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Original article

Associations of maternal gestational weight gain with the risk of offspring obesity and body mass index Z scores beyond the mean

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ABSTRACT

Purpose: We examined the association of meeting the 2009 Institute of Medicine gestational weight gain (GWG) guidelines with offspring obesity and body mass index Z score (BMIZ) at age six overall and by maternal weight status.
Methods: Data were from the Infant Feeding Practices Survey II Study (2005–2007) and their Year Six Follow-Up Study (2012). Logistic regression and quantile regression models were used.
Results: Eleven percent of children were obese. Children born to mothers who gained excessive weight during pregnancy had an increased risk of obesity as compared with those born to mothers who gained adequate weight (adjusted odds ratio: 1.67). The association was stronger among normal-weight mothers (adjusted odds ratio: 3.50). Inadequate GWG was not associated with offspring obesity overall or in subsamples by maternal prepregnancy BMI. Children born to mothers who gained excessive weight had higher BMIZ. This distributional association was more pronounced among normal-weight mothers. Children born to obese mothers who gained inadequate weight had lower BMIZ at some percentiles of the BMIZ distribution.
Conclusions: Excessive GWG was associated with increased risk of offspring obesity and higher BMIZ at age six, whereas inadequate GWG was protective of high BMIZ among children born to obese mothers.

Introduction

Childhood obesity is a serious public health challenge. Childhood obesity tracks into adulthood, and if unmanaged, almost half of overweight children will remain overweight or obese as adults, putting them at risk for adverse health outcomes [1]. Reversing the obesity trend in children may minimize the negative health consequences associated with adult obesity [2]. Rising levels of childhood obesity are driven by prenatal and early life factors. Empirical evidence suggests that gestational weight gain (GWG) is associated with both short- and long-term health consequences in mothers and their offspring [3,4]. According to the 2009 Institute of Medicine (IOM) guidelines, ~43% of U.S. women gained excessive weight during pregnancy, although this percentage can be as high as two-thirds in women who are overweight or obese before pregnancy [5].

Recent findings on the association between GWG and the risk of obesity in children under age 18 years have been mixed, with some studies reporting null associations [6,7] and others reporting positive associations [3,8–10]. A meta-analysis of 12 cohort studies concluded that excessive GWG is associated with offspring childhood obesity [11]. Associations of inadequate maternal GWG with offspring obesity are inconclusive, with findings showing negative [12], null [3,13–16], or positive associations [9,10,17]. Furthermore, maternal prepregnancy body mass index (BMI) and GWG might jointly affect childhood obesity [13,16,18]. Yet, only a few studies have reported results by maternal prepregnancy BMI status [3,8,13,16], and the associations were only reported in subgroups, such as underweight [3], normal-weight [8], overweight, or obese mothers [13,15,16]. Overall, these studies indicated that the association between GWG and childhood overweight status or obesity might differ by the mother's prepregnancy BMI status.

Existing studies also investigated the impact of maternal GWG on the mean values of their offspring's BMI Z scores (BMIZ) using

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linear regression models. These findings are mixed [10,13,19,20], with some indicating that the association depends on maternal prepregnancy BMI [13,20]. It is possible that some percentiles of BMIZ might be more affected by maternal GWG. Thus, prior studies are limited in terms of focusing mainly on the BMIZ upper centiles (i.e., obesity) using logistic regression or on the mean value using linear regression. Neither of these methods captures possible different associations at different percentiles of BMIZ. Thus, the objectives of this study were to examine the associations of meeting the IOM GWG guidelines and with offspring obesity at age six using logistic regression models and then with BMIZ across the deciles of BMIZ at age six. For each association, we examined the potential moderating role of maternal prepregnancy BMI.

Material and methods

Data were from the Infant Feeding Practices Survey II (IFPS II) and its Year Six Follow-Up (Y6FU) study sponsored by the U.S. Food and Drug Administration and the U.S. Centers for Disease Control and Prevention (CDC). Pregnant women were recruited in the third trimester ($n = 4902$) and followed up until their offspring reached one year of age during the period 2005–2007. One thousand five hundred forty-two mother-child pairs had completed the Y6FU study visit in 2012 when their children reached the age of six years.

The inclusion criteria for IPFS II were as follows: mothers had to be at least 18 years old and had a singleton birth with birth weight at least 2.25 kg and gestational age ≥35 weeks. For the Y6FU study, children were excluded if they had incomplete information on the neonatal (month 1) questionnaire, were diagnosed with a condition likely affecting feeding, or were living in a geographic area to which the postal service was not available because of the Gulf Coast hurricanes of 2005 [21]. We excluded participants with missing values on maternal prepregnancy BMI ($n = 19$), GWG ($n = 47$), and child's weight and height at age six ($n = 134$). We also excluded children with biologically implausible values of BMIZ ($n = 25$) at age six based on the CDC's recommendations [22]. This resulted in 1296 mother-child pairs in our analytical sample (Supplemental Fig. 1).

Exposure

Total maternal GWG in pounds was self-reported in a neonatal questionnaire administered three weeks after delivery. We defined the GWG adequacy ratio as the total reported GWG divided by the 2009 IOM-recommended GWG corresponding to the gestational age at delivery, given the maternal prepregnancy BMI category [23]. Maternal weight gain was further categorized as inadequate, adequate, or excessive [24]. Consistent with IOM's guideline [24], maternal prepregnancy BMI in kg/m^2 was categorized as underweight (<18.5), normal weight (18.5–24.9), overweight (25.0–29.9), or obese (≥30.0).

Outcomes

Our main outcomes were offspring obesity and BMIZ at age six. In the Y6FU questionnaire, mothers were sent instructions on how to measure their child's height and weight. Sex- and age-specific BMIZ and percentiles were calculated using SAS [22], and obesity was defined as BMIZ ≥95th percentile according to the 2000 CDC growth charts [22].

Covariates

IFPS II's prenatal questionnaire included information on maternal sociodemographic and reproductive factors such as mother's age at childbirth, race/ethnicity, education, household income, parity, smoking during pregnancy, and gestational diabetes. Gestational age at delivery was calculated from the due date on the prenatal questionnaire and the infant's date of birth collected by birth screener or neonatal questionnaire. Household income was expressed as a percent of the federal poverty level using poverty guidelines published by the U.S. Census Bureau [25]. Children's sex and birth weight were reported by their mothers in the neonatal questionnaire. Data on infant feeding practices, including breastfeeding and age at solid food introduction, were reported by their mothers in 10 postnatal questions at ages 1, 2, 3, 4, 5, 6, 7, 9, 10.5, and 12 months of life. For those who reported still breastfeeding at 12 months, breastfeeding duration data reported in Y6FU were used. Adherence to the 2005 American Academy of Pediatrics breastfeeding guidelines was defined using data on breastfeeding initiation, duration, and exclusivity. Similar to previous studies using IFPS II, age at solid food introduction was calculated as the midpoint between the child's age when the mother reported no solid food consumption and when she first reported her child had consumed solid foods in the previous seven days on the basis of 10 postnatal survey questionnaires [26]. Children's characteristics on weight, height, daily screen time, physical activity, and consumption of sugar-sweetened beverages at age six were reported by their mothers in the Y6FU questionnaire.

Statistical analyses

Descriptive statistics were calculated for maternal and offspring characteristics by GWG categories and offspring BMIZ deciles. χ^2 Tests were used to compare categorical variables, and analysis of variance was used for continuous variables.

We used logistic regression models to examine the associations of meeting IOM weight gain guidelines with offspring obesity at age six. We used quantile regression models to examine the associations of GWG categories with offspring BMIZ across decile intervals of offspring BMIZ at age six. All covariates adjusted in the models, including their categorizations, are shown in Table 1.

We evaluated potential effect measure modification by conducting stratified analyses according to maternal prepregnancy BMI, and we also tested for moderation using multiplicative interaction terms in adjusted models. The likelihood ratio test was used for logistic models, and the Wald test was used for quantile regression models. Underweight women (comprising only 2.9% of the sample) were not included in the stratified analysis. Model 1 was a crude model. Model 2 adjusted for potential confounders, including maternal prepregnancy BMI, age at childbirth, race/ethnicity, education, household income, parity, smoking during pregnancy, gestational diabetes, and gestational duration. In model 3, we additionally adjusted for potential mediating factors from birth and early feeding practices, including birth weight for gestational age, adherence to breastfeeding recommendations, and age at solid food introduction. In model 4, in addition to the factors adjusted in model 3, we further adjusted for potential mediators such as days of daily physical activity, daily screen time, and weekly consumption of sugar-sweetened beverages for children at age six. Results from models 3 and 4 were used to evaluate whether the additionally adjusted variables were potential intermediates for the association of GWG and offspring BMI.

All statistical analyses were performed using SAS version 9.4 (SAS Institute, Cary NC) and R software version 3.2.4. The SAS procedure PROC QUANTREG was used for quantile regression analysis. $P < .05$ was considered statistically significant.

Table 1
Basic characteristics of mothers and their offspring according to 2009 Institute of Medicine gestational weight gain guidelines in a sample of participants in the Infant Feeding Practice Survey II linked with its year six follow-up study, 2004–2005 and 2012

Maternal and offspring characteristics	Total sample $n = 1296$	Gestational weight gain			*P* values
		Inadequate $n = 210$	Adequate $n = 366$	Excessive $n = 720$	
Maternal characteristics					
Age (y), %					.55
18–24	14	15	14	14	
25–34	66	63	64	68	
≥35	20	21	22	18	
Race/ethnicity, %					.12
Non-hispanic white	86	85	84	88	
Non-hispanic black	3	3	2	4	
Hispanic	5	6	6	4	
Other	6	6	8	5	
Married, %					.47
Yes	81	81	84	80	
Education, %					.39
High school or less	15	17	13	16	
Some college	37	37	35	38	
College graduate or higher	48	46	52	46	
Household income as percent of poverty level, %					.36
<185%	35	40	31	35	
185%–350%	38	37	39	38	
>350%	28	24	29	28	
Parity, %					.009
Multiparous	72	76	76	68	
Smoking during pregnancy, %					.623
Yes	7	8	6	7	
Prepregnancy BMI status, %					<.001
Underweight (<18.5)	3	4	4	2	
Normal weight (18.5–24.9)	43	46	54	36	
Overweight (25.0–29.9)	28	14	22	34	
Obese (≥30)	27	36	20	27	
Gestational diabetes, %					.002
Yes	8	13	8	6	
Gestational age (wk)	39.3 (1.2)	39.4 (1.3)	39.4 (1.2)	39.3 (1.2)	.039
Offspring characteristics					
Child's sex, %					.222
Girl	50	55	51	48	
Birth weight for gestational age, %					<.001
Small for gestational age	7	9	10	5	
Appropriate for gestational age	81	84	83	80	
Large for gestational age	11	8	7	15	
Age at solid food introduction, %					.60
<4 mo	42.3	41.9	39.9	43.6	
4 to <6 mo	48.6	48.3	49.4	48.4	
≥6 mo	9.0	9.9	10.7	8.0	
*Adherence to breastfeeding recommendations, %					.32
1	13.4	12.4	14.2	13.3	
2	65.9	70.5	61.5	66.8	
3	4.2	2.9	4.4	4.4	
4	16.5	14.3	20.0	15.4	
Days of daily physical activity ≥60 min, %					.41
≥3 d	86.2	84.3	85.2	87.3	
Daily screen time, %					.49
≥60 min	77	76	76	78	
Weekly consumption of sugar-sweetened beverages, %					.15
0	19	19	22	17	
1 time	68	66	68	68	
≥2 times	13	15	10	15	
Obesity at age six					.02
Yes	11	13	7	12	

* 1: Never initiated breastfeeding; 2: Initiated breastfeeding, did not exclusively breastfeed for ≥4 mo, duration <12 mo; 3: Adherence to exclusivity for ≥4 mo, duration <12 mo; 4: Adherence to both exclusivity for ≥4 mo and duration for ≥12 mo. Categorical variables are expressed as percentages, and continuous variables are expressed as mean and SD. Obesity was defined as body mass index (BMI) ≥ the 95th percentile of the CDC sex-specific BMI-for-age growth charts [22].

Results

Sample characteristics

Fifty-six percent of women gained excessive weight during pregnancy, and 54% were overweight or obese before pregnancy. Eighty-six percent of women were non-Hispanic white, 48% had a college education or higher, 7% were smokers during pregnancy, and 8% had gestational diabetes. Nearly nine of every 10 infants were breastfed for some duration; only one in five infants was exclusively breastfed for four months. Eighty-one percent of children had a birth weight appropriate for the gestational age at delivery, whereas 7% and 12% were small and large for gestational age, respectively. Most children had more than three days of daily physical activity for more than 60 minutes at age six (86%), had more than 60 minutes of daily screen time (77%), and consumed sugar-sweetened beverages at least once per week (81%). Parity, maternal prepregnancy BMI, gestational diabetes, gestational age, and children's birth weight were statistically significantly associated with GWG category (Table 1). Across the deciles of offspring BMIZ distribution, we observed statistically significant differences in subgroup characteristics for maternal race/ethnicity, marital status, education, household income, prepregnancy BMI, infant sex, birth weight for gestational age, daily screen time, and weekly consumption of sugar-sweetened beverages (Table 2).

Associations of GWG categories with offspring obesity at age six

At age six, 11% of children were obese. The percentages of obese children born to mothers who gained inadequate, adequate, or excessive weight during pregnancy were 12.9%, 7.1%, and 12.5%,

Table 2
Basic characteristics of mothers and their offspring across deciles of BMIZ in a sample of participants in the Infant Feeding Practice Survey II linked with its Year Six Follow-Up Study, 2004–2005 and 2012

Variables	Deciles of BMIZ distribution									
	D1 ($n = 129$)	D2 ($n = 131$)	D3 ($n = 129$)	D4 ($n = 130$)	D5 ($n = 129$)	D6 ($n = 130$)	D7 ($n = 130$)	D8 ($n = 128$)	D9 ($n = 130$)	D10 ($n = 130$)
Maternal characteristics										
Age (y),%										
18–24	20 (15.5)	20 (15.3)	13 (10.1)	19 (14.6)	20 (15.6)	12 (9.2)	19 (14.6)	17 (13.3)	19 (14.6)	25 (19.2)
25–34	79 (61.2)	82 (62.6)	88 (68.2)	86 (66.2)	84 (65.6)	89 (68.5)	84 (64.6)	93 (72.7)	90 (69.2)	81 (62.3)
≥35	30 (23.3)	29 (22.1)	28 (21.7)	25 (19.2)	24 (18.8)	29 (22.3)	27 (20.8)	18 (14.1)	21 (16.2)	24 (18.5)
Race/ethnicity,%										
Non-hispanic white	111 (86.1)	109 (83.2)	119 (92.3)	118 (90.8)	115 (89.2)	104 (80.0)	110 (84.6)	116 (90.6)	109 (83.9)	107 (82.3)
Non-hispanic black	3 (2.3)	7 (5.3)	1 (0.8)	0	2 (1.6)	1 (0.8)	4 (3.1)	3 (2.3)	8 (6.2)	11 (8.5)
Hispanic	6 (4.7)	4 (3.1)	3 (2.3)	5 (3.9)	7 (5.4)	11 (8.5)	6 (4.6)	5 (3.9)	7 (5.4)	8 (6.2)
Other	9 (7.0)	11 (8.4)	6 (4.7)	7 (5.4)	5 (3.9)	14 (10.8)	10 (7.7)	4 (3.1)	6 (4.6)	4 (3.1)
Married,%	101 (78.3)	104 (79.4)	115 (89.2)	108 (83.1)	113 (87.6)	111 (85.4)	109 (83.9)	104 (81.3)	99 (76.2)	89 (68.5)
Education, %										
High school or less	22 (17.9)	20 (16.5)	13 (10.1)	19 (15.2)	14 (11.1)	12 (9.4)	11 (9.0)	19 (15.3)	26 (20.5)	34 (27.9)
Some college	51 (41.5)	36 (29.8)	47 (36.4)	41 (32.8)	40 (31.7)	49 (38.6)	44 (36.1)	52 (41.9)	47 (37.0)	52 (42.6)
College graduate or higher	50 (40.7)	65 (53.7)	69 (53.5)	65 (52.0)	72 (57.1)	66 (52.0)	67 (54.9)	53 (42.7)	54 (42.5)	36 (29.5)
Household income,%										
<185%	53 (41.1)	40 (30.5)	42 (32.6)	36 (27.7)	43 (33.3)	45 (34.6)	35 (26.9)	49 (38.3)	40 (30.8)	65 (50.0)
185%–350%	41 (31.8)	48 (36.6)	46 (35.7)	53 (40.8)	45 (34.9)	57 (43.9)	61 (46.9)	48 (37.5)	55 (42.3)	37 (28.5)
>350%	35 (27.1)	43 (32.8)	41 (31.8)	41 (31.5)	41 (31.8)	28 (21.5)	34 (26.2)	31 (24.2)	35 (26.9)	28 (21.5)
Parity,%										
Multiparous	95 (73.6)	88 (68.8)	98 (77.2)	92 (70.8)	79 (62.2)	89 (69.5)	93 (73.8)	93 (75.0)	93 (73.8)	96 (74.4)
Smoking during pregnancy,%	11 (8.5)	9 (6.9)	5 (3.9)	9 (6.9)	7 (5.5)	8 (6.2)	8 (6.3)	8 (6.3)	12 (9.2)	15 (11.5)
Prepregnancy BMI status, %										
Underweight	14 (10.9)	4 (3.1)	4 (3.1)	1 (0.8)	3 (2.3)	3 (2.3)	4 (3.1)	2 (1.6)	2 (1.5)	1 (0.8)
Normal weight	58 (45.0)	66 (50.4)	70 (54.3)	72 (55.4)	70 (54.3)	56 (43.1)	50 (38.5)	44 (34.4)	37 (28.5)	31 (23.9)
Overweight	31 (24.0)	40 (30.5)	28 (21.7)	29 (22.3)	22 (17.1)	41 (31.5)	41 (31.5)	38 (29.7)	45 (34.6)	42 (32.3)
Obese	26 (20.2)	21 (16.0)	27 (20.9)	28 (21.5)	34 (26.4)	30 (23.1)	35 (26.9)	44 (34.4)	46 (35.4)	56 (43.1)
Gestational diabetes, %	4 (3.1)	7 (5.3)	7 (5.4)	14 (10.8)	14 (10.9)	9 (6.9)	11 (8.5)	7 (5.5)	9 (6.9)	16 (12.3)
Gestational duration (wk)	39.2 (1.2)	39.4 (1.2)	39.4 (1.1)	39.4 (1.4)	39.1 (1.3)	39.3 (1.2)	39.3 (1.1)	39.4 (1.2)	39.4 (1.3)	39.5 (1.2)
Adherence to breastfeeding recommendations,%										
Never initiated	20 (15.5)	21 (16.0)	20 (15.5)	16 (12.3)	10 (7.8)	20 (15.4)	18 (13.9)	9 (7.0)	18 (13.9)	22 (16.2)
Initiated, did not exclusively breastfeed for ≥4 mo	82 (63.5)	80 (61.1)	72 (55.8)	87 (66.9)	90 (69.8)	84 (64.6)	85 (65.4)	94 (73.4)	88 (67.7)	92 (70.8)
Adherence to exclusivity for ≥4 mo, duration<12 mo	5 (3.9)	6 (4.6)	5 (3.9)	5 (3.9)	3 (2.3)	8 (6.2)	11 (8.5)	3 (2.3)	5 (3.9)	3 (2.3)
Adherence to both exclusivity for ≥4 mo and duration for ≥12 mo	22 (17.1)	24 (18.3)	32 (24.8)	22 (16.9)	26 (20.2)	18 (13.9)	16 (12.3)	22 (17.2)	19 (14.6)	16 (12.3)
Offspring characteristics										
Infant gender, %										
Girl	53 (41.1)	72 (55.0)	67 (51.9)	54 (41.5)	70 (54.3)	76 (58.5)	65 (50.0)	58 (45.3)	73 (56.2)	62 (47.7)
Birth weight for gestational age, %										
SGA	16 (12.4)	14 (10.7)	8 (6.2)	10 (7.7)	8 (6.2)	4 (3.1)	10 (7.7)	8 (6.3)	9 (6.9)	7 (5.4)
AGA	103 (79.8)	112 (85.5)	106 (82.2)	105 (80.8)	116 (89.9)	111 (85.4)	101 (77.7)	103 (81.1)	97 (74.6)	98 (75.4)
LGA	10 (7.8)	5 (3.8)	15 (11.6)	15 (11.5)	5 (3.9)	15 (11.5)	19 (14.6)	16 (12.6)	24 (18.5)	25 (19.2)
Age at solid food introduction,%										
<4 mo	59 (49.2)	51 (41.5)	31 (26.3)	54 (42.9)	42 (34.7)	50 (40.3)	49 (40.5)	55 (46.2)	59 (46.8)	65 (54.6)
4 to <6 mo	53 (44.2)	59 (48.0)	77 (65.3)	59 (46.8)	66 (54.5)	61 (49.2)	63 (52.1)	55 (46.2)	56 (44.4)	43 (36.1)
≥6 mo	8 (6.6)	13 (10.6)	10 (8.5)	13 (10.3)	13 (10.7)	13 (10.5)	9 (7.4)	9 (7.6)	11 (8.7)	11 (9.2)
Daily physical activity, %										
≥3 d	106 (82.2)	114 (87.7)	108 (83.7)	110 (84.6)	106 (82.8)	118 (90.8)	112 (86.2)	118 (92.2)	115 (89.1)	108 (83.1)
Daily screen time,%										
≥60 min	97 (77.0)	91 (71.1)	89 (69.0)	96 (75.0)	97 (75.8)	100 (77.5)	97 (75.2)	105 (83.3)	111 (86.0)	104 (81.9)
Weekly consumption of sugar-sweetened beverages,%										
0	27 (20.9)	25 (19.1)	37 (28.7)	24 (18.5)	20 (15.6)	28 (21.5)	32 (24.6)	16 (12.6)	17 (13.1)	18 (13.9)
1 time	79 (61.2)	94 (71.8)	85 (65.9)	90 (69.2)	91 (71.1)	87 (66.9)	79 (60.8)	93 (73.2)	92 (70.8)	87 (66.9)
≥2 times	23 (17.8)	12 (9.2)	7 (5.4)	16 (12.3)	17 (13.3)	15 (11.5)	19 (14.6)	18 (14.2)	21 (16.2)	25 (19.2)

AGA = average for gestational age; BMIZ = body mass index Z score; LGA = large for gestational age; SGA = small for gestational age.

respectively (Table 1). The children born to normal-weight mothers who gained adequate weight during pregnancy had the lowest percentage of obesity at age six in our study sample (2.03%), whereas the obesity percentage was the highest in offspring of obese women overall and by maternal GWG (range: 17%–20%) (Fig. 1).

In the crude model, compared with mothers who gained adequate weight, those who gained inadequate or excessive weight had increased odds of obese offspring [odds ratio (OR) = 1.93 (95% confidence interval [CI]: 1.10, 3.39) and OR = 1.84 (1.17, 2.90), respectively]. After adjusting for maternal sociodemographic and reproductive factors in model 2, the association of inadequate maternal weight gain during pregnancy with obesity at age six became attenuated (adjusted odds ratio: 1.35, 95% CI: 0.75, 2.44), whereas the positive association of excessive weight gain with obesity was maintained (adjusted odds ratio: 1.67, 95% CI: 1.04, 2.63). The ORs in model 3 were attenuated, and no statistically significant associations were observed. In model 4, after further adjusting for children's characteristics at age six, the ORs were slightly changed from model 3 (Table 3).

We further performed a stratified analysis according to the women's prepregnancy BMI status despite the statistically insignificant interaction term ($P = .25$). Among normal-weight mothers, women who gained excessive weight had increased odds of their offspring being obese at age six (Fig. 2). We did not observe any statistically significant associations among women who were overweight or obese before pregnancy.

Association of GWG with offspring BMIZ across the distribution of BMIZ

The associations between GWG categories and offspring BMIZ were generally not constant across deciles (Table 4). For example, the 20th quantile of BMIZ at age six for the children born to mothers who gained excessive weight were 0.25 unit higher than those born to mothers who gained adequate weight (95% CI [0.05, 0.45], model 2). The magnitudes of the associations were different across deciles of the BMIZ distribution (10th to 90th deciles). The impact of excessive GWG in mothers was larger on offspring at the 80th quantile of BMIZ (the coefficient: 0.30 [0.12, 0.48]). After adjusting for potential mediators, the magnitudes of the associations between excessive weight gain and BMIZ across the distribution of BMIZ were somewhat diluted (models 3 and 4). Conversely, no differences were found between BMIZ among children born to mothers who gained inadequate weight and those born to mothers who gained adequate weight across the centiles of BMIZ.

We performed stratified analyses by maternal prepregnancy BMI, and the results based on model 2 are shown in Supplemental Figure 2. In general, the associations of inadequate and excessive maternal weight gain in comparison to adequate weight gain with offspring BMIZ distributions were not homogeneous across deciles. We observed a similar pattern of heterogeneity in normal-weight mothers, that is, excessive GWG was associated with higher offspring BMIZ, and the magnitude was larger at higher BMIZ centiles. Inadequate GWG was also associated with higher BMIZ, although these associations were for the most part not statistically significant. Excessive and inadequate GWG were not significantly associated with offspring BMIZ in overweight or obese women, with the exception of inadequate GWG in obese women being associated with reduced BMIZ in the 10th (−0.81, 95% CI: −1.18, −0.44), 50th (−0.44, 95% CI: −0.85, −0.04), and 60th (−0.42, 95% CI: −0.80, −0.03) centiles.

Discussion

In this study, we found that excessive maternal GWG was positively associated with offspring obesity at age six in the overall sample and among mothers who were normal weight before pregnancy. Conversely, inadequate weight gain was not associated with offspring obesity.

Our findings relating excessive maternal GWG with childhood obesity are largely in agreement with previous studies in overall samples, but the findings by maternal prepregnancy weight status are still inconsistent [3,8–10,17]. Wrotniak et al [3] reported similar positive associations of excessive GWG with offspring obesity at age 7 overall and a null association of inadequate GWG with obesity. In our subgroup analysis, we found that the positive association in the overall sample was stronger among mothers who were underweight before pregnancy. Another study [19] conducted in Germany reported a positive association of excessive weight gain with offspring obesity at age five to six among underweight and normal-

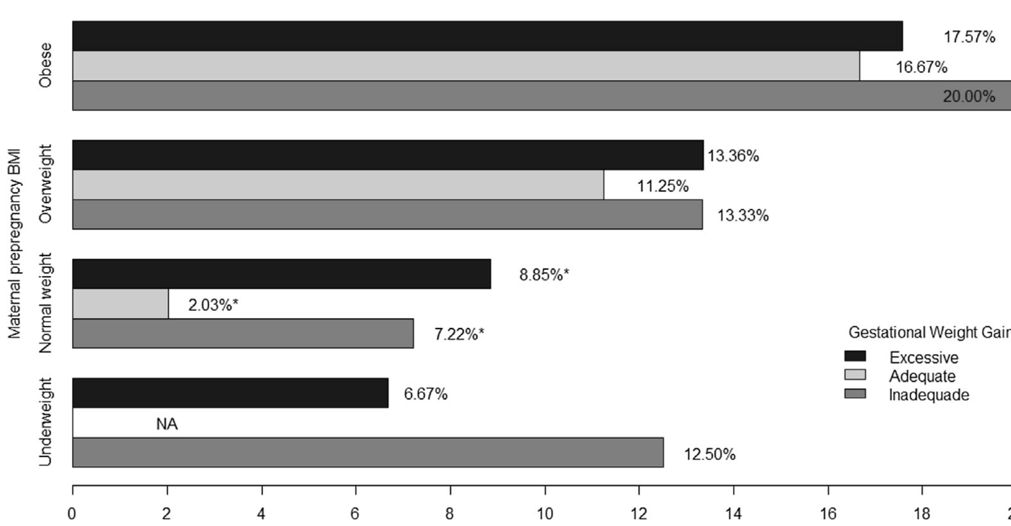

Fig. 1. Percentage of children who were obese at age six according to 2009 IOM gestational weight gain guidelines and maternal prepregnancy BMI. * indicates statistically significant differences in offspring obesity at age six among normal-weight mothers (P-value = .0093). BMI = body mass index; IOM = Institute of Medicine.

Table 3
Maternal weight gain during pregnancy (according to 2009 IOM guidelines) and subsequent offspring odds of obesity at age six estimated from logistic regression models

GWG categories according to GWG guidelines	Odds ratios (95% confidence intervals)			
	Model 1	Model 2	Model 3	Model 4
Inadequate weight gain	1.93 (1.10, 3.39)*	1.35 (0.75, 2.44)	1.36 (0.76, 2.45)	1.30 (0.72, 2.34)
Adequate weight gain	1.00	1.00	1.00	1.00
Excessive weight gain	1.84 (1.17, 2.90)*	1.67 (1.04, 2.63)*	1.54 (0.97, 2.44)	1.49 (0.94, 2.35)

BMI = body mass index; GWG = gestational weight gain; IOM = Institute of Medicine.
Model 1: Unadjusted model; model 2: Adjusted for maternal sociodemographic and reproductive factors, including age at childbirth, race/ethnicity, education, household income as percent of poverty level, maternal prepregnancy BMI, parity, smoking during pregnancy, and gestational diabetes; model 3: model 2 + additionally adjusted for infant early life factors, including birth weight for gestational age, adherence to breastfeeding recommendations, and age at solid food introduction; Model 4: model 3 + additionally adjusted for children characteristics at age six, including days of daily physical activity ≥60 min, daily screen time, and weekly consumption of sugar-sweetened beverages.
* Indicates $P < .05$.

weight mothers. In contrast, three prior studies reported that inadequate maternal weight gain was positively associated with offspring obesity at 4 years, 6 years, and 18 years, respectively [27–29]. A more recent study conducted by Diesel et al [8] classified GWG using a novel method of maternal weight gain Z score and reported that excessive GWG increased the risk of offspring obesity. Furthermore, the positive associations were only maintained among lean mothers (pregravid BMI<25 kg per m^2). Furthermore, our individual findings are supported by a recent systematic review [30] and metaanalysis reporting that the combined OR for excessive weight gain was 1.43 (95% CI: 1.24–1.65) for childhood obesity among children aged two to 20 years, whereas no association was observed for inadequate weight gain.

We additionally investigated the heterogeneous associations of GWG categories with offspring BMIZ across the entire distribution of BMIZ and by maternal pregravid BMI. We observed that excessive weight gain was positively associated with offspring BMIZ across the distribution of BMIZ in the overall sample and among normal-weight mothers. The magnitude of the association was stronger at some centiles such as the 30th, 50th, 60th, and 80th in the overall sample and at the 20th, 70th, 80th, and 90th centiles in overweight women. On the other hand, inadequate maternal weight gain was inversely associated with certain percentiles (the 10th and 50th centiles) of offspring BMIZ among obese mothers. For offspring BMIZ, previous research focused mainly on the mean value using linear regression. Ehrenthal et al. reported a positive association of inadequate GWG with BMIZ at age four, but no such association was found for excessive GWG [31]. In contrast, Hinkle et al observed that excessive GWG was associated with an increase in child mean BMIZ at age five among normal-weight and overweight mothers [20], whereas no association was observed among underweight or obese mothers. Our findings indicate that utilization of mean regression may miss important heterogeneous associations between maternal GWG and offspring BMIZ across the distribution of BMIZ. Another German study using quantile regression [19] showed positive heterogeneous associations between GWG and offspring BMIZ at age five to six among normal-weight mothers. Our study extends previous findings by demonstrating heterogeneous associations of GWG categories according to the current IOM GWG guidelines with offspring BMIZ beyond the mean. Our findings, consistent with those of another study [10] looking at offspring BMI, suggest that gaining weight above the IOM-recommended amount may not be more harmful for child BMIZ in obese compared with normal-weight mothers. Inadequate weight gain by mothers among obese women was beneficial for offspring in terms of having lower BMIZ at the 10th and 50th centiles of BMIZ distribution.

The mechanisms explaining the relationships between maternal GWG meeting IOM recommendations and offspring BMI remain unknown; however, there are several possibilities. Body size tracks from birth across the life course [16,32], as the association in our study was substantively changed after adjusting for birth weight, which is also reflected in another article using the same sample [33]. Offspring might inherit a genetic predisposition to weight gain, although we and others could not assess this [3,6,13,14]. Mothers and offspring may have shared environmental and

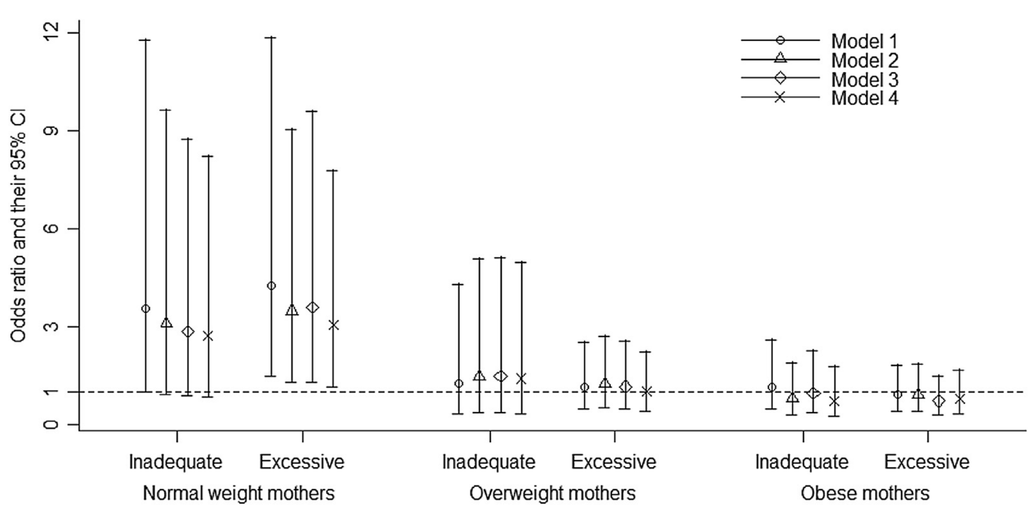

Fig. 2. The estimated odds ratios and 95% confidence intervals (CIs) for inadequate and excessive weight gain during pregnancy compared with adequate weight gain in four models by maternal prepregnancy BMI. BMI = body mass index.

Table 4
Quantile coefficients and 95% confidence intervals for the association of maternal GWG categories with offspring BMIZ across the distribution of BMIZ using quantile regression models*

Quantiles	Inadequate weight gain				Excessive weight gain			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
10th	−0.17 (−0.60, 0.26)	−0.32 (−0.69, 0.05)	−0.27 (−0.59, 0.06)	−0.02 (−0.36, 0.32)	0.18 (−0.14, 0.50)	0.14 (−0.13, 0.41)	−0.01 (−0.25, 0.23)	0.07 (−0.18, 0.32)
20th	0.21 (−0.12, 0.54)	0.11 (−0.16, 0.38)	0.00 (−0.25, 0.25)	0.08 (−0.17, 0.32)	**0.29 (0.05, 0.54)**	**0.25 (0.05, 0.45)**	0.17 (−0.02, 0.35)	**0.24 (0.06, 0.42)**
30th	0.16 (−0.09, 0.40)	0.12 (−0.11, 0.36)	0.11 (−0.09, 0.32)	0.10 (−0.11, 0.32)	**0.27 (0.08, 0.45)**	**0.30 (0.11, 0.47)**	**0.25 (0.10, 0.40)**	**0.20 (0.05, 0.36)**
40th	**0.33 (0.09, 0.56)**	0.12 (−0.10, 0.34)	0.16 (−0.05, 0.36)	0.17 (−0.03, 0.36)	**0.37 (0.19, 0.54)**	**0.28 (0.12, 0.44)**	**0.21 (0.06, 0.36)**	**0.24 (0.09, 0.38)**
50th	**0.29 (0.05, 0.53)**	0.16 (−0.06, 0.39)	**0.20 (0.01, 0.39)**	**0.24 (0.05, 0.44)**	**0.36 (0.19, 0.54)**	**0.31 (0.15, 0.48)**	**0.24 (0.10, 0.39)**	**0.25 (0.10, 0.39)**
60th	**0.28 (0.05, 0.51)**	0.10 (−0.11, 0.31)	0.10 (−0.10, 0.31)	0.12 (−0.08, 0.33)	**0.39 (0.22, 0.57)**	**0.33 (0.18, 0.49)**	**0.25 (0.10, 0.41)**	**0.21 (0.06, 0.37)**
70th	**0.27 (0.02, 0.51)**	0.06 (−0.15, 0.28)	0.02 (−0.18, 0.23)	0.00 (−0.22, 0.22)	**0.40 (0.22, 0.58)**	**0.24 (0.09, 0.40)**	**0.17 (0.02, 0.33)**	**0.16 (0.01, 0.33)**
80th	0.16 (−0.12, 0.45)	0.08 (−0.17, 0.32)	0.00 (−0.20, 0.20)	−0.05 (−0.23, 0.13)	**0.48 (0.26, 0.69)**	**0.30 (0.12, 0.48)**	**0.21 (0.06, 0.36)**	**0.18 (0.04, 0.31)**
90th	**0.41 (0.10, 0.73)**	−0.21 (−0.48, 0.06)	−0.14 (−0.35, 0.06)	0.00 (−0.20, 0.21)	**0.36 (0.13, 0.59)**	0.17 (−0.03, 0.36)	**0.18 (0.03, 0.34)**	**0.31 (0.15, 0.45)**

BMIZ = body mass index Z score; GWG = gestational weight gain.
Model 1, 2, 3, and 4 adjusted for the same covariates as in the logistic regression analysis.
Bold indicates statistically significant associations at $P < .05$.
* The deciles of a distribution are the nine values that split the data set into ten equal parts.

lifestyle factors [34]. Indeed, after adjusting for maternal prenatal and perinatal factors, the positive association of inadequate weight gain with offspring obesity disappeared and the magnitude of association between excessive weight gain and obesity was attenuated. Intrauterine metabolic programming and epigenetic modifications might result in persistent and adverse influences on the fetus arising from the greater influx of glucose, amino acids, and free fatty acids to the developing fetus in utero [35], leading to permanent changes in appetite control, neuroendocrine functioning, and energy metabolism [36]. The heterogeneous findings by maternal prepregnancy BMI in our study suggest that these proposed mechanisms might act differently among women with different prepregnancy BMI status.

The major strength of our study is the longitudinal assessment of maternal prenatal and postnatal characteristics and offspring characteristics at birth and six years. Rich data in IFPS II and Y6FU made it possible to control for a number of potential confounders. However, this study has several limitations. First, although the study population is well distributed throughout the United States, it is not representative of the U.S. population. Second, all data were self-reported by the child's mother. For example, GWG was self-reported by mothers shortly after the delivery without being verified with medical records. Thus, the reporting error might have occurred. Yet, the error is likely nondifferential and unlikely related to offspring's BMIZ or obesity six years later, given the longitudinal design of the study. In addition, however, the study included detailed instruction plus a standard tape for mothers to measure weight and height of their 6-year-olds. These anthropometric data were susceptible to measurement errors although these data were of better quality than mother's self-reports. It is possible that more educated mothers might measure weight or height more accurately than those not well educated. Third, loss to follow-up at age six might have introduced bias. According to CDC's study [21], compared with nonrespondents, mothers who responded to Y6FU were more likely to be older, married, and white, have higher education and income, and less likely to smoke. Children of respondents were more likely to be breastfed for a longer duration.

Conclusions

We found that excessive GWG was positively associated with offspring obesity, and this association was stronger among normal-weight mothers. Our study provides evidence that excessive GWG increases BMIZ differently across deciles of BMIZ distribution and its influences are stronger at higher BMIZ deciles and particularly among normal-weight mothers. Inadequate GWG might not be associated with offspring obesity, but inadequate GWG was inversely associated with BMIZ among obese mothers at some centiles. Future studies are warranted to further investigate the GWG offspring's obesity relationship and the heterogeneous effects of maternal GWG on BMIZ at different centiles especially among subgroups of maternal prepregnancy BMI using quantile regression methods. A potential nonlinear relationship between GWG and offspring obesity risk varying by maternal BMI warrants further investigation.

Acknowledgment

JX Liu and JH Liu designed and conceived this study. JX Liu drafted this article and conducted the analyses as part of her doctoral dissertation. All authors critically reviewed the articles, contributed to interpretation and revision of the article. Dr. JX Liu received SPARC Graduate Research Grant sponsored by the University of South Carolina. Dr. JH Liu's contribution to this work was partially funded by Eunice Kennedy Shriver National Institute of Child Health and Human Development (R01 HD078407).

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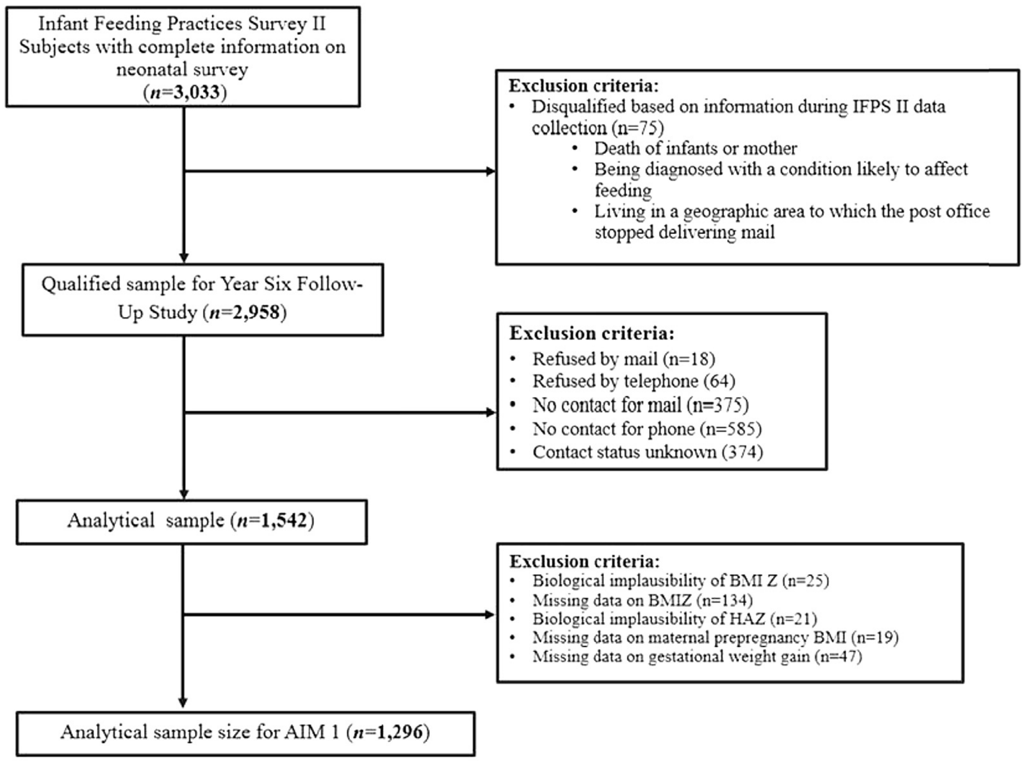
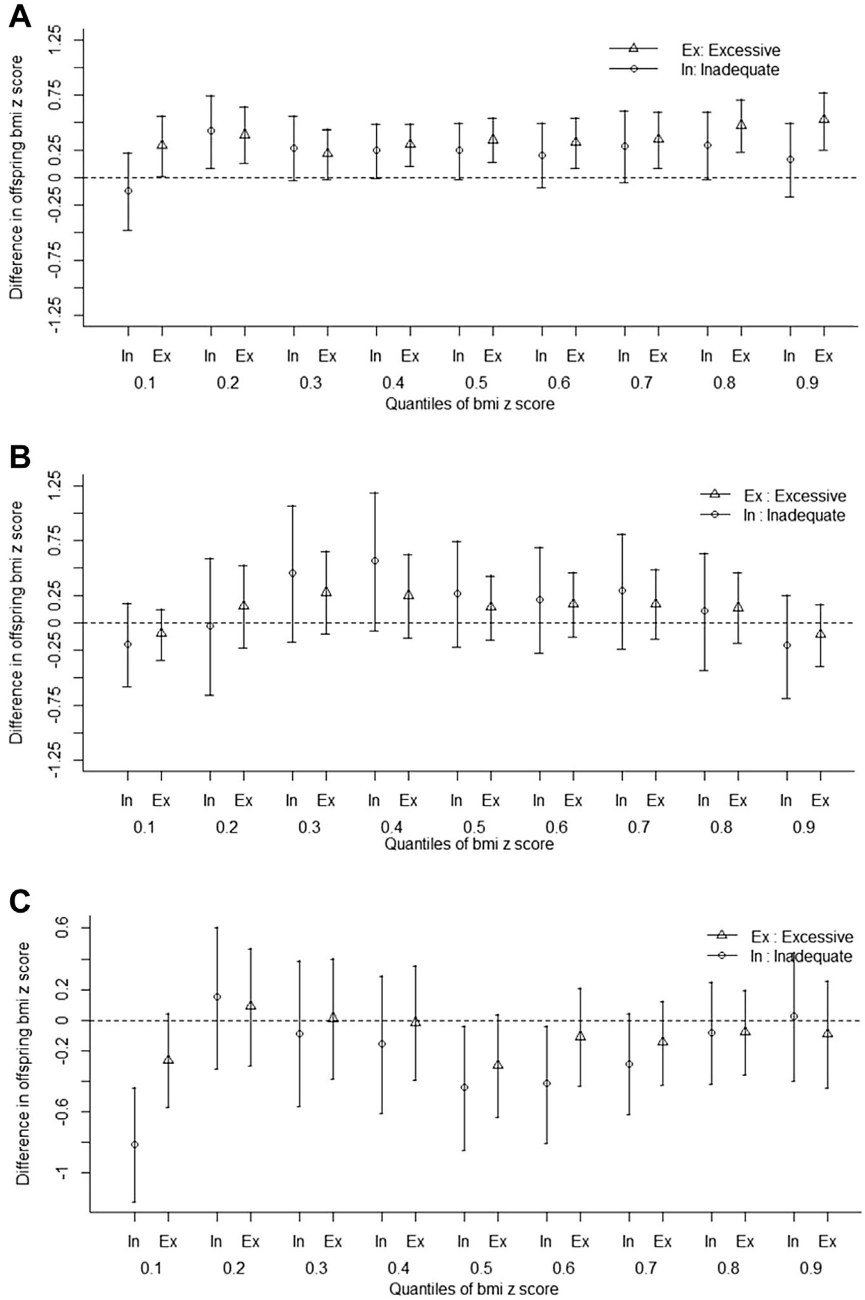
Appendix



The flowchart of study participants

Supplementary Resource 1. Flowchart of study participants.



Supplementary Resource 2. (A) Association of gestational weight gain with offspring BMIZ across the distribution of BMIZ among normal-weight mothers. (B) Association of gestational weight gain with offspring BMIZ across the distribution of BMIZ among overweight mothers. (C) Association of gestational weight gain with offspring BMIZ across the distribution of BMIZ among obese mothers.