Appalachian
STATE UNIVERSITY

Department of Economics Working Paper

Number 14-10 | November 2014

Maternal Pre-pregnancy BMI, Gestational Weight Gain, and Infant Birth Weight: A Within-Family Analysis in the United States

Ji Yan
Appalachian State University

Department of Economics
Appalachian State University
Boone, NC 28608
Phone: (828) 262-2148
Fax: (828) 262-6105
www.business.appstate.edu/economics

Maternal Pre-pregnancy BMI, Gestational Weight Gain, and Infant Birth Weight: A Within-Family Analysis in the United States[1]

Ji Yan[2]

First Draft: Nov 2012

This Version: Oct 2014

Abstract

In the United States, the high prevalence of unhealthy preconception body weight and inappropriate gestational weight gain among pregnant women is an important public health concern. However, the relationship among pre-pregnancy BMI, gestational weight gain, and newborn birth weight has not been well established. This study uses a very large dataset of sibling births and a within-family design to thoroughly address this issue. The baseline regression controlling for mother fixed effects indicates maternal preconception overweight, preconception obesity, and excessive gestational weight gain significantly increase the risk of having a high birth weight baby, while underweight before pregnancy and inadequate gestational weight gain increase the low birth weight incidence. The benchmark results are robust in a variety of sensitivity checks. Since poor birth outcomes especially high birth weight and low birth weight have lasting adverse impacts on newborn's health, education and socio-economic outcomes later in life, the findings of this research suggest promoting healthy weight among women before pregnancy and preventing inappropriate weight gain during pregnancy can generate significant intergenerational benefits.

Keywords: Pre-pregnancy BMI; Gestational weight gain; Birth weight; High birth weight; Low birth weight

JEL Codes: I12, I18

[1] This paper benefits from helpful comments by Josh Berning, Jeremy Bray, Karen Conway, Anca Cotet, Angela Dills, Zheng Fang, Gregory Gilpin, Jennifer Graves, Tiffany Green, Bob Pollak and other participants of Southern Economic Association meeting, Eastern Economic Association Meeting, and the Work, Families and Public Policy workshop in Washington University in Saint Louis. Research grants have been provided by the Center for New Institutional Social Science at Washington University in Saint Louis and ASU Walker College of Business Deans Club.

[2] Department of Economics, Walker College of Business, Appalachian State University, Boone, NC 28608, USA. Phone: (1-828)262-6123, Fax: (1-828)262-6105, Email:yanj@appstate.edu.

1. Introduction

The last two decades have seen a rapid increase in the prevalence of overweight and obesity among American women of reproductive age (National Center for Health Statistics, 2014). Among the women who had delivered live infants, the rate of pre-pregnancy overweight and obesity increased from 23.2% in 1993-1994 to 44.8% in 2009 (Kim et al., 2007; Fisher et al., 2013). As another important concern on pregnant women, excessive gestational weight gain has become increasingly common, even for the women with high body mass index (BMI) before pregnancy (Frederick et al., 2008). In contrast, while maternal obesity is on the rise, pre-pregnancy underweight and gestational inadequate weight gain due to deficient nutrient intake or supplementation remain a significant health problem among low socioeconomic status women. A recent report by Institute of Medicine (IOM) shows about 32% of the American low income underweight women had inadequate weight gain during pregnancy in 2007 (IOM, 2009). The high prevalence of unhealthy preconception body weight and inappropriate gestational weight gain among pregnant women is of great concern for the public health community. This is because unhealthy BMI before pregnancy and inappropriate weight gain in pregnancy have been linked to poor birth outcomes especially high birth weight (HBW) and low birth weight (LBW).[3]

Both HBW and LBW have lasting negative impacts on one's health, education, and socio-economic outcomes. HBW babies are at a greater risk for overweight, obesity, diabetes, cancer, and other disorders later in life (Hjalgrim et al., 2003; Danielzik et al., 2004; Harder et al., 2007; Wei et al., 2007; Mandl et al., 2009). Moreover, HBW negatively affects cognitive function, learning, and school performance (Richards et al., 2001; Kirkegarrd et al., 2006; Cesur and Kelly, 2010). LBW is also a costly birth outcome. The short run excess hospital costs of all LBW singleton births in 1989

[3] High birth weight is defined as weight at birth more than 4,000 grams (g) or 8.8 pounds (lbs) and low birth weight is defined as weight at birth less than 2,500 g or 5.5 lbs (IOM, 1990, 2009).

were estimated to be at least 1.07 billion (Almond et al., 2005). In the long term, LBW leads to poor health (Currie and Hyson, 1999), developmental problems (Hack et al., 1995), low educational attainment (Conley and Bennett, 2000), and adverse labor market outcomes (Behrman and Rosenzweig, 2004). In the United States, reducing the incidence of adverse birth outcomes has been an important goal of several large-scale social programs. In this sense, findings from investigating the effects of pre-pregnancy BMI and gestational weight gain on newborn birth weight will have strong policy implications.

This research is also related to the empirical studies on Barker's fetal origins perspective (Barker, 1990). By Barker's theory and its extension, under-nutrition and over-nutrition during pregnancy due to adverse fetal environment presage some of the most common health disorders in adult life. Recent studies further show the "fetal origins" effects can extend to a broader range of lifetime outcomes and in particular, poor health at birth is a key pathway through which deficient or excessive nutrient intake during fetal development exerts persistent effects (Almond and Currie, 2011). This study will shed new light on such a pathway, since gestational weight gain is a good measure of nutrition in utero and both HBW and LBW are crucial indicators of poor infant health. Furthermore, exploring the impact of pre-pregnancy BMI on birth weight is important too, because the corresponding estimates capture the intergenerational returns by promoting healthy preconception weight among women. Such often-ignored returns should be incorporated into the cost-benefit analysis of various weight management programs for women of reproductive age (Siega-Riz and Laraia, 2006).

To date, the relationship among pre-pregnancy BMI, gestational weight gain, and infant birth weight has not been well established. Some studies only look at the association between preconception BMI and birth weight (Abenhaim et al., 2007; Gilboa et al., 2008; McDonald et al.,

2010). Lacking the data of gestational weight gain, these studies are unable to address how pre-pregnancy BMI affects birth weight net of its impact that operates through influencing gestational nutritional intake, an important policy-relevant issue. Their results are quite mixed. The second body of literature evaluates the effects of gestational weight gain only, without controlling for preconception body weight (Hediger et al., 1989; Abrams and Selvin, 1995; Hickey et al., 1996; Ludwig and Currie, 2010; McDonald et al., 2011). However, the omitted pre-pregnancy BMI clearly biases the parameter estimate on weight gain, since women in various preconception BMI categories differ systematically in gestational weight gain. The third literature investigates the combined effects of the two birth weight inputs (Doherty et al., 2006; Rode et al., 2007; Frederick et al., 2008; Crane et al., 2009; Bodnar et al., 2010). Past studies on this topic, like the previous two strands of research, rarely deal with the unobserved generic, mother, or family level factors. Such factors, when not controlled for, will markedly confound the relationship between the two inputs and birth weight. Indeed, the results of these studies are varying and inconsistent. Finally, the datasets used in the whole literature above are often drawn from a few hospitals or small areas and lack of important mother or family socioeconomic control variables.

This study uses a very large dataset of about 0.3 million sibling births to thoroughly evaluate the effects of pre-pregnancy BMI and gestational weight gain on infant birth weight. This dataset has several noteworthy advantages. One, it is constructed from the natality records of all the live births in two states. In contrast, much of the prior research uses convenience samples. Two, the dataset records maternal weight and height before pregnancy plus weight at delivery, which makes it feasible to create indicators of both pre-pregnancy BMI and gestational weight gain. Three, it provides a rich set of infant, mother, and family control variables. Four, this panel dataset allows a comparison of birth weights of singleton births to the same mother. This within-family design can

remove the bias due to unobserved mother heterogeneity. Five, the large sample size gives more precise estimates, relative to the previous estimates.

With this unique dataset, mother fixed effects models are applied to address the effects of maternal preconception body weight and gestational weight gain on the mean and two tails of the newborn birth weight distribution. The baseline estimation suggests preconception overweight, preconception obesity, and excessive gestational weight gain all significantly increase the risk of having a HBW baby, while underweight before pregnancy and inadequate gestational weight gain lead to an elevated risk of delivering a LBW infant. Then, a series of sensitivity checks or extensions are performed, with the results highly consistent with the benchmark estimates.

2. Data

The dataset of sibling births is constructed from vital statistics natality records in the states of Pennsylvania and Washington.[4] These natality records in general cover all the live births every year. However, this research focuses on a sample of infants born during 2003-2010 in Pennsylvania and during 2003-2006 in Washington for two reasons. One, it is in 2003 that both states began using the new U.S. Standard Certificates of Live Birth (2003 revision). This revised certificate codes quite a few new maternal characteristics important for the present study, such as mother's height, weight at three months before pregnancy, and weight at delivery. Two, the latest data which can be released were collected in 2010 for Pennsylvania and in 2006 for Washington, when this research project was started. Using the records of the universe birth, consecutive sibling births are linked to the same mother over time by mother's name, date of birth, race, and newborn parity. Next, multiple-birth pregnancies (twins, triplets, etc.) are dropped, such that the sample only includes the women with

[4] The public natality birth files are available at the following web of the U.S. Centers for Disease Control and Prevention: www.cdc.gov/nchs/data_access/Vitalstatsonline.htm. Access to the restricted birth files has been provided by the department of public health in both states.

singleton sibling births. In addition, the sample excludes a few women who had more than three births in the short period of newborn sampling or did not reside in either state. The final sample is composed of 148,986 mothers with two living births and 18,991 mothers with three living births, totally 354,945 mother-singleton birth pairs.

Pre-pregnancy BMI is calculated using maternal weight before pregnancy in kilograms (kg) divided by maternal height in meters (m) squared (kg/m^2). Then, women are sorted into four categories: <18.5 kg/m^2 (underweight), 18.5-25 kg/m^2 (normal weight, the reference group), 25-30 kg/m^2 (overweight), and ≥30 kg/m^2 (obese). The above cutoff points come from the World Health Organization's (WHO) criteria for BMI categorization in 1995, which has been commonly adopted (WHO, 1995). A continuous measure of gestational weight gain is calculated by subtracting maternal pre-pregnancy weight from weight at delivery. Next, according to the new guideline issued by the U.S. institute of medicine in 2009, women in different pre-pregnancy BMI categories should gain appropriate weights within different recommended ranges during pregnancy (IOM, 2009). This is because weight gain within the ranges can provide the optimal tradeoff between lowering the risk of having a LBW baby and reducing the chance of delivering a HBW infant (Rasmussen et al., 2009).[5] By this guideline (Appendix table A.1, the upper panel), two indicators of weight gain beyond the ranges are created, with the within-range weight gains as the reference: excessive weight gain (gestational weight gain above the recommended ranges) and inadequate weight gain (gestational weight gain below the recommended ranges).

It is worth noting an old IOM guideline in 1990 (Appendix table A.1, the lower panel), also widely used in the prior research (Frederick et al., 2008; Rode et al., 2007), can be applied to define

[5] Although low gestational weight gain is associated with a lower chance of having an overgrown HBW baby, it can substantially increase the risk of delivering a LBW infant. A similar concern applies to the effects of high gestational weight gain on the incidence of LBW and HBW. As such, all the IOM's recommended pregnancy weight gain ranges are based on a delicate balance of the risks and benefits of varying weight gain on newborn birth weight (Abrams et al., 2000).

excessive and inadequate weight gain. The 2009 version is generally close to the one in 1990 except for two salient changes (Rasmussen et al., 2010). One, the 2009 guideline uses the 1995 WHO BMI cutoff points to replace the traditional BMI cutoff values from the Metropolitan Life Insurance Table. Two, the 2009 version provides a closed and conservative weight gain range for women who are obese before pregnancy. Such modifications have been made because: first, overweight and obesity have become increasingly common in American women before they get pregnant; second, the recommended range in the 1990 guideline for obese pregnant women has been criticized for being too liberal (DeVader et al., 2007). Whether the 1990 or 2009 guideline is superior has been controversial (Abrams et al., 2000; Thorsdottir et al., 2002; DeVader et al., 2007; Rasmussen et al., 2010). Staying neutral in the debate, this research applies both guidelines and compares the results.[6]

Three birth outcomes are explored in this study: birth weight, HBW, and LBW. Birth weight, a continuous variable, is the primary indicator of an infant's health in most studies of newborn wellbeing. Augmenting birth weight causally increases educational achievement, height, and earnings in adulthood (Behrman and Rosenzweig, 2004; Black et al., 2007). HBW and LBW are two salient poor birth outcomes which have adverse impacts on a number of lifetime outcomes (Almond and Currie, 2011). In addition to maternal BMI and weight gain, a lot of other determinants of infant birth weight are controlled for in the regression analysis. They include infant characteristics (infant sex, birth order, birth year and month), parental demographics (age, education, race, and ethnicity[7]), maternal socioeconomic status variables (marital status, Medicaid and other

[6] While the 1990 guideline does not provide a closed gestational weight gain range for obese women, we use 11.5 kg as the upper limit of this range (the same as the upper limit for overweight women), following the literature (Rode et al., 2007).

[7] Maternal race and ethnicity indicators will not be included in the regressions with mother fixed effects, since they are birth invariant. For illustration purpose, section 4 still reports the descriptive statistics of maternal race and ethnicity such as non-Hispanic White, non-Hispanic Black, and Hispanic.

types of infant delivery payment, WIC enrollment), maternal health behavior and health status (prenatal care initiation in the first trimester, prenatal smoking, height, pre-pregnancy risk factors).

3. Methods

To examine the relationship of maternal pre-pregnancy body weight, gestational weight gain, and infant birth weight, the following linear model is used in the baseline analysis:

$$Y_{ij} = \alpha + \beta BMI_{ij} + \gamma GWG_{ij} + \delta X_{ij} + \mu_j + \varepsilon_{ij}\,, \tag{1}$$

where Y_{ij} is a birth weight measure of infant i born to mother j; BMI_{ij} is a vector of three pre-pregnancy BMI categories; GWG_{ij} is a vector of two gestational weight gain indicators; and X_{ij} is a rich set of infant, mother, and family level control variables (Voigt et al., 2004). Finally, μ_j represents the mother fixed effect of mother j, which captures the unobserved generic, mother, family, and fetal environment characteristics common to the sibling births of this mother. Such unobserved confounding factors are correlated with pre-pregnancy BMI, gestational weight gain, as well as infant birth weight. As such, controlling for these factors by mother fixed effects will give unbiased within-family estimates on the effects of BMI (β) and gestational weight gain (γ). In addition, this specification groups together gestational weight gains across all BMI categories to increase the precision of estimates, while one extension in the next section will relax this restriction and explore the heterogeneous effects.

In equation (1) that controls for gestational weight gain, γ indicates a partial impact of pre-pregnancy BMI, because it does not include an indirect effect of BMI on newborn birth weight which operates through changing weight gain in pregnancy.[8] Jansson et al. (2008) illustrates this indirect effect and shows how pre-pregnancy BMI and unhealthy dietary patterns jointly alter

[8] However, γ does contain the indirect effects of preconception BMI on infant birth weight which work through BMI-related maternal morbidities in pregnancy not controlled in equation (1), such as gestational diabetes and hypertension.

maternal metabolic hormones, thereby affecting placental nutrient transport, gestational weight gain, and fetal growth. Such an indirect pathway from pre-pregnancy BMI to birth weight cannot be estimated, without data on dietary patterns. Nevertheless, at least from a health policy perspective, this unquantified indirect impact is neither important nor interesting, to the extent that weight gain in pregnancy can be substantially modified by social and nutrition programs. In contrast, the estimates of the vector γ are quite policy relevant, since they inform policy makers that aside from conventional intervention on gestational weight gain, promoting healthy weight before pregnancy among women can generate appreciable extra cross-generational returns.

When the dependent variable is binary (HBW or LBW), equation (1) is essentially a linear probability model. One typical concern on this model is that the estimated marginal effects on the outcome probability are constant (non-diminishing), when the continuous independent variables are increased to very large values. This is a minor issue here, since the main variables of interest maternal body weight and weight gain are dummy variables. In addition, near the mean values of those continuous control variables, the estimates of a linear probability model are generally pretty good compared with nonlinear models (Wooldridge, 2010). As to nonlinear models, a fixed effects logit model has a unique feature of yielding unbiased estimates on the log-odds ratio of HBW and LBW for different BMI or weight gain categories. But such estimates only allow a "relative" group-wise comparison, since theoretically this nonlinear model cannot give the true marginal effects of preconception BMI and gestational weight gain at the individual level (Wooldridge, 2010). This is an important reason why the baseline analysis applies a fixed effects linear probability model on HBW and LBW.

With the above pros and cons of nonlinear specifications in mind, consider the following logit specification with mother fixed effects:

(2) $$Pr(Z_{ij}=1)=\frac{e^{\eta+\theta \mathrm{BMI}_{ij}+\lambda \mathrm{GWG}_{ij}+\varphi \mathrm{X}_{ij}+\omega_j+\nu_{ij}}}{1+e^{\eta+\theta \mathrm{BMI}_{ij}+\lambda \mathrm{GWG}_{ij}+\varphi \mathrm{X}_{ij}+\omega_j+\nu_{ij}}},$$

where Z_{ij} is either HBW or LBW; the independent variables are all the same as those in equation (1); and ω_j represents a set of mother fixed effects. Conditional maximum likelihood estimation of equation (2) provides unbiased estimates of θ and λ. The natural exponents of these estimates give the odds ratios of neonatal HBW or LBW of different pre-pregnancy BMI and gestational weight gain groups. For example, suppose $\hat{\theta}_1$ is the coefficient estimate of pre-pregnancy obesity from equation (2) with HBW as the outcome, then $e^{\hat{\theta}_1}$ gives the following odds ratio of having a HBW baby for obese women relative to normal weight women:

(3) $$OR_{HBW}=\frac{[Pr(HBW=1|OB=1)/Pr(HBW=0|OB=1)]}{[Pr(HBW=1|NW=1)/Pr(HBW=0|NW=1)]}.$$

Clearly, this odds ratio makes a relative comparison on the odds of delivering a HBW infant between obese and normal weight women.[9] If $e^{\hat{\theta}_1}$ is greater than 1, then obese women are $e^{\hat{\theta}_1}$ times more likely to deliver a HBW infant than normal weight women. The corresponding estimates of the other BMI or weight gain categories can be interpreted in a similar manner.

4. Results

Table 1 reports the summary statistics of newborn birth weight, infant characteristics, and the key parental control variables.[10] Column (1) focuses on the full sample of sibling births. It shows 11% of all the infants are HBW and 5% of them are LBW. About 21% of the babies were delivered by obese women with pre-pregnancy BMI above 30 kg/m^2, 24% of them by overweight women, and 4% by underweight women. As to weight gain during pregnancy, 54% of the newborns' mothers gained more than the recommended ranges in the IOM 2009 guideline, and 20% of them gained less than

[9] In this comparison, both groups of women have appropriate gestational weight gain within the 2009 (or 1990) IOM recommended ranges.

[10] Additional birth variant control variables not shown for brevity include other infant delivery payment types and indicators of pre-pregnancy risk factors.

the recommended ranges.[11] In addition, most of the mothers in the sample are either non-Hispanic White or non-Hispanic Black and having at least 12 years of education.

[Insert Table 1 Here]

Columns (2) to (4) stratify the full sample by birth weight category. Compared with the women having normal birth weight infants (column 3), the women who delivered HBW babies were more likely to be overweight or obese prior to conception and have excessive weight gain in pregnancy (column 2), suggesting over-nutrition is associated with fetal overgrown. Moreover, they were older, more educated, and more likely to be married and initiate prenatal care in the first trimester, as well as were less likely to enroll in WIC or Medicaid or smoke in pregnancy. By contrast, the mothers with LBW newborns were more likely than the mothers with normal birth weight infants to be underweight before pregnancy and gain inadequate weight during pregnancy (column 4). Nutrient deficiencies before and during pregnancy appear strongly correlated with low socioeconomic status, since the women with LBW babies tended to be younger, less educated, unmarried, and enroll in WIC and Medicaid. Furthermore, these women also had a higher propensity to smoke during pregnancy and initiate prenatal care after the first trimester. Finally, relative to the LBW and normal birth weight infants, the HBW infants generally are more likely to be a male and have a high birth order.

Table 2 presents the baseline results on the effects of pre-pregnancy BMI and gestational weight gain, by estimating equation (1) with the full sample of sibling births. All the infant and parental control variables have been included in the regression.[12] The first three columns use the IOM 2009 guideline to define the two inappropriate weight gain categories. Column (1) shows pre-pregnancy overweight and obesity significantly increase newborn birth weight by about 31 g and 82 g, while

[11] The results are similar by the 1990 guideline, where about 47% of the newborns' mothers had excessive weight gain in pregnancy and 23% had inadequate weight gain.
[12] The coefficient estimates of these control variables are suppressed to save room.

underweight reduces birth weight by 34 g. Moreover, excessive weight gain during pregnancy results in a significant birth weight increase of 107 g, but inadequate weight gain leads to a birth weight decrease of 87 g. Columns (2) and (3) demonstrate the women who are overweight before pregnancy, obese before pregnancy, or gain excessive weight during pregnancy are 1.3, 3, or 3.5 percentage points more likely to have a HBW baby, although such women also have a lower chance of delivering a LBW infant. The two columns also show while the women who are underweight before conception or gain inadequate weight in pregnancy are somewhat less likely to give birth to a HBW baby, they have a substantially higher risk of delivering a LBW newborn by 1.5 or 2.5 percentage points, respectively. As discussed above, the parameter estimates on preconception body weight capture a partial impact of pre-pregnancy BMI on neonatal birth weight which does not operate through changing gestational weight gain. But they are not small, compared with the corresponding coefficient estimates on weight gain in pregnancy.

[Insert Table 2 Here]

Overall, the benchmark estimates generally suggest over-nutrition before and during pregnancy impairs infant health mainly at the upper end of the birth weight distribution, while the adverse effects of deficient nutrient intake are manifest at the lower end. Columns (4)-(6) of table 2 present similar estimates, when the IOM 1990 recommendation is used to define excessive and inadequate weight gain.[13] Table 3 applies the baseline specification to subsample analysis. The upper panel stratifies the full sample by number of sibling births. The results are quite similar to Table 2. For the two-birth mothers, preconception overweight, preconception obesity, and excessive weight gain in pregnancy increase the risk of delivering a HBW baby by 1.3, 2.8 and 3.3 percentage points, respectively. In contrast, pre-pregnancy underweight and inadequate gestational weight gain lead to

[13] Since both guidelines give very close results, the subsequent tables only report the estimates when the IOM 2009 guideline is used.

a significant increase in the LBW incidence by 1.4 and 2.5 percentage points (columns 1-3). Similar results hold for the three-birth mothers, in which the estimated impacts of obesity and excessive weight gain on HBW are somewhat larger (columns 4-6). The lower panel considers the Pennsylvania and Washington state subsamples. Again, the findings of either state are consistent with the results from the pooled sample in table 2.

[Insert Table 3 Here]

Table 4 performs two other robustness checks. First, while the samples used above have marked variations in the newborn birth order, columns (1)-(3) use a more homogenous sibling subsample which consists of only the first- and second-born infants. The new coefficient estimates of pre-pregnancy BMI and gestational weight gain are again very similar to their counterparts in table 2. Second, gestational weight gain takes negative values for a small proportion of the mothers in the original sample. One explanation is that some pregnant women attempted weight loss (Bodnar et al., 2010). However, as another possibility, such negative weight changes are due to recall error which may systematically bias the estimates. Columns (4)-(6) address this concern by studying only the mothers whose gestational weight gains are greater than zero. Still, this sample restriction does not significantly alter the benchmark results, compared with table 2.

[Insert Table 4 Here]

Several additional sensitivity checks are also conducted, with the full results available upon request. One, a series of Hausman specification tests all reject the null hypothesis that models with mother random effects are preferred to the baseline model with mother fixed effects. Two, no evidence is found that previous birth outcomes (e.g., birth weight) significantly affects a woman's future pre-pregnancy BMI or gestational weight gain. This finding corroborates the validity of the strict exogeneity condition, a necessary condition to give unbiased estimates in equation (1). Three,

when gestational weight gain enters equation (1) alternatively as a continuous measure and pre-pregnancy BMI is not controlled for, the regression results are similar to Ludwig and Currie (2010) which uses sibling births to study the birth weight effect of weight gain subject to lack of preconception BMI in their data. Interestingly, after pre-pregnancy BMI is controlled to correct for this omitted variable bias, we find the estimated effect of weight gain on birth weight becomes about 30 percent larger.

Table 5 studies two extensions of the benchmark analysis. The first three columns explore if the effects of gestational weight gain differ by BMI category. Column (1) shows the effects of excessive and inadequate weight gain on newborn birth weight are smaller for the women with a high BMI relative to the underweight women. However, the impacts of unhealthy weight gain on HBW or LBW are generally similar across different pre-pregnancy BMI categories, as shown in columns (2) and (3). The last two columns use the fixed effects logit model in equation (2) for the two binary birth outcomes. On one hand, column (4) indicates the overweight women and obese women are 1.19 and 1.47 times more likely to have a HBW baby than the normal weight women. And, the odds of delivering a HBW infant is about 1.59 for the women with excessive gestational weight gain, relative to the women with appropriate weight gain. On the other hand, column (5) shows again that deficient nutrient supplementation before or during pregnancy adversely affects the lower end of the birth weight spectrum. Relative to the normal weight women, the odds ratio of giving birth to a LBW infant is 1.38 for the underweight women. In addition, the women with inadequate gestational weight gain are 1.60 times more likely to have a LBW baby than the women with appropriate weight gain.

[Insert Table 5 Here]

5. Conclusion

Poor birth outcomes such as HBW and LBW impose a huge burden on families, the healthcare care system, education, and social services. As such, improving the health and well-being of infants has been a crucial public health goal in the United States. Both pre-pregnancy BMI and gestational weight gain are two key determinants of infant health. However, the exact relationship between the two inputs and newborn birth weight has not been well understood. This article uses a unique large sample of sibling births to provide new evidence on this issue. The preliminary sample analysis indicates about 49% of the newborns' mothers were obese, overweight, or underweight before pregnancy and 74% of them had excessive or inadequate weight in pregnancy. The in-depth regression analysis controls for the mother fixed effects and a rich set of infant, mother, and family characteristics. Overall, the baseline estimation shows preconception overweight, preconception obesity, and excessive weight gain during pregnancy significantly increase the risk of having a HBW baby by 1.3, 3, and 3.5 percentage points, respectively. In contrast, underweight before pregnancy and inadequate gestational weight gain result in an increase in the LBW incidence by 1.5 and 2.5 percentage points.

The benchmark results are robust in a variety of sensitivity checks: using an alternative weight gain guideline, stratifying the sample by number of sibling births and by state, restricting the sample to the women with positive gestational weight changes, and exploring heterogeneous effects of weight gain by BMI category, etc. This study also opens up several avenues of future research. One, more work is needed to study the effects of pre-pregnancy BMI and gestational weight gain on other neonatal health measures and various outcomes later in life. Two, the mother fixed effects models are readily applied to examine maternal health during pregnancy, childbirth, and the postpartum period. Three, it is interesting to explore the relation between patterns of weight gain by

trimester and birth weight, when pre-pregnancy BMI and mother fixed effects are controlled for. Finally, the analysis can be extended to mothers and their infants in other states.

The high incidence of adverse birth outcomes provides large scope for early intervention during the preconception and antenatal periods (Doyle et al., 2009). The findings of this study suggest one approach to enhance infant health is promoting healthy weight before pregnancy. To achieve this goal, it is important to offer women of reproductive age guidelines and programs on diet, nutrition, physical activity, and weight management. The second strategy is to prevent and decrease inappropriate weight gain among pregnant women. Integration of the two approaches in practice is particularly encouraging. The partnership of the Centers for Disease Control and Prevention, the Association of Maternal and Child Health Programs and CityMatCh is making such an effort, by building federal, state, and local capacity to promote healthy weight among women before pregnancy and prevent inappropriate weight gain during pregnancy.

References

Abenhaim, H. A., Kinch, R. A., Morin, L., Benjamin, A., Usher, R., 2007. Effect of pre-pregnancy body mass index categories on obstetrical and neonatal outcomes. Archives of Gynecology and Obstetrics, 275(1), 39-43.

Abrams, B., Altman, S. L., Pickett, K. E., 2000. Pregnancy weight gain: still controversial. The American Journal of Clinical Nutrition, 71(5), 1233-1241.

Abrams, B., Selvin, S., 1995. Maternal weight gain pattern and birth weight. Obstetrics & Gynecology, 86(2), 163-169.

Almond, D., Chay, K. Y., Lee, D. S., 2005. The costs of low birth weight. The Quarterly Journal of Economics, 120(3), 1031-1083.

Almond, D., Currie, J., 2011. Human capital development before age five. Handbook of Labor Economics, 4, 1315-1486.

Barker, D. J., 1990. The fetal and infant origins of adult disease. British Medical Journal, 301(6761), 1111.

Behrman, J. R., Rosenzweig, M. R., 2004. Returns to birthweight. Review of Economics and Statistics, 86(2), 586-601.

Black, S. E., Devereux, P. J., Salvanes, K. G., 2007. From the cradle to the labor market? The effect of birth weight on adult outcomes. The Quarterly Journal of Economics, 122(1), 409-439.

Bodnar, L. M., Siega-Riz, A. M., Simhan, H. N., Himes, K. P., Abrams, B., 2010. Severe obesity, gestational weight gain, and adverse birth outcomes. The American Journal of Clinical Nutrition, 91(6), 1642-1648.

Cesur, R., Kelly, I. R., 2010. From cradle to classroom: High birth weight and cognitive outcomes. Forum for Health Economics & Policy, 13(2), 1-26.

Conley, D., Bennett, N. G., 2000. Is biology destiny? Birth weight and life chances. American Sociological Review, 65, 458-467.

Currie, J., Hyson, R., 1999. Is the impact of health shocks cushioned by socioeconomic status? The case of low birthweight. American Economic Review Papers and Proceedings, 89(2), 245-250.

Crane, J. M., White, J., Murphy, P., Burrage, L., Hutchens, D., 2009. The effect of gestational weight gain by body mass index on maternal and neonatal outcomes. Journal of Obstetrics and Gynecology Canada, 31(1), 28-35.

Danielzik, S., Czerwinski-Mast, M., Langnäse, K., Dilba, B., Müller, M. J., 2004. Parental overweight, socioeconomic status and high birth weight are the major determinants of overweight and obesity in 5-7 year-old children: baseline data of the Kiel Obesity Prevention Study (KOPS). International Journal of Obesity, 28(11), 1494-1502.

DeVader, S. R., Neeley, H. L., Myles, T. D., Leet, T. L., 2007. Evaluation of gestational weight gain guidelines for women with normal pre-pregnancy body mass index. Obstetrics & Gynecology, 110(4), 745-751.

Doherty, D. A., Magann, E. F., Francis, J., Morrison, J. C., Newnham, J. P., 2006. Pre-pregnancy body mass index and pregnancy outcomes. International Journal of Gynecology & Obstetrics, 95(3), 242-247.

Doyle, O., Harmon, C. P., Heckman, J. J., Tremblay, R. E., 2009. Investing in early human development: timing and economic efficiency. Economics & Human Biology, 7(1), 1-6.

Fisher, S. C., Kim, S. Y., Sharma, A. J., Rochat, R., Morrow, B., 2013. Is obesity still increasing among pregnant women? Pre-pregnancy obesity trends in 20 states, 2003–2009. Preventive Medicine, 56(6), 372-378.

Frederick, I. O., Williams, M. A., Sales, A. E., Martin, D. P., Killien, M., 2008. Pre-pregnancy body mass index, gestational weight gain, and other maternal characteristics in relation to infant birth weight. Maternal and Child Health Journal, 12(5), 557-567.

Gilboa, S. M., Correa, A., Alverson, C. J., 2008. Use of spline regression in an analysis of maternal pre-pregnancy body mass index and adverse birth outcomes: does it tell us more than we already know? Annals of Epidemiology, 18(3), 196-205.

Hack, M., Klein, N. K., Taylor, H. G., 1995. Long-term developmental outcomes of low birth weight infants. The Future of Children, 5(1), 176-196.

Harder, T., Rodekamp, E., Schellong, K., Dudenhausen, J. W., Plagemann, A., 2007. Birth weight and subsequent risk of type 2 diabetes: a meta-analysis. American Journal of Epidemiology, 165(8), 849-857.

Hediger, M. L., Scholl, T. O., Belsky, D. H., Ances, I. G., Salmon, R. W., 1989. Patterns of weight gain in adolescent pregnancy: effects on birth weight and preterm delivery. Obstetrics & Gynecology, 74(1), 6-12.

Hickey, C. A., Cliver, S. P., McNeal, S. F., Hoffman, H. J., Goldenberg, R. L., 1996. Prenatal weight gain patterns and birth weight among nonobese black and white women. Obstetrics & Gynecology, 88, 490-496.

Hjalgrim, L. L., Westergaard, T., Rostgaard, K., Schmiegelow, K., Melbye, M., Hjalgrim, H., Engels, E. A., 2003. Birth weight as a risk factor for childhood leukemia: a meta-analysis of 18 epidemiologic studies. American Journal of Epidemiology, 158(8), 724-735.

Institute of Medicine, 1990. Nutrition during Pregnancy: Part I, Weight gain; part II, Nutrient Supplements. Washington, DC: National Academy Press.

Institute of Medicine, 2009. Weight Gain during Pregnancy: Reexamining the Guidelines. Washington, DC: National Academy Press.

Jansson, N., Nilsfelt, A., Gellerstedt, M., Wennergren, M., Rossander-Hulthén, L., Powell, T. L., Jansson, T., 2008. Maternal hormones linking maternal body mass index and dietary intake to birth weight. American Journal of Clinical Nutrition, 87(6), 1743-1749.

Kim, S. Y., Dietz, P. M., England, L., Morrow, B., Callaghan, W. M., 2007. Trends in pre-pregnancy obesity in nine states, 1993–2003. Obesity, 15(4), 986-993.

Kirkegaard, I., Obel, C., Hedegaard, M., Henriksen, T. B., 2006. Gestational age and birth weight in relation to school performance of 10-year-old children: a follow-up study of children born after 32 completed weeks. Pediatrics, 118(4), 1600-1606.

Ludwig, D. S., Currie, J., 2010. The association between pregnancy weight gain and birthweight: a within-family comparison. The Lancet, 376, 984-990.

Mandl, L. A., Costenbader, K. H., Simard, J. F., Karlson, E. W., 2009. Is birthweight associated with risk of rheumatoid arthritis? Data from a large cohort study. Annals of the Rheumatic Diseases, 68(4), 514-518.

McDonald, S. D., Han, Z., Mulla, S., Beyene, J., 2010. Overweight and obesity in mothers and risk of preterm birth and low birth weight infants: systematic review and meta-analyses. British Medical Journal, 341, 1-20.

McDonald, S. D., Han, Z., Mulla, S., Lutsiv, O., Lee, T., Beyene, J., 2011. High gestational weight gain and the risk of preterm birth and low birth weight: a systematic review and meta-analysis., Journal of Obstetrics and Gynecology Canada, 33(12), 1223-1233.

National Center for Health Statistics, 2014. Health, United States, 2013: With Special Feature on Prescription Drugs. Hyattsville, MD.

Rasmussen, K. M., Abrams, B., Bodnar, L. M., Butte, N. F., Catalano, P. M., Siega-Riz, A. M., 2010. Recommendations for weight gain during pregnancy in the context of the obesity epidemic. Obstetrics & Gynecology 116(5), 1191-1195.

Rasmussen, K. M., Catalano, P. M., Yaktine, A. L., 2009. New guidelines for weight gain during pregnancy: what obstetrician/gynecologists should know. Current Opinion in Obstetrics and Gynecology, 21, 521-526.

Richards, M., Hardy, R., Kuh, D., Wadsworth, M. E., 2001. Birth weight and cognitive function in the British 1946 birth cohort: longitudinal population based study. BMJ: British Medical Journal, 322, 199-204.

Rode, L., Hegaard, H. K., Kjargaard, H., Moller, L. F., Tabor, A., Ottesen, B., 2007. Association between maternal weight gain and birth weight. Obstetrics & Gynecology, 109(6), 1309-1315.

Siega-Riz, A. M., Laraia, B., 2006. The implications of maternal overweight and obesity on the course of pregnancy and birth outcomes. Maternal and Child Health Journal, 10(1), 153-156.

Thorsdottir, I., Torfadottir, J. E., Birgisdottir, B. E., Geirsson, R. T., 2002. Weight gain in women of normal weight before pregnancy: complications in pregnancy or delivery and birth outcome. Obstetrics & Gynecology, 99(5), 799-806.

Voigt, M., Heineck, G., Hesse, V., 2004. The relationship between maternal characteristics, birth weight and pre-term delivery: evidence from Germany at the end of the 20th century. Economics & Human Biology, 2(2), 265-280.

Wei, J. N., Li, H. Y., Sung, F. C., Lin, C. C., Chiang, C. C., Li, C. Y., Chuang, L. M., 2007. Birth weight correlates differently with cardiovascular risk factors in youth. Obesity, 15(6), 1609-1616.

Wooldridge, J. M., 2002. Econometric Analysis of Cross Section and Panel Data. MIT press, Cambridge, MA.

World Health Organization, 1995. Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee. WHO Technical Report Series 854.

Table 1

Summary statistics by infant birth weight category.

	(1) All the infants		(2) HBW infants		(3) Normal BW infants		(4) LBW infants	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Birth weight (g)	3396.41	537.14	4262.67	239.84	3358.97	354.02	2045.37	498.63
HBW	0.11	0.31	1.00	0.00	0.00	0.00	0.00	0.00
LBW	0.05	0.21	0.00	0.00	0.00	0.00	1.00	0.00
Pre-pregnancy obesity	0.21	0.40	0.27	0.45	0.20	0.40	0.21	0.41
Pre-pregnancy overweight	0.24	0.43	0.28	0.45	0.24	0.43	0.21	0.40
Pre-pregnancy underweight	0.04	0.19	0.01	0.11	0.04	0.20	0.07	0.25
Excessive weight gain	0.54	0.50	0.72	0.45	0.52	0.50	0.33	0.47
Inadequate weight gain	0.20	0.40	0.09	0.29	0.20	0.40	0.38	0.49
Infant male	0.51	0.50	0.64	0.48	0.50	0.50	0.47	0.50
Infant birth order	2.12	1.21	2.32	1.41	2.10	1.17	2.05	1.25
Mother's age	27.64	5.57	28.83	5.35	27.56	5.55	26.35	5.83
Mother non-Hispanic White	0.82	0.38	0.89	0.31	0.82	0.38	0.72	0.45
Mother non-Hispanic Black	0.08	0.28	0.04	0.21	0.08	0.28	0.17	0.37
Mother Hispanic	0.04	0.21	0.03	0.17	0.04	0.21	0.06	0.24
Mother Asian	0.03	0.16	0.01	0.11	0.03	0.17	0.03	0.17
Mother education=12 years	0.25	0.43	0.21	0.41	0.25	0.44	0.32	0.47
Mother education=13-15 years	0.27	0.44	0.28	0.45	0.27	0.44	0.25	0.43
Mother education ≥16 years	0.34	0.47	0.39	0.49	0.34	0.47	0.22	0.42
Mother married	0.70	0.46	0.80	0.40	0.70	0.46	0.54	0.50
Prenatal care in trimester 1	0.76	0.43	0.78	0.42	0.76	0.43	0.67	0.47
Prenatal smoking	0.14	0.35	0.06	0.24	0.15	0.35	0.28	0.45
Mother in WIC	0.33	0.47	0.26	0.44	0.34	0.47	0.44	0.50
Mother in Medicaid	0.26	0.44	0.19	0.39	0.26	0.44	0.38	0.49
Father's age	30.37	6.00	31.21	5.81	30.31	6.00	29.54	6.27
Father non-Hispanic White	0.76	0.43	0.84	0.37	0.76	0.43	0.63	0.48
Father non-Hispanic Black	0.09	0.29	0.06	0.23	0.09	0.29	0.17	0.37
Father Hispanic	0.11	0.31	0.08	0.27	0.11	0.31	0.16	0.37
Father Asian	0.02	0.15	0.01	0.10	0.02	0.15	0.02	0.15
Father education=12 years	0.29	0.45	0.25	0.43	0.29	0.45	0.34	0.48
Father education=13-15 years	0.24	0.42	0.25	0.44	0.24	0.42	0.20	0.40
Father education ≥16 years	0.29	0.45	0.34	0.47	0.29	0.45	0.19	0.40
N	354,945		38,167		300,639		16,139	

Notes: The full sample which is constructed from vital statistics natality birth records consists of all the mothers having delivered two or three live births in the state of Pennsylvania in 2003-2010 and in the state of Washington in 2003-2006.

Table 2

Pre-pregnancy BMI, gestational weight gain, and infant birth weight: baseline results.

	IOM 2009 Guideline			IOM 1990 Guideline		
	(1) Birth Weight	(2) HBW	(3) LBW	(4) Birth Weight	(5) HBW	(6) LBW
Pre-pregnancy obesity	82.466***	0.030***	-0.014***	87.371***	0.032***	-0.014***
	(5.320)	(0.004)	(0.002)	(4.927)	(0.003)	(0.002)
Pre-pregnancy overweight	30.731***	0.013***	-0.007***	24.928***	0.015***	-0.003*
	(3.406)	(0.002)	(0.002)	(3.628)	(0.003)	(0.002)
Pre-pregnancy underweight	-34.078***	-0.010***	0.015***	-46.271***	-0.010***	0.014***
	(6.710)	(0.004)	(0.004)	(4.361)	(0.003)	(0.002)
Excessive weight gain	106.570***	0.035***	-0.025***	105.883***	0.035***	-0.023***
	(2.587)	(0.002)	(0.001)	(2.538)	(0.002)	(0.001)
Inadequate weight gain	-87.328***	-0.014***	0.025***	-93.203***	-0.016***	0.026***
	(3.093)	(0.002)	(0.002)	(2.931)	(0.002)	(0.002)
Infant control variables?	Y	Y	Y	Y	Y	Y
Parental control variables?	Y	Y	Y	Y	Y	Y
Mother fixed effects?	Y	Y	Y	Y	Y	Y
N	354,945	354,945	354,945	354,945	354,945	354,945

Notes: All the regressions use the full sibling-birth sample, where the mothers had delivered two or three live births in the state of Pennsylvania in 2003-2010 and in the state of Washington in 2003-2006. The infant control variables include infant sex, birth order, birth year and month fixed effects. The parental control variables include mother's age, mother's education, marital status, prenatal care initiation in trimester one, prenatal smoking, mother's height, WIC enrollment, delivery payment types, indicators of pre-pregnancy risk factors, father's age, father's race, and father's education. Robust standard errors clustered at the mother's level are reported in parentheses.

*Significant at 10% level.

** Significant at 5% level.

***Significant at 1% level.

Table 3

Pre-pregnancy BMI, gestational weight gain, and infant birth weight: by number of births and by state.

	Mothers with Two Births			Mothers with Three Births		
	(1) Birth Weight	(2) HBW	(3) LBW	(4) Birth Weight	(5) HBW	(6) LBW
Pre-pregnancy obesity	78.274***	0.028***	-0.015***	77.457***	0.034***	-0.009*
	(5.979)	(0.004)	(0.003)	(11.661)	(0.008)	(0.005)
Pre-pregnancy overweight	26.097***	0.013***	-0.007***	37.489***	0.011**	-0.006*
	(3.826)	(0.003)	(0.002)	(7.480)	(0.005)	(0.003)
Pre-pregnancy underweight	-32.109***	-0.009**	0.014***	-40.758***	-0.015*	0.016*
	(7.456)	(0.004)	(0.005)	(15.463)	(0.008)	(0.009)
Excessive weight gain	107.339***	0.033***	-0.027***	110.683***	0.044***	-0.020***
	(2.887)	(0.002)	(0.001)	(5.826)	(0.004)	(0.003)
Inadequate weight gain	-88.500***	-0.015***	0.025***	-84.983***	-0.012***	0.025***
	(3.484)	(0.002)	(0.002)	(6.707)	(0.004)	(0.004)
Infant control variables?	Y	Y	Y	Y	Y	Y
Parental control variables?	Y	Y	Y	Y	Y	Y
Mother fixed effects?	Y	Y	Y	Y	Y	Y
N	297,972	297,972	297,972	56,973	56,973	56,973
	Mothers in PA			Mothers in WA		
	(1) Birth Weight	(2) HBW	(3) LBW	(4) Birth Weight	(5) HBW	(6) LBW
Pre-pregnancy obesity	72.353***	0.030***	-0.012***	97.751***	0.026***	-0.020***
	(5.700)	(0.004)	(0.003)	(13.681)	(0.010)	(0.006)
Pre-pregnancy overweight	27.377***	0.013***	-0.007***	26.023***	0.012**	-0.006*
	(3.682)	(0.003)	(0.002)	(8.458)	(0.006)	(0.004)
Pre-pregnancy underweight	-33.672***	-0.008**	0.015***	-40.730**	-0.018*	0.017*
	(7.173)	(0.004)	(0.004)	(17.896)	(0.011)	(0.010)
Excessive weight gain	108.165***	0.033***	-0.027***	108.968***	0.042***	-0.019***
	(2.788)	(0.002)	(0.001)	(6.507)	(0.005)	(0.003)
Inadequate weight gain	-86.105***	-0.013***	0.026***	-84.070***	-0.016***	0.022***
	(3.342)	(0.002)	(0.002)	(7.459)	(0.005)	(0.004)
Infant control variables?	Y	Y	Y	Y	Y	Y
Parental control variables?	Y	Y	Y	Y	Y	Y
Mother fixed effects?	Y	Y	Y	Y	Y	Y
N	304,025	304,025	304,025	50,920	50,920	50,920

Notes: Columns (1)-(3) in the upper panel examine all the mothers with two live births, and columns (4)-(6) in the upper panel focus on all the mothers with three live births. Columns (1)-(3) in the lower panel study all the mothers in the state of Pennsylvania (PA), and columns (4)-(6) in the lower panel focuses on all the mothers in the state of Washington (WA). The infant control variables include infant sex, birth order, birth year and month fixed effects. The parental control variables include mother's age, mother's education, marital status, prenatal care initiation in trimester one, prenatal smoking, mother's height, WIC enrollment, delivery payment types, indicators of pre-pregnancy risk factors, father's age, father's race, and father's education. Robust standard errors clustered at the mother's level are reported in parentheses.

*Significant at 10% level.

** Significant at 5% level.

***Significant at 1% level.

Table 4

Pre-pregnancy BMI, gestational weight gain, and infant birth weight: further robustness checks.

	The First and Second Births			Gestational Weight Gain>0		
	(1) Birth Weight	(2) HBW	(3) LBW	(4) Birth Weight	(5) HBW	(6) LBW
Pre-pregnancy obesity	74.236***	0.028***	-0.012***	72.274***	0.028***	-0.011***
	(6.865)	(0.005)	(0.003)	(5.688)	(0.004)	(0.003)
Pre-pregnancy overweight	22.784***	0.011***	-0.005**	25.589***	0.011***	-0.006***
	(4.367)	(0.003)	(0.002)	(3.559)	(0.003)	(0.002)
Pre-pregnancy underweight	-28.822***	-0.013***	0.013***	-31.528***	-0.010***	0.012***
	(8.318)	(0.004)	(0.005)	(6.825)	(0.004)	(0.004)
Excessive weight gain	115.568***	0.034***	-0.025***	110.295***	0.036***	-0.026***
	(3.300)	(0.002)	(0.002)	(2.640)	(0.002)	(0.001)
Inadequate weight gain	-90.448***	-0.013***	0.027***	-95.313***	-0.016***	0.026***
	(4.013)	(0.002)	(0.002)	(3.324)	(0.002)	(0.002)
Infant control variables?	Y	Y	Y	Y	Y	Y
Parental control variables?	Y	Y	Y	Y	Y	Y
Mother fixed effects?	Y	Y	Y	Y	Y	Y
N	225,994	225,994	225,994	333,043	333,043	333,043

Notes: Columns (1)-(3) focus on the mothers who had delivered only the first and second live birth in the sampling period. Columns (4)-(6) restrict the sample to the mothers whose weight gains are greater than zero. The infant control variables include infant sex, birth order, birth year and month fixed effects. The parental control variables include mother's age, mother's education, marital status, prenatal care initiation in trimester one, prenatal smoking, mother's height, WIC enrollment, delivery payment types, indicators of pre-pregnancy risk factors, father's age, father's race, and father's education. Robust standard errors clustered at the mother's level are reported in parentheses.

*Significant at 10% level.

** Significant at 5% level.

***Significant at 1% level.

Table 5

Pre-pregnancy BMI, gestational weight gain, and infant birth weight: heterogeneous effects and logit regression.

	Heterogeneous Effects of Weight Gain			Logit (Odds Ratios)	
	(1)	(2)	(3)	(4)	(5)
	Birth Weight	HBW	LBW	HBW	LBW
Pre-pregnancy obesity	81.452***	0.028***	-0.020***	1.474***	0.635***
	(7.085)	(0.005)	(0.003)	(0.077)	(0.050)
Pre-pregnancy overweight	34.593***	0.014***	-0.010***	1.190***	0.788***
	(5.030)	(0.003)	(0.003)	(0.042)	(0.043)
Pre-pregnancy underweight	-36.735***	-0.009**	0.014***	0.838*	1.380***
	(7.948)	(0.004)	(0.005)	(0.082)	(0.114)
Excessive weight gain				1.586***	0.505***
				(0.046)	(0.020)
Inadequate weight gain				0.767***	1.596***
				(0.029)	(0.063)
Excessive weight gain for obese women	67.175***	0.036***	-0.018***		
	(7.828)	(0.004)	(0.006)		
Excessive weight gain for overweight women	81.744***	0.033***	-0.018***		
	(4.656)	(0.003)	(0.002)		
Excessive weight gain for normal weight women	95.674***	0.035***	-0.026***		
	(2.991)	(0.002)	(0.002)		
Excessive weight gain for underweight women	119.061***	0.032***	-0.026***		
	(10.211)	(0.006)	(0.007)		
Inadequate weight gain for obese women	-63.022***	-0.011*	0.021***		
	(9.925)	(0.006)	(0.003)		
Inadequate weight gain for overweight women	-75.211***	-0.014***	0.025***		
	(6.801)	(0.004)	(0.004)		
Inadequate weight gain for normal weight women	-75.291***	-0.015***	0.020***		
	(3.490)	(0.002)	(0.002)		
Inadequate weight gain for underweight women	-89.494***	-0.015***	0.026***		
	(11.192)	(0.005)	(0.009)		
Infant control variables?	Y	Y	Y	Y	Y
Parental control variables?	Y	Y	Y	Y	Y
Mother fixed effects?	Y	Y	Y	Y	Y
N	354,945	354,945	354,945	354,945	354,945

Notes: All the regressions use the full sibling-birth sample, where the mothers had delivered two or three live births in the state of Pennsylvania in 2003-2010 and in the state of Washington in 2003-2006. The infant control variables include infant sex, birth order, birth year and month fixed effects. The parental control variables include mother's age, mother's education, marital status, prenatal care initiation in trimester one, prenatal smoking, mother's height, WIC enrollment, delivery payment types, indicators of pre-pregnancy risk factors, father's age, father's race, and father's education. Robust standard errors clustered at the mother's level are reported in parentheses.

*Significant at 10% level.

** Significant at 5% level.

***Significant at 1% level.

Appendix

Table A.1
Institute of Medicine 2009 and 1990 guidelines of total gestational weight gain ranges for women with singleton fetuses: by pre-pregnancy BMI category.

	2009 Guideline	
BMI Category	Ranges for BMI Categories (kg/m^2)	Recommended Weight Gain Ranges (kg)
Underweight	<18.5	12.5-18
Normal weight	18.5-25	11.5-16
Overweight	25-30	7-11.5
Obese	≥30	5-9
	1990 Guideline	
	Ranges for BMI Categories (kg/m^2)	Recommended Weight Gain Ranges (kg)
Underweight	<19.8	12.5-18
Normal weight	19.8-26	11.5-16
Overweight	26-29	7-11.5
Obese	≥29	>6.8

Source: IOM, 1990 and IOM, 2009.