferential tests were conducted at a 2-tailed alpha level of 0.05.

In addition, as there was insufficient power to do a formal test of interaction, we descriptively examined changes in fat measures by weight gain, categorized as below, within, or above guidelines according to the National Academy (formerly Institute) of Medicine's BMI-specific recommendations for second- and third-trimester rates of gain in kilograms per week (13).

Rationale for sample size

The only available estimate for a VAT change related to pregnancy comes from 1 prior study that measured VAT using computed tomography among 122 initially nonpregnant women over a 5-year observation period. This study found that a sample of 14 women who had an interval pregnancy during the observation period had a 40% increase in VAT, while women who did not have a pregnancy had a 14% increase over the same period ($n = 108$) (2). No data were present at the time to determine the impact of pregnancy on ectopic lipid changes. Given the lack of reliable effect size estimates for the relationships of interest that occur during pregnancy, we based our power analyses on the minimum effect sizes that could be detected given the maximal feasibly achievable sample size ($N = 48$). We conducted all power analyses using PASS 2008 (14). Assuming a 2-tailed alpha level of 0.05 and an autocorrelation of 0.70, 48 women provided 80% power to detect an observed Cohen's _d_ of 0.32 using a paired-samples _t_-test. he Pearson correlation analyses have 80% power to detect a correlation as small as ±0.39 with a sample size of 48 and 2-tailed alpha level of 0.05. We assumed we would have 20% attrition from early pregnancy to late pregnancy; thus, we aimed to recruit 60 women to achieve the target sample size for the analyses.

Results

Fifty women attended both visits 1 and 2. The average time between visits was 18.6 weeks (SD, 1.5 weeks; min-max, 16–22 weeks). Participants were primarily White (84%) and non-Hispanic (88%), and just over half (58%) were nulliparous. The mean age was 30 years (min-max, 19–39 years) and the mean preconception BMI was 25.8 kg/m^2 (min-max, 17.1–35.9 kg/m^2), with 36% and 14% falling into the overweight and obese categories, respectively.

Between early and late pregnancy, weight and BMI increased as expected (Table 1). There were also net increases in both total fat mass and fat-free mass, but no significant change in
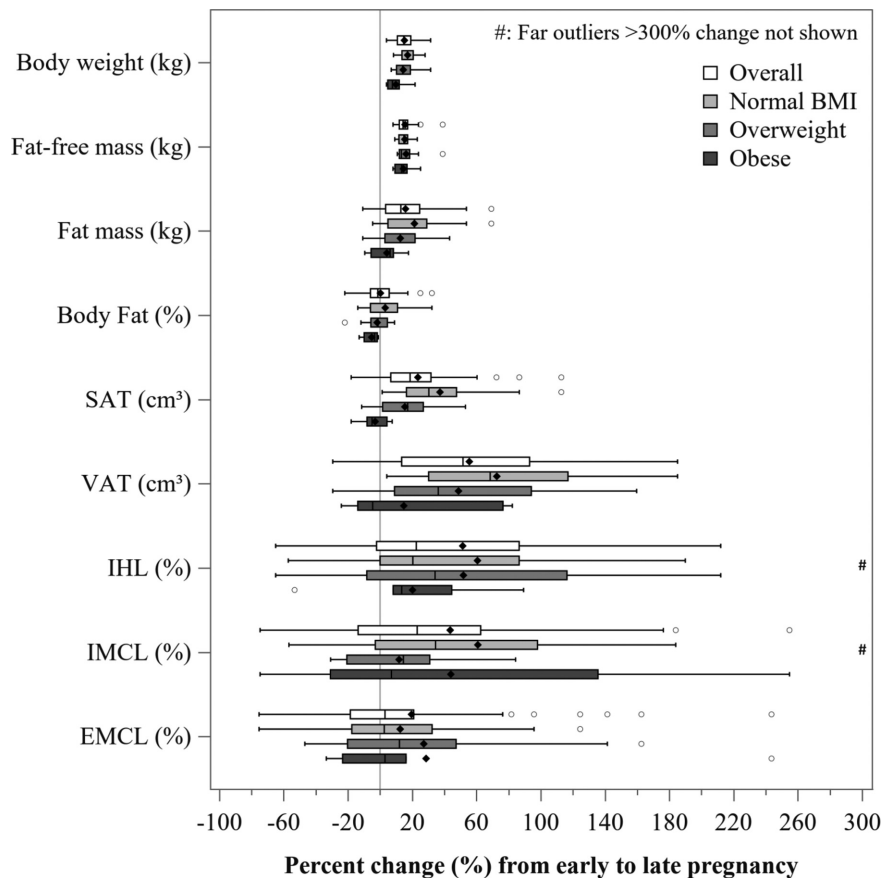
FIGURE 1 Proportional change in fat stores from early to late pregnancy. #There was 1 outlier each for IHL and IMCL. Abbreviations: EMCL, extramyocellular lipids; IHL, intrahepatic lipids; IMCL, intramyocellular lipids; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue.

percentage body fat. Abdominal adiposity measures of SAT, VAT, and IHL also increased. In comparison, IMCL and EMCL values did not significantly change. On average, the greatest site-specific proportional increases occurred in VAT (mean, 56%; SD, 55%) and IHL (51%; SD, 104%). However, there was substantial variability across participants in the changes in abdominal and ectopic adipose tissue measures (**Figure 1**).

The change in gestational weight gain showed the strongest, positive correlations with changes in fat mass ($r = 0.83$; $P < 0.001$) and SAT volume ($r = 0.74$; $P < 0.001$; Table 1). The change in gestational weight gain was also positively correlated with changes in VAT volume ($r = 0.63$; $P < 0.001$), percentage body fat ($r = 0.52$; $P < 0.001$), and fat-free mass ($r = 0.44$; $P = 0.001$), but was not significantly related to changes in ectopic lipid stores (IHL, IMCL, and EMCL; Figure 2).

In the exploratory analysis examining changes in adipose tissue stores as a function of the preconception BMI category, we found that women with obesity started pregnancy with greater fat stores, differing from women with lower BMIs in measures of total fat mass, SAT, and VAT (Table 2). However, women with obesity had the least adipose tissue gain from early to late pregnancy and, in fact, experienced a net loss in SAT volume [mean change of -370 cm³ (95% CI: -1011 to 271) compared to $+943$ cm³ (95% CI: 590–1297) and $+822$ cm³ (95% CI: 398–1246) for women with normal weight and overweight, respectively; $P = 0.003$]. There were no significant differences in VAT deposition among women with obesity, overweight, or normal-weight BMIs, and net loss of IMCL among women with obesity (-0.22% water peak; 95% CI: -0.89 to 0.45)

compared to net gain among women with normal weight ($+0.47$; 95% CI: 0.09–0.85; $P = 0.12$).

We found that there were greater increases in total fat mass, SAT, and VAT values among women with weight gain above the guidelines compared to those with weight gain within or below the guidelines (Table 3). However, this pattern was not observed for IHL, IMCL, or EMCL values.

Discussion

To our knowledge, this study is the first to describe changes in VAT stores and ectopic lipids during normal pregnancy in women across a BMI range from normal weight to obesity using MRI and MRS. While data for our cohort suggest that most adipose tissue stores increase during gestation, these changes appear to vary widely between participants and are influenced by both the preconception BMI and the amount of gestational weight gain. When considering fat mass changes relative to gestational weight gain, we found that gestational expansion of total fat mass and abdominal SAT and VAT values were highly correlated with gestational weight gain, whereas changes in ectopic lipid stores (IHL, IMCL, EMCL) were not significantly correlated. These data suggest that as a function of total weight gain, lipid deposition during pregnancy favors expansion of existing fat depots rather than ectopic sites in liver and muscle, sites that have been strongly implicated in expression of insulin resistance in nonpregnant adults.

Two prior studies using abdominal ultrasound measures have also reported increases in VAT stores during gestation.
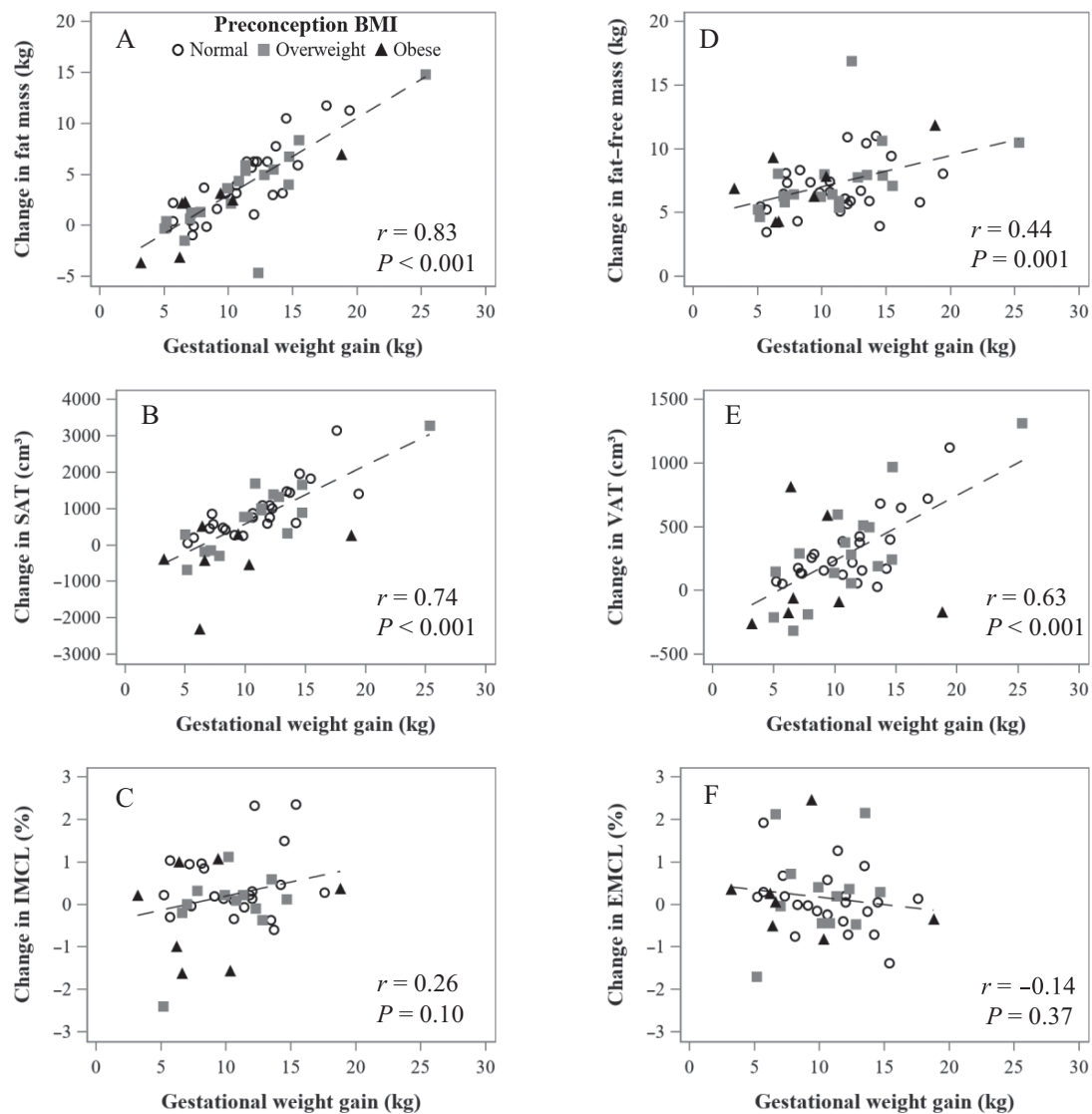
FIGURE 2 Relationship between changes in weight and (A) fat mass, (B) SAT, (C) IMCL, (D) fat-free mass, (E) VAT, and (F) EMCL from early to late pregnancy, stratified by maternal preconception BMI category. Abbreviations: EMCL, extramyocellular lipids; IMCL, intramyocellular lipids; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue.

In a prospective study of 32 women, investigators found that preperitoneal fat thickness (the preperitoneal portion of VAT) increased between the first and third trimesters of pregnancy in proportion to the total weight gain, but did not significantly change between 34–36 weeks of gestation and 4–6 weeks postpartum (4). In a longitudinal study of 75 nulliparous adolescents, investigators found a 30% increase in visceral fat thickness between the second trimester of pregnancy and the immediate postpartum period, but no significant correlations between changes in visceral fat and maternal BMI or gestational weight gain (5). However, ultrasound measures of visceral fat thickness have only been validated against a representative measure of the VAT volume in nonpregnant adults, and not during pregnancy, when gestational uterine growth results in significant visceral tissue displacement (15). In the Coronary Artery Risk Development in Young Adults (CARDIA) study, investigators found that women who had 1 birth compared to no births over a 5-year period of observation experienced a greater increase in VAT over a 5-year observation period (40% compared with 14% above initial levels, respectively)

(2), even after controlling for gains in total body fat and covariates. In the Lifestyle Intervention For Two (LIFT) study, a subgroup of 68 mothers with overweight and obesity underwent whole-body MRI in early and late pregnancy and at up to 59 weeks postpartum (6). The LIFT investigators reported abdominal SAT measurements at all 3 study visits, but VAT measurements were only reported in early pregnancy and postpartum visits, as MRI methodologic difficulties prevented investigator confidence in the VAT measurement late in pregnancy. However, the MRI slice prescription in our acquisition protocol differed from the protocol in that study in regard to the slice thickness (smaller in the present study) and slice number (greater in the present study), and by being contiguous (compared with noncontiguous in the LIFT study) in acquisition so as to include the whole abdominal compartment where the VAT was expected to expand during fetal and uterine growth. Participants in LIFT were reported to experience an approximately 30% increase in VAT by 59 weeks postpartum compared to early pregnancy, despite returning to their baseline, preconception weight. In addition, postpartum VAT measures

TABLE 2 Changes in weight and fat measures, stratified by preconception BMI[1]

Measure		Normal,[2] Mean (95% CI)	Overweight,[3] Mean (95% CI)	Obese,[4] Mean (95% CI)	P Value for ANOVA
Weight, kg	Baseline	64.1 (60.1–68.1)	77.1 (72.4–81.8)	91.3 (83.8–98.8)	
	Absolute Change	11.0 (9.3–12.8)	11.2 (9.1–13.2)	8.7 (5.4–12.0)	0.41
Fat-free mass, kg	Baseline	44.7 (42.3–47.2)	48.3 (45.4–51.2)	50.8 (46.2–55.5)	0.04
	Absolute Change	6.9 (5.9–7.9)	7.6 (6.5–8.8)	7.2 (5.4–9.1)	0.61
Fat mass, kg	Baseline	19.4 (17.1–21.7)	28.8 (26.1–31.6)	40.5 (36.1–44.8)	<0.001
	Absolute Change	4.1 (2.5–5.7)	3.5 (1.7–5.4)	1.4 (−1.5 to 4.4)	0.29
SAT, cm³	Baseline	2785 (2214–3357)	4875 (4190–5559)	7866 (6831–8902)	<0.001
	Absolute Change	943 (590–1297)[a]	822 (398–1246)[a]	− 370 (−1011 to 271)	0.003
VAT, cm³	Baseline	473 (278–667)	847 (613–1080)	1530 (1177–1883)	<0.001
	Absolute Change	307 (160–455)	308 (131–485)	92 (−175 to 360)	0.34
IHL, %[5]	Baseline	0.48 (0.38–0.62)	0.55 (0.41–0.76)	0.54 (0.36–0.90)	0.76
	Absolute Change[5]	0.16 (0, 0.33)	0.16 (−0.07, 0.38)	0.13 (0.03, 0.25)	0.89
IMCL, %	Baseline	0.79 (0.58–1.08)[a]	1.2 (0.76–1.8)[ab]	1.8 (1.1–3.2)[b]	0.03
	Absolute Change	0.47 (0.09–0.85)	− 0.03 (−0.54 to 0.48)	− 0.22 (−0.89 to 0.45)	0.12
EMCL, %	Baseline	1.5 (1.2–1.8)	1.9 (1.5–2.6)	1.9 (1.3–2.7)	0.27
	Absolute Change	0.09 (−0.30 to 0.48)	0.27 (−0.26 to 0.79)	0.20 (−0.48 to 0.89)	0.85

[1] Means in a row without a common superscript letter significantly differ from those that do. No letters mean all means differ from each other. Abbreviations: EMCL, extramyocellular lipid; IHL, intrahepatic lipid; IMCL, intramyocellular lipid; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue volume.
[2] Normal weight was defined as a BMI <25.0 kg/m² (n = 25).
[3] Overweight was defined as a BMI of 25.0–29.9 kg/m² (n = 18).
[4] Obesity was defined as a BMI ≥30.0 kg/m² (n = 7).
[5] IHL results are reported as the median (IQR).

in the LIFT study were positively correlated with measures of triglycerides and the cholesterol/HDL cholesterol ratio and were negatively correlated with HDL cholesterol (6). By obtaining a larger number of slices and contiguous slices extending up to the dome of the liver, where visceral fat could spread during uterine enlargement, we feel confident that we are adequately capturing changes in VAT volume during gestation. Indeed, our finding of a 56% increase in VAT from early to late pregnancy is consistent with their report of an increase of ∼30% in VAT postpartum, as some VAT reduction is expected when the mothers return to their prepregnancy weight. In addition, no ectopic lipid measurements were obtained in that study. Our data, combined with findings from prior studies, provide strong evidence that all abdominal fat depots (subcutaneous, preperitoneal, and visceral) increase with pregnancy. Moreover, data from the CARDIA and LIFT studies suggest that these changes persist after delivery, with the potential to contribute to increased long-term cardiometabolic risks.

We conducted exploratory analyses to assess the impacts of excessive gestational weight gain on abdominal adipose tissue and ectopic lipid accumulation. While the numbers of participants within the gestational weight gain strata were small and the statistical power was limited, the data are compelling and suggest that women with excessive gestational weight gain experience the greatest expansion in abdominal adipose tissue stores. These findings, combined with the significant positive correlations of gestational weight gain with measures of abdominal adiposity and postpartum weight retention (3, 13, 16), may help explain the detrimental impact of excessive gestational weight gain on longer-term maternal health (3, 13, 16).

Changes in ectopic myocellular and intrahepatic lipid stores during pregnancy have not been previously reported. We found that IHL stores, but not IMCL or EMCL stores, increased during gestation. However, changes in IHL stores were not significantly correlated with gestational weight gain, suggesting that the factors influencing expansion of liver fat differ from those driving expansion of total and abdominal fat depots. It should be acknowledged that overall, IHL levels were low in this population, with only 1 participant meeting the criteria

TABLE 3 Changes in fat measures relative to weight gain according to NAM guidelines

	Gestational weight gain		
Outcome measure	Below guidelines (n = 3)	Within guidelines (n = 10)	Above guidelines (n = 37)
Fat mass, kg	0.79 (1.3)	0.14 (2.1)	4.7 (3.8)
SAT, cm³	131 (110)	212 (476)	879 (1013)
VAT, cm³	66 (13)	60 (228)	350 (364)
IHL, %	0.13 (−0.07, 0.33)	0.10 (−0.16, 0.25)	0.17 (0, 0.32)
IMCL, %	0.33 (0.67)	0.06 (1.1)	0.24 (0.89)
EMCL, %	0.80 (0.98)	0.09 (1.1)	0.12 (0.81)

NAM guidelines for gestational weight gain in the second and third trimester of pregnancy, by preconception BMI, are 0.44–0.58 kg/week for underweight, 0.35–0.50 kg/week for normal weight, 0.23–0.33 kg/week for overweight, and 0.17–0.27 kg/week for obese women (13). Results are shown as the mean (SD), except for IHL data, which are reported as the median (IQR). Abbreviations: EMCL, extramyocellular lipid; IHL, intrahepatic lipid; IMCL, intramyocellular lipid; NAM, National Academy of Medicine; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue.

for nonalcoholic fatty liver disease (hepatic fat content above 5.5%) (17). Although a much larger sample of women would be needed to determine the prevalence of or progression to nonalcoholic fatty liver disease among women during pregnancy or in the postpartum period, these data suggest that accumulated adiposity during gestation favors SAT and VAT depots over ectopic stores.

Another important finding is that changes in both total adipose tissue mass and distribution in tissue stores during gestation varied substantially across preconception BMI categories. Similar to Subhan et al. (18), who used air displacement plethysmography to examine fat mass changes relative to gestational weight gain in a prospective study of 1820 pregnant women in Alberta, Canada, we found that women with obesity started pregnancy with higher total fat mass stores than those with normal weight or overweight, but they had less gestational fat gain and, in some cases, a net loss. Additionally, we found that abdominal adipose stores, both subcutaneous and visceral, were much greater at baseline in women with obesity but, during pregnancy, women with obesity had a mean net loss of abdominal SAT, whereas women who started pregnancy with a normal-weight or overweight BMI had a net gain. Further, while not significant, the overall mean gain in VAT over pregnancy was smaller for women with obesity than for women with normal or overweight BMI. These findings suggest that the degree of preconception adiposity alters the body's lipid storage and utilization during gestation, favoring the greatest accumulation in those with the least adiposity, with less in those with the greatest adiposity. This may serve to limit excess risks on adverse maternal-fetal outcomes during gestation in those with the highest preconception BMIs.

The strengths of our study include the use of advanced imaging techniques to examine maternal fat stores, which allowed us to provide novel data on visceral and ectopic lipid changes during pregnancy. We acknowledge the potential for selection bias effects on the results, given that the participants who chose to participate may differ substantially from those who did not in characteristics or lifestyle practices (e.g., diet and exercise) that could affect lipid accumulation and deposition. Further, we chose to first examine VAT and ectopic lipid changes among individuals without preexisting medical conditions, and it is possible that women with underlying health conditions have differential patterns of fat storage over pregnancy. We acknowledge the inherent limitations of body composition assessments during pregnancy and, like others (8, 10), made our best attempt to address them in our methods and calculations. While we were not able to obtain directly measured thoracic gas volumes in all participants at both time points, we believe the impact on the reported results is minimal given prior research showing the use of predicted volumes yields only a very slight bias, even in later pregnancy as the thoracic gas volume declines (19). Additional limitations include relatively small numbers of participants with obesity compared to participants of normal weight, and our inability to study women with severe obesity (BMI $\geq$40 kg/m^2) due to physical constraints of the MRI bore. There was also minimal racial or ethnic diversity in our sample.

In conclusion, we found that changes in SAT and VAT fat patterning mostly follow changes in whole-body fat during gestation but vary with preconception BMI and gestational weight gain. We also found that while liver fat increases during pregnancy, the levels remain very low and lipid content in muscle does not significantly change. Preliminary analyses also suggest abdominal adipose tissue deposition during pregnancy is greatest among women with excessive gestational weight

gain, regardless of their preconception BMI. These changes in ectopic and visceral fat during pregnancy may have implications for how glucose and the lipid metabolism are affected during pregnancy (20), and provide an antepartum basis for studies linking postpartum retention of accumulated VAT with adverse metabolic consequences for long-term maternal health (6).

Data Availability

Data described in the manuscript, code book, and analytic code will be made available upon request pending completion of institutional and data transfer agreements.

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