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ORIGINAL ARTICLE

Maternal macronutrient intake during pregnancy and 5 years postpartum and associations with child weight status aged five

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BACKGROUND/OBJECTIVES: Animal models have demonstrated that maternal overnutrition during pregnancy influences offspring adiposity. Few human studies of normal pregnancy have replicated these findings. We examined the association between child body mass index at age 5 years and maternal nutrient intake during pregnancy and 5 years postpartum.
SUBJECTS/METHODS: Five-year-old children ($n = 585$) and their mothers were recruited during pregnancy from two maternity hospitals in Ireland. Data are from the Lifeways Cross-Generation Cohort study with detailed dietary information obtained during pregnancy and postpartum using a food frequency questionnaire. Nutrient intake was adjusted for energy intake (EI) and expressed in quartiles. Heights and weights were measured when the children were aged 5 years. We performed multivariate logistic regression analyses to examine the independent associations of macronutrients (protein, fat and carbohydrate) and their components (saturated fatty acid (SFA)/monounsaturated fatty acid/polyunsaturated fatty acid and sugar/starch) with child overweight/obesity. Associations were examined for nutrient intake during pregnancy (T1), at 5 years postpartum (T2) and the change in nutrient intake between T1 and T2.
RESULTS: Total mean (s.d.) EI was significantly higher during pregnancy (2548 ± 1239 kcal) than 5 years postpartum (2084 ± 718 kcal). Increased odds of overweight/obesity were found in mothers with higher intakes of sugar at T1 (Q4 odds ratio (OR): 4.57, 95% confidence interval (CI): 1.01–20.69) and high intakes of SFA at T2 (Q4 OR: 3.35, 95% CI: 0.97–11.57). Mothers with persistently high intakes of SFA and those who reduce their sugar intake between T1 and T2 were more likely to have overweight/obese children.
CONCLUSION: Maternal prenatal sugar and pre/postnatal SFA was associated with offspring adiposity.

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Keywords: maternal diet; child BMI; fat; sugar; cohort

INTRODUCTION

Fetal nutrition, prenatal growth and body composition reflect the supply of energy and nutrients from the maternal diet and nutritional stores.[1] Some authors have suggested that 'outside the realm of chronic energy deficiency, maternal diet may not merit special attention'.[2] Yet, animal studies have consistently demonstrated a relationship between prenatal nutritional environment, patterns of postnatal growth and adult adiposity.[3] Thus far, maternal-child cohort studies have not demonstrated an association between maternal diet and offspring body composition, possibly because of inadequate nutritional data.[4]

In the Avon Longitudinal Study of Parents and Children (ALSPAC), diet during pregnancy was assessed for 5593 mother–offspring pairs, yet Brion *et al.*[5] could not demonstrate an association between maternal macronutrient (protein, fat and carbohydrate) intake during pregnancy and offspring adiposity or lean mass at age 9 and 11 years. However, emerging evidence suggests that the balance of macronutrient components may be of more interest. In a review of animal models, Ainge *et al.*[6] reported that pregnant rodents fed a diet high in saturated fat consistently have offspring with a higher risk of developing type 2 diabetes and obesity. An opposing effect has been demonstrated for polyunsaturated fat in human studies where a high maternal *n*-3 polyunsaturated fatty acid (PUFA) status during pregnancy was associated with lower childhood adiposity at 3 years.[7] In relation to carbohydrate status, the Perinatal Infant Nutrition study found that high maternal glucose concentration during pregnancy was associated with a higher risk of child overweight/obesity at 3 years.[8]

These studies suggest that macronutrient balance from the maternal diet may be a critical exposure for the developing fetus. However, critics would argue that offspring adiposity is just as likely to be influenced by the postnatal environment where mother and child are consuming similar foods. In the current study, maternal macronutrient and macronutrient components (saturated fatty acid (SFA), monounsaturated fatty acid (MUFA), and PUFA; starch and sugar) during the first trimester of pregnancy (Time 1 (T1)) and maternal intakes when the child was aged 5 years (Time 2 (T2)) were examined in association with their offspring's weight status at the age of 5 years. We also sought to examine whether a change in mothers' nutrient intake from the time of pregnancy to 5 years postpartum was related to their child's weight status.

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MATERIALS AND METHODS

Subjects

This longitudinal observational study was established between 2001 and 2003 with the recruitment of 1124 mothers from two maternity hospitals in Ireland (Figure 1). Mothers were approached by a midwife at their first ante-natal booking visit to participate in the study, and only Irish born mothers were recruited.[9] A cohort of 1094 live infants were born to these mothers including 12 sets of twins ($n = 1082$ mothers). In 2007–2008, the 1082 families were contacted when the children were aged 5 years on average, and 669 (62%) agreed to the follow-up. Height and weight measurements were available from $n = 585$ children.

Methods

Dietary assessment. On providing consent, mothers completed a questionnaire with sections relating to general health, smoking and alcohol use, and social characteristics. Dietary intake during the first trimester of pregnancy and 5 years postnatally was assessed by a 149-item semi-quantitative food frequency questionnaire (FFQ) based on the European Prospective Investigation into Cancer and Nutrition instrument,[10] which has been validated extensively in several populations.[11] The version used in this study was originally validated using food diaries and a protein biomarker in a volunteer sample[12] and was then incorporated into the Irish Surveys of Lifestyle Attitudes and Nutrition 1998, 2002, 2006.[13–15] The FFQ was also validated using a 7-day weighed food record completed by a subsample of Lifeways mothers at the time of follow-up, with reasonable agreement ($r > 0.40$) for fat, carbohydrate and their components, and with lower agreement for protein ($r = 0.25$).[16]

Respondents indicated their average use of each food item since becoming pregnant or during the first 12–16 weeks of pregnancy (T1) and over the last year (T2). Frequency of consumption of a medium serving or common household unit was asked for each food and later converted to quantities using standard portion sizes.[17] The frequency categories were 'never or less than once per month', '1–3 per month', 'once a week', '2–4 per week', '5–6 per week', 'once a day', '2–3 per day', '4–5 per day' and '6 + per day'. The daily intake of energy and nutrients was computed from FFQ data using a tailored computer program (FFQ_Software Ver 1.0; developed by the National Nutrition Surveillance Centre, School of Public Health, Physiotherapy and Population Science, University College Dublin), which linked frequency selections with the food equivalents in McCance and Widdowson Food Tables.[17] The frequency proportion was applied to a standard food portion size to determine the equivalent daily intake of a food. For instance, consumption of roast beef 'once a day' was assigned a standard portion size of 100 g (1 day × 100 g); '1–3 per month' was assigned a quantity of 6.45 g (2/31days × 100 g). The nutrient content of each proportion of food was calculated, and an estimate of daily nutrient intake was calculated by the sum of all the nutrients for each individual.

Total energy intake (EI) was the primary criterion for exclusion for implausible dietary intakes, with those outside the range of 500–3500 kcal/day being excluded. Once the overall EI was computed for each mother, the percentage of respondents that under- and over-reported EIs was estimated. Schofield equations were used to estimate basal metabolic rate.[18] A factor was included for the energy demands during the first trimester of pregnancy (+ 5%).[19] The ratio of EI to basal metabolic rate was calculated. Cut-off limits based on physiologically plausible levels of EI on a habitual basis, developed by Goldberg and colleagues[20,21], were used to identify under-, normal and over-reporters. Under-reporters were those with EI/basal metabolic rate < 1.35, normal reporters were in the range of 1.35–2.39 and over-reporters $\geqslant 2.4$.[21,22] Twenty-six percent of mothers were under-reporters; the remainder being normal/over-reporters.

Mothers repeated the baseline questionnaire at T2 and provided information about their child's health and lifestyle, including whether they were breastfed. By administering the FFQ during pregnancy (T1) and again at 5 years postpartum (T2), changes in nutrient intake could be examined.

Macronutrients were adjusted for EI using the energy density method. Mothers were ranked into quartiles according to intakes of each macronutrient (protein, fat and carbohydrate) and their components (SFA, MUFA, and PUFA; starch and sugar).

Assessment of body-weight status. Mothers reported their height and weight before they became pregnant. Hospital record data for mother and

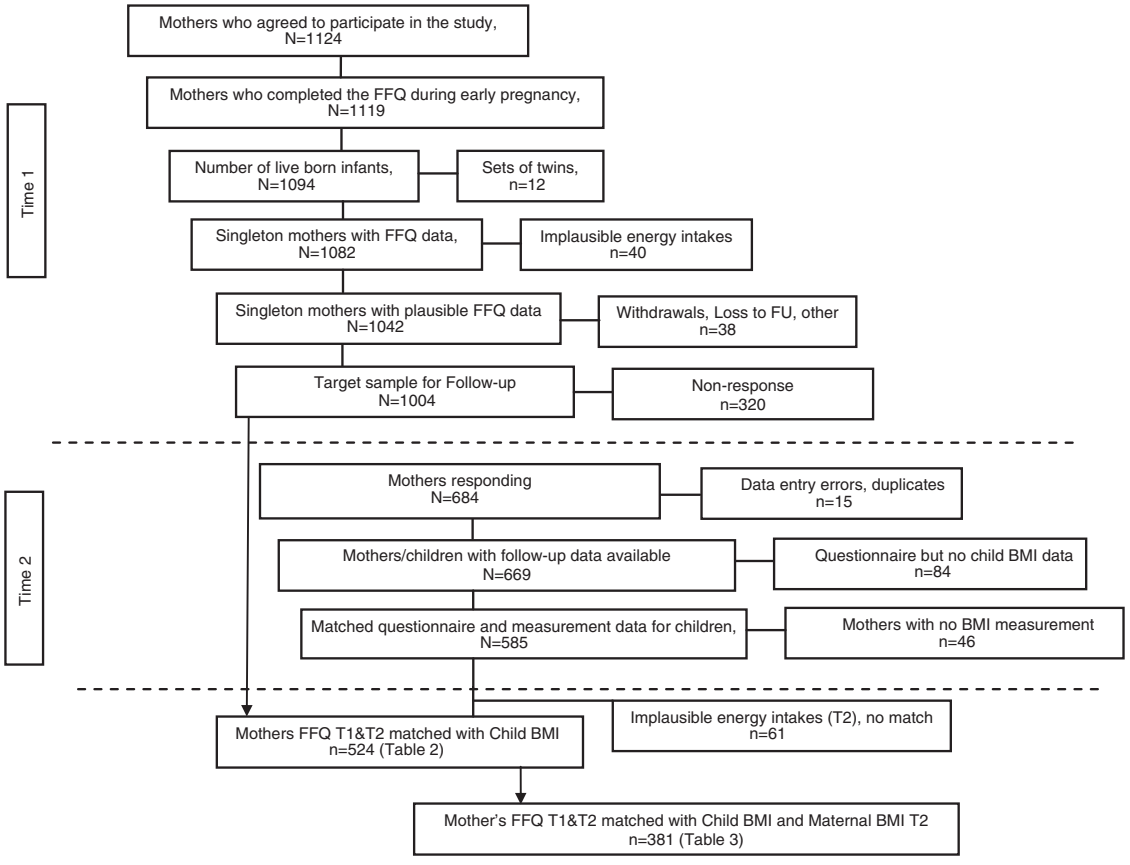

Figure 1. Flow diagram of cohort sample size from baseline to analysis.

infant were collated to provide information on obstetrical and birth outcomes, including gestational diabetes mellitus and birthweight.

At the time of follow-up, weight and height measurements for the mother and child were conducted by trained researchers in the family home. Standardised protocols were applied to measure height to the nearest 0.1 cm and weight to the nearest 0.1 kg.[23,24] Materials included a portable Leicester Height Scale for measurement of height and a SECA digital weighing scale for weight measurement (purchased and calibrated from Chasmors Ltd, London, UK). Body mass index (BMI) was calculated by dividing weight (kg) by height squared (m^2), and mothers were classified as normal ($<25\,kg/m^2$), overweight ($\geqslant 25\,kg/m^2$) or obese ($30\,kg/m^2$) according to the World Health Organisation criteria. Normal, overweight and obesity in children were classified using the International Obesity Taskforce cut-offs[25] and then dichotomised to provide the outcome variable (normal vs overweight/obese).

Statistical analysis. Mean EIs and the percentage energy from macronutrients were compared for mothers during pregnancy and at the time of follow-up by paired *t*-test. The relationship between the nutrients consumed at T1 and T2 was assessed using Pearson's correlation. The change in maternal intake between T 1 and T2 was identified by examining whether mothers shifted intakes across quartiles. These were categorised accordingly: Group A—those who remained low consumers of a nutrient; Group B—those who shifted to a higher consumption; Group C—those who shifted to a lower consumption; Group D—those who remained high consumers. Logistic regression methods were employed to identify associations between maternal intake of individual of nutrients, the change in nutrient intake and the child's weight status. This approach was used to allow for the nutrient intake in T2 to be adjusted for nutrient intake in T1. Univariate analysis examined the association of each nutrient with child overweight/obesity. A series of multivariate analyses followed with the final model adjusting for maternal BMI and height, child birthweight, child age and gender, mother's age, smoking status during pregnancy, socioeconomic status and whether the child was breastfed. Generalised Linear Modelling was used to calculate *P*-value for trend across categories in Tables 2 and 3.

RESULTS

Comparisons of energy and macronutrient intake between the two time points are presented in Table 1. Mean EIs during pregnancy were significantly higher than that at follow-up. The percentage energy from macronutrients also differed between time points. Total carbohydrate and its sugar constituent were significantly higher during pregnancy, as was SFA intake. In contrast, protein and starch intakes were higher at 5 years postpartum.

Table 1. Comparison between in average daily intake of energy and nutrients in mothers during pregnancy (T1) and 5 years postpartum (T2)

Energy and nutrients	*Time*	*Mean*	*s.d.*	P-*value*[a]
Energy (Kcal)	T1	2548.1	1239.3	0.000
	T2	2084.2	717.7	
% Protein	T1	17.1	3.9	0.000
	T2	18.1	3.4	
% Fat	T1	35.3	6.5	0.163
	T2	34.8	5.9	
% Carbohydrate	T1	50.4	7.9	0.003
	T2	49.0	6.9	
% MUFA	T1	11.4	2.5	0.274
	T2	11.5	2.5	
% PUFA	T1	5.7	2.1	0.172
	T2	6.8	2.0	
% SFA	T1	13.8	13.8	0.000
	T2	11.7	11.7	
% Sugar	T1	23.0	23.0	0.000
	T2	20.5	20.5	
% Starch	T1	26.9	26.9	0.011
	T2	28.0	28.0	

Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid. [a]Paired *t*-test (two-tailed).

Univariate analysis of quartiles of individual nutrients during pregnancy demonstrated significant associations with fat, carbohydrate, SFA and starch intakes, and offspring overweight/obesity (Table 2). Partial adjustment for all nutrients in the one model resulted in significant associations only for carbohydrate and sugar. In the fully adjusted model during pregnancy (Table 2), there was a clear gradient for the percentage of energy derived from sugar and offspring overweight/obesity at age 5 years, with mothers in the highest quartile of intake being 4.5 times more likely to have a child who was overweight/obese (Q4 odds ratio (OR) 4.57, 95% confidence interval (CI): 1.01–20.69, *P* for trend = 0.07). In this model, child overweight/obesity was also significantly associated with maternal BMI before pregnancy (OR 1.09, 95% CI: 1.01–1.16) and high ($\geqslant$ 4.0 kg) infant birthweight (OR 1.97, 95% CI: 0.99–3.91).

The analysis was repeated for maternal nutrient intakes at 5 years postpartum to examine the influence of concurrent maternal diet and offspring adiposity. Table 3 shows that mothers with higher intakes of sugar are less likely to have overweight/obese children than those with low intakes. Furthermore, in the fully adjusted model, the direction of the sugar associations occur with the opposing direction of SFA intakes. Mothers in the highest quartile of SFA intake postpartum were associated with child overweight/obesity (Q4 OR 3.35, 95% CI: 0.97–11.57, *P* for trend = 0.12).

The final analysis examined the change in nutrient intake between the two time points (Table 4). Mothers whose intake of SFA remains in the highest quartile during pregnancy and postnatally were over three times more likely to have an overweight or obese child (Group D OR 3.72, 95% CI: 1.12–12.33). The change in sugar intake between pregnancy and 5 years postpartum was also significant in the fully adjusted model where mothers who changed from having a high sugar consumption during pregnancy to a lower consumption 5 years postpartum were more likely to have an overweight/obese child (Group C: OR 2.48, 95% CI: 1.14–5.41). Increasing maternal BMI and high birthweight continued to remain as significant predictors of child weight status.

The correlation matrix in Table 5 demonstrates that there was a relationship between the nutrient intake at T1 and T2, which ranged from $r = 0.14$ for starch to $r = 0.30$ for total fat.

DISCUSSION

In the present study, the saturated fat and sugar components of maternal diet were associated with offspring weight status, whereas total fat and total carbohydrate did not demonstrate any effect. Our findings also suggest that persistent high maternal SFA intake is a strong indicator of child overweight and obesity both during pregnancy and in the concurrent diet. Maternal sugar intake, however, appears to have a strong positive predictive effect during pregnancy, but in the postnatal environment, mothers with high intakes were less likely to have overweight or obese children.

Few human observational studies have examined the association between maternal pre- and postnatal nutrient intake and childhood adiposity. Brion *et al.*[5] were unable to demonstrate an association, perhaps as a result of analysing total macronutrient content only rather than the nutrient components, as we have demonstrated here. Nevertheless, they did find that parental–offspring macronutrient associations had stronger effects for prenatal maternal fat and protein intake than for postnatal intakes. Furthermore, we have recently reported an association between familial total macronutrient intake and offspring macronutrient intake across three generations, strongest across the maternal line.[26]

Table 2. Quartiles of maternal macronutrient intake during pregnancy (Time 1) on predicting offspring overweight/obesity

	Normal weight	*Overweight/ obese*	*Univariate nutrients*	*Multivariate nutrients*	*Multivariate fully adjusted 95% CI*			
	n	n	*OR*	*OR*	*OR*	*Lower*	*Upper*	P-*value*
			(n = *524*)	(n = *524*)		(n = *343*)		
Energy (Kcal)								
Q1	100	31	1.00	1.00	1.00			
Q2	92	39	1.37	1.24	1.27	0.59	2.72	0.54
Q3	97	34	1.13	0.94	0.63	0.27	1.50	0.30
Q4	101	30	0.96	0.76	0.70	0.29	1.71	0.44
P_{trend}			0.73	0.36	0.22			
% Protein								
Q1	87	32	1.00	1.00	1.00			
Q2	104	29	0.76	0.81	1.07	0.45	2.57	0.87
Q3	98	34	0.94	1.09	1.13	0.41	3.12	0.82
Q4	102	38	1.01	1.50	1.63	0.51	5.25	0.41
P_{trend}			0.77	0.15	0.25			
% Fat								
Q1	107	23	1.00	1.00	1.00			
Q2	103	37	1.67†	3.21	2.65	0.70	10.05	0.15
Q3	92	41	2.07*	2.86	2.04	0.34	12.18	0.43
Q4	89	33	1.72†	1.99	2.10	0.22	20.15	0.52
P_{trend}			0.05	0.32	0.32			
% Carbohydrate								
Q1	92	31	1.00	1.00	1.00			
Q2	89	52	1.73*	2.06†	2.74	0.90	8.29	0.08†
Q3	112	21	0.56†	0.69	0.70	0.16	3.17	0.65
Q4	99	30	0.90	1.64	1.38	0.17	10.93	0.76
P_{trend}			0.11	0.55	0.83			
% MUFA								
Q1	102	29	1.00	1.00	1.00			
Q2	95	33	1.22	0.65	0.56	0.18	1.74	0.32
Q3	106	34	1.13	0.49	0.59	0.17	2.03	0.40
Q4	85	38	1.57	0.89	0.77	0.17	3.59	0.74
P_{trend}			0.16	0.67	0.67			
% PUFA								
Q1	87	29	1.00	1.00	1.00			
Q2	108	29	0.81	0.94	1.01	0.42	2.45	0.98
Q3	95	37	1.17	1.53	1.02	0.38	2.74	0.97
Q4	96	38	1.19	1.54	1.30	0.44	3.86	0.64
P_{trend}			0.29	0.10	0.65			
% SFA								
Q1	109	29	1.00	1.00	1.00			
Q2	105	33	1.18	1.06	1.62	0.62	4.20	0.32
Q3	85	30	1.33	1.26	1.63	0.45	5.83	0.45
Q4	91	42	1.73*	2.11	3.40	0.66	17.48	0.14
P_{trend}			0.04	0.17	0.15			
% Sugar								
Q1	100	26	1.00	1.00	1.00			
Q2	106	37	1.34	1.30	2.61	1.04	6.56	0.04*
Q3	94	39	1.60	2.13†	3.56	1.19	10.60	0.02*
Q4	90	32	1.37	2.29	4.57	1.01	20.69	0.05*
P_{trend}			0.23	0.13	0.07			
% Starch								
Q1	89	39	1.00	1.00	1.00			
Q2	85	36	0.97	1.19	1.80	0.70	4.64	0.22
Q3	108	31	0.65	0.91	2.56	0.82	7.97	0.10
Q4	109	27	0.56*	1.31	4.26	0.96	18.79	0.06†
P_{trend}			0.02	0.74	0.05			
Mother's BMI at T1 (kg/m^2)					1.09	1.01	1.16	0.02*
Mother's height at T1 (cm)					0.98	0.93	1.02	0.31

Table 2. (Continued)

	Normal weight	*Overweight/ obese*	*Univariate nutrients*	*Multivariate nutrients*	*Multivariate fully adjusted 95% CI*			
	n	n	*OR*	*OR*	*OR*	*Lower*	*Upper*	P-*value*
			(n = *524*)	(n = *524*)	(n = *343*)			
Child's birthweight								
Normal birthweight (2.5–4 kg)					1.00			
Low birthweight (<2.5 kg)					1.77	0.52	6.03	0.36
High birthweight (⩾4 kg)					1.97	0.99	3.91	0.05*
Child's age (years)					0.62	0.24	1.63	0.33
Child's gender (male[a] vs female)					1.16	0.66	2.03	0.60
Mother's age (years)					0.99	0.94	1.05	0.76
Mother's smoking in pregnancy (no[a] vs yes)					1.41	0.68	2.90	0.36
Mother's entitled to subsidised health care (no[a] vs yes)					1.23	0.49	3.09	0.66
Breastfed (yes[a] vs no)					1.28	0.70	2.36	0.43

Abbreviations: BMI, body mass index; CI, confidence interval; OR, odds ratio; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid. $^{\dagger}P<0.1$, $^{*}P<0.05$. For adjusted multivariate model-2 likelihood = 336.71; Nagelkerke R square = 0.192. [a]Reference category.

Table 3. Quartiles of maternal macronutrient 5 years postpartum (Time 2) on predicting offspring overweight/obesity

	Normal weight	*Overweight/ obese*	*Univariate nutrients*	*Multivariate nutrients*	*Multivariate fully adjusted 95% CI*			
	n	n	*OR*	*OR*	*OR*	*Lower*	*Upper*	P-*value*
			(n = *381*)	(n = *381*)	(n = *358*)			
Energy (Kcal)								
Q1	70	26	1.00	1.00	1.00			
Q2	76	19	0.67	0.73	0.60	0.27	1.34	0.21
Q3	70	25	0.96	0.90	0.85	0.37	1.94	0.70
Q4	66	29	1.18	1.45	1.01	0.43	2.36	0.99
P_{trend}			0.42	0.29	0.82			
% Protein								
Q1	74	22	1.00	1.00	1.00			
Q2	68	26	1.29	1.30	1.01	0.45	2.45	0.90
Q3	71	24	1.14	1.08	0.71	0.30	1.79	0.47
Q4	69	27	1.32	1.29	0.85	0.29	2.45	0.76
P_{trend}			0.51	0.72	0.61			
% Fat								
Q1	70	26	1.00	1.00	1.00			
Q2	70	25	0.96	1.64	1.61	0.57	4.59	0.37
Q3	72	23	0.86	1.35	1.02	0.26	3.90	0.98
Q4	70	25	0.96	0.75	0.38	0.05	2.87	0.35
P_{trend}			0.83	0.71	0.31			
% Carbohydrate								
Q1	68	27	1.00	1.00	1.00			
Q2	70	26	0.94	1.29	1.75	0.64	4.77	0.28
Q3	75	20	0.67	0.86	0.98	0.25	3.80	0.98
Q4	79	26	0.95	1.61	1.17	0.21	6.46	0.86
P_{trend}			0.65	0.68	0.96			
% MUFA								
Q1	67	29	1.00	1.00	1.00			
Q2	67	28	0.97	0.52	0.45	0.17	1.22	0.11
Q3	78	16	0.47*	0.26*	0.19	0.05	0.69	0.01*
Q4	70	26	0.86	0.30†	0.34	0.07	1.68	0.19
P_{trend}			0.29	0.06	0.13			

Table 3. (Continued)

	Normal weight	*Overweight/ obese*	*Univariate nutrients*	*Multivariate nutrients*	*Multivariate fully adjusted 95% CI*			
	n	n	*OR*	*OR*	*OR*	*Lower*	*Upper*	P-*value*
			(n = *381*)	(n = *381*)		(n = *358*)		
% PUFA								
Q1	70	26	1.00	1.00	1.00			
Q2	72	23	0.86	1.00	0.93	0.40	2.17	0.87
Q3	69	26	1.01	1.47	1.51	0.59	3.84	0.39
Q4	71	24	0.91	1.54	1.55	0.51	4.69	0.44
P_{trend}			0.91	0.31	0.33			
% SFA								
Q1	74	22	1.00	1.00	1.00			
Q2	65	29	1.50	1.90	1.99	0.85	4.65	0.11
Q3	77	19	0.83	1.32	1.34	0.49	3.71	0.57
Q4	66	29	1.48	2.84†	3.35	0.97	11.57	0.06†
P_{trend}			0.56	0.15	0.12			
% Sugar								
Q1	65	30	1.00	1.00	1.00			
Q2	68	28	0.89	0.77	0.68	0.30	1.54	0.35
Q3	73	22	0.65	0.49	0.44	0.16	1.18	0.10
Q4	76	19	0.54†	0.24*	0.26	0.07	0.97	0.05*
P_{trend}			0.04	0.02	0.05			
% Starch								
Q1	64	32	1.00	1.00	1.00			
Q2	81	14	0.35*	0.27**	0.19	0.07	0.47	0.00**
Q3	72	22	0.61	0.40*	0.38	0.16	0.94	0.04*
Q4	65	31	0.95	0.42	0.36	0.10	1.24	0.11
P_{trend}			0.79	0.19	0.18			
Mother's BMI at T2 (kg/m^2)					1.11	1.05	1.17	0.00**
Mother's Height at T2 (cm)					1.00	0.96	1.05	0.86
Child's birthweight								
Normal birthweight (2.5–4 kg)					1.00			
Low birthweight (< 2.5 kg)					0.75	0.19	2.93	0.68
High birthweight (⩾4 kg)					1.89	0.96	3.74	0.07†
Child's age (years)					0.67	0.21	2.16	0.50
Child's gender (male[a] vs female)					1.24	0.71	2.16	0.44
Mother's age (year)					1.02	0.96	1.08	0.53
Mother's smoking in pregnancy (no[a] vs yes)					1.64	0.76	3.54	0.21
Mother's entitled to subsidised health care (yes[a] vs no)					0.92	0.37	2.28	0.85
Breastfed (yes[a] vs no)					0.94	0.53	1.66	0.83

Abbreviations: BMI, body mass index; CI, confidence interval; OR, odds ratio; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid. †$P<0.1$, *$P<0.05$, **$P<0.01$. For adjusted multivariate model-2 likelihood = 349.15; Nagelkerke R square = 0.230. [a]Reference category.

The observation that a diet that is high in SFA at both time points is the strongest predictor of offspring overweight/obesity supports the evidence in experimental studies.[6,27–29] Several possible mechanisms have been proposed that may mediate the developmental programming of obesity. Maternal dietary fat has been implicated in fetal development, specifically PUFA *n*-6 and *n*-3, which have key roles in brain development. It has been suggested that foods high in non-PUFA may interfere with metabolism of these essential fatty acids, leading to alterations in the development of the hypothalamic centres that control appetite.[30] Indeed, Donahue *et al.*[7] have recently demonstrated a protective effect of prenatal *n*-3 PUFAs on adiposity in 3-year olds. Postnatal nutrient intake may reflect prenatal intake, and we did find correlations between the two time points, however, these relationships only explained up to 9% of the variance in the case of total fat intake. Furthermore, the inclusion of dietary change as a categorical variable in the multivariate model allowed for adjustment where nutrient intake at T1 may confound the association at T2 and also allowed for the problem of multicollinearity between the time points.

There was a clear gradient in the effect of sugar intake during pregnancy and offspring weight status. This is supported by evidence from several studies that have looked at maternal glucose concentration in relation to offspring size.[8,31–33] A direct effect of prenatal sugar intake and offspring adiposity is highly plausible. Glucose is derived from the metabolism of carbohydrate in the diet, and is the principal source of fuel for the growing fetus. High-glucose concentrations cross the placenta but maternal insulin does not, leading to increased insulin production in the fetus, which stimulates growth and high levels of subcutaneous fat in the

Table 4. The effect of change in quartiles of maternal macronutrient between Time 1 and Time 2 on offspring overweight/obesity

	Normal Weight	*Overweight/ obese*	*Univariate nutrients*	*Multivariate nutrients*	*Multivariate nutrients*	*Multivariate fully adjusted 95% CI*			
	n	n	*OR*	*OR*	*OR*	*OR*	*Lower*	*Upper*	P-*value*
			(n = *381)*	(n = *376)*	(n = *368)*	(n = *358)*			
Energy (Kcal)									
Group A	139	53	1.00	1.00	1.00	1.00			
Group B	28	9	0.84	0.85	0.76	0.78	0.29	2.07	0.62
Group C	83	21	0.66	0.65	0.58	0.61	0.31	1.19	0.15
Group D	32	16	1.31	1.10	1.08	1.16	0.51	2.65	0.73
% Protein									
Group A	102	36	1.00	1.00	1.00	1.00			
Group B	70	21	0.85	0.84	0.72	0.71	0.33	1.56	0.40
Group C	40	12	0.85	0.79	0.77	0.73	0.30	1.83	0.51
Group D	70	30	1.21	1.38	1.34	1.32	0.59	2.93	0.50
% Fat									
Group A	124	37	1.00	1.00	1.00	1.00			
Group B	51	17	1.12	1.03	1.13	1.51	0.48	4.70	0.48
Group C	55	25	1.52	1.49	1.65	1.56	0.58	4.17	0.38
Group D	52	20	1.29	0.96	0.93	0.94	0.27	3.29	0.93
% Carbohydrate									
Group A	134	53	1.00	1.00	1.00	1.00			
Group B	26	15	1.46	1.20	1.04	0.85	0.31	2.38	0.76
Group C	68	18	0.67	0.57	0.51	0.46	0.18	1.15	0.10
Group D	54	13	0.61	0.57	0.49	0.44	0.15	1.33	0.15
% MUFA									
Group A	113	40	1.00	1.00	1.00	1.00			
Group B	59	16	0.77	0.58	0.53	0.36	0.12	1.11	0.07
Group C	49	19	1.10	0.62	0.65	0.72	0.29	1.81	0.48
Group D	61	24	1.11	0.60	0.57	0.53	0.18	1.53	0.24
% PUFA									
Group A	76	23	1.00	1.00	1.00	1.00			
Group B	96	33	1.14	1.08	1.05	1.09	0.50	2.37	0.82
Group C	24	11	1.51	1.07	1.06	1.09	0.40	2.95	0.87
Group D	86	32	1.23	1.36	1.35	1.37	0.59	3.17	0.47
% SFA									
Group A	158	46	1.00	1.00	1.00	1.00			
Group B	18	7	1.34	2.52	2.71	2.53	0.79	8.12	0.12
Group C	85	34	1.37	1.54	1.47	1.33	0.58	3.01	0.50
Group D	21	12	1.96†	3.22*	3.68	3.72	1.12	12.33	0.03*
% Sugar									
Group A	136	49	1.00	1.00	1.00	1.00			
Group B	33	10	0.84	1.11	1.24	1.36	0.49	3.80	0.55
Group C	69	31	1.25	2.34*	2.59	2.48	1.14	5.41	0.02*
Group D	44	9	0.57	0.81	0.97	1.08	0.37	3.19	0.89
% Starch									
Group A	94	34	1.00	1.00	1.00	1.00			
Group B	72	29	1.11	0.95	1.16	1.26	0.56	2.79	0.51
Group C	18	81	0.79	1.00	1.21	1.34	0.55	3.26	0.58
Group D	18	71	0.94	1.40	1.77	2.12	0.80	5.57	0.13
Mother's BMI at T2 (kg/m^2)				1.10**	1.11	1.11	1.05	1.17	0.00**
Mother's height at T2 (cm)				1.00	1.00	1.01	0.97	1.06	0.17
Child's birthweight									
Normal birthweight (2.5–4 kg)				1.00	1.00	1.00			
Low birthweight (< 2.5 kg)				1.01	1.00	1.03	0.28	3.84	0.96
High birthweight (⩾4 kg)				2.04*	2.16	1.91	0.98	3.74	0.06†
Child's age (years)					0.70	0.57	0.18	1.84	0.35
Child's gender (male[a] vs female)					1.41	1.32	0.77	2.27	0.31
Mother's age (yr)					1.01	1.02	0.97	1.07	0.50
Mother's smoking in pregnancy (no[a] vs yes)					1.48	1.53	0.73	3.20	0.26
Mother's entitled to subsidised health care (yes[a] vs no)					0.98	0.87	0.35	2.13	0.76
Breastfed (yes[a] vs no)						0.92	0.53	1.62	0.78

Abbreviations: BMI, body mass index; CI, confidence interval; OR, odds ratio; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid. Group A (reference), remained low consumers; Group B, shifted to higher consumption; Group C, shifted to lower consumption; Group D, remained high consumers. $^{\dagger}P<0.1$, $^{*}P<0.05$, $^{**}P<0.01$. For model 4–2 likelihood = 364.07; Nagelkerke R square = 0.177. [a]Reference category.

Table 5. Correlation matrix of maternal nutrients intakes during pregnancy (Time 1) and 5 years postpartum (Time 2)

	Maternal macronutrient intake during pregnancy (Time 1)							
	% Protein	*% Fat*	*% Carbohydrate*	*% MUFA*	*% PUFA*	*% SFA*	*% Sugar*	*% Starch*
Maternal macronutrient intake 5 years postpartum (Time 2)								
n	381	381	381	381	381	381	381	381
% Protein								
r	**0.29**	−0.15	−0.03	−0.14	−0.11	−0.09	−0.06	0.02
P-value	0.000	0.003	0.590	0.006	0.028	0.083	0.213	0.642
% Fat								
r	−0.04	**0.30**	−0.24	0.28	0.15	0.23	−0.19	−0.12
P-value	0.425	0.000	0.000	0.000	0.003	0.000	0.000	0.020
% Carbohydrate								
r	−0.13	−0.19	**0.25**	−0.18	−0.08	−0.14	0.23	0.09
P-value	0.013	0.000	0.000	0.000	0.100	0.005	0.000	0.093
% MUFA								
r	−0.01	0.21	−0.18	**0.22**	0.09	0.16	−0.16	−0.08
P-value	0.888	0.000	0.000	0.000	0.097	0.002	0.002	0.144
% PUFA								
r	−0.03	0.14	−0.09	0.12	**0.27**	−0.02	−0.12	0.00
P-value	0.516	0.008	0.092	0.020	0.000	0.752	0.024	0.983
% SFA								
r	−0.06	0.25	−0.19	0.23	0.00	**0.27**	−0.12	−0.12
P-value	0.275	0.000	0.000	0.000	0.981	0.000	0.018	0.017
% Sugar								
r	−0.06	−0.13	0.16	−0.10	−0.10	−0.09	**0.25**	−0.04
P-value	0.236	0.010	0.002	0.063	0.051	0.067	0.000	0.427
% Starch								
r	−0.09	−0.07	0.12	−0.10	0.01	−0.06	0.00	**0.14**
P-value	0.095	0.158	0.024	0.048	0.859	0.238	0.930	0.006

Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid. Bold signifies the correlation co-efficient of the same nutrient at Time 1 and Time 2.

offspring. Studies of gestational diabetes mellitus have demonstrated that glucose supply to the fetus is positively associated with birthweight and later body composition.[31,34,35] High maternal glucose concentrations were also found to be significantly associated with fetal macrosomia in infants of non-diabetic mothers.[36–38]

During pregnancy, women commonly report craving sweet foods,[1,39] which may correspond with high sugar intakes, and randomized diet trials have found that the typical 'western' diet may induce insulin insensitivity in pregnant women.[40] Energy-dense diets have been found to positively influence gestational weight gain.[41] In trials with pregnant animals, feeding rats a 'junk' food diet, characterised by high fat, high sugar and high salt, has demonstrated increased risk of adiposity in adult offspring.[42] Further studies that have examined the use of the glycaemic index as a method of classifying the response to carbohydrate during pregnancy found an increased risk of birthweight and infant adiposity in women consuming a high glycaemic index diet.[43]

The observation that child obesity is more likely in mothers who reduce their sugar intake from the time of pregnancy was unexpected, particularly because, unlike SFA, those who remained as high consumers were no more likely to increase the risk of overweight/obesity than those who were low consumers. One possible explanation is that mothers who reported a high sugar intake during pregnancy were subsequently identified as having hyperglycaemia or impaired glucose tolerance and either reduced their sugar intake or may have under-reported their sugar intake at the 5-year follow-up. Maternal gestational diabetes mellitus was previously included in an analysis (not shown here) but, similar to the findings of Hillier *et al.*,[32] gestational diabetes mellitus was no longer significant following multivariate adjustment.

An alternative explanation for these findings is that during pregnancy, mothers may be more likely to 'indulge' with foods that are both high in fat and sugar. During the postnatal period, mothers may try to 'improve' their diet or revert to their pre-pregnancy diet by reducing their sugar intake, but continue to consume high-fat foods. This scenario supports the fetal origin hypothesis of overnutrition in the intrauterine environment, predisposing the offspring to later overweight and obesity.

A particular strength of the Lifeways study is that it is one of a few longitudinal studies to have maternal dietary information early in pregnancy and at a postnatal stage measured at the same time as the child's BMI. Furthermore, it allows for control of a large number of potentially confounding factors, which are important predictors of childhood obesity including pre-pregnancy BMI, maternal smoking, and other socioeconomic and lifestyle variables not considered elsewhere. The cohort represents women from both rural and urban regions with a spread of socioeconomic backgrounds, which provides for more representative data.

As with all longitudinal studies, the impact of attrition can have marked effects. There was evidence of a socioeconomic bias in relation to non-response, but there was no evidence of selection bias in terms of pre-pregnancy BMI of the mothers, which is

important as BMI is one of the key variables of interest. However, BMI as a measure of adiposity is limited as it is measuring both lean and fat mass. Mothers remaining in the study were more likely to be of higher socioeconomic status, and these women possibly had more awareness of healthy dietary practices with some social desirability bias in reporting of dietary intake.[44] However, in a previous analysis, similar percentages of under-reporting were found in responders and non-responders (31.6% and 29.8%, respectively),[16] which were lower than those reported in other studies of diet in pregnant mothers.[45] Over-reporting was, however, significantly different between responders and non-responders with a marked sociodemographic gradient, possibly explained by difficulty with literacy or comprehension of the instructions for the FFQ.[46]

In conclusion, we found that maternal intakes of total macronutrients did not demonstrate any significant effect on offspring adiposity, but strong effects were observed for the macronutrient components SFA and sugar. This would suggest that studies of diet and body composition should investigate both total macronutrient intake and their components to provide a more comprehensive understanding of the associations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1 King JC. Physiology of pregnancy and nutrient metabolism. *Am J Clin Nutr* 2000; **71**: 1218S–1225S.
2 Jackson AA, Robinson SM. Dietary guidelines for pregnancy: a review of current evidence. *Public Health Nutr* 2001; **4**: 625–630.
3 McMillen IC, Robinson JS. Developmental origins of the metabolic syndrome: prediction, plasticity, and programming. *Physiol Rev* 2005; **85**: 571–633.
4 Poston L. Gestational weight gain: influences on the long-term health of the child. *Curr Opin Clin Nutr Metab Care* 2012; **15**: 252–257.
5 Brion M-JA, Ness AR, Rogers I, Emmett P, Cribb V, Davey Smith G *et al.* Maternal macronutrient and energy intakes in pregnancy and offspring intake at 10 y: exploring parental comparisons and prenatal effects. *Am J Clin Nutr* 2010; **91**: 748–756.
6 Ainge H, Thompson C, Ozanne SE, Rooney KB. A systematic review on animal models of maternal high fat feeding and offspring glycaemic control. *Int J Obes (Lond)* 2011; **35**: 325–335.
7 Donahue SM, Rifas-Shiman SL, Gold DR, Jouni ZE, Gillman MW, Oken E. Prenatal fatty acid status and child adiposity at age 3 y: results from a US pregnancy cohort. *Am J Clin Nutr* 2011; **93**: 780–788.
8 Deierlein AL, Siega-Riz AM, Chantala K, Herring AH. The association between maternal glucose concentration and child BMI at age 3 years. *Diabetes Care* 2011; **34**: 480–484.
9 O'Mahony D, Fallon UB, Hannon F, Kloeckner K, Avalos G, Murphy AW *et al.* The Lifeways Cross-Generation Study: design, recruitment and data management considerations. *Ir Med J* 2007; **100**(Suppl 8): 3–6.
10 Riboli E, Elmstahl S, Saracci R, Gullberg B, Lindgarde F. The Malmo Food Study: validity of two dietary assessment methods for measuring nutrient intake. *Int J Epidemiol* 1997; **26**: S161.
11 Bingham SA, Gill C, Welch A, Cassidy A, Runswick SA, Oakes S *et al.* Validation of dietary assessment methods in the UK arm of EPIC using weighed records, and 24-hour urinary nitrogen and potassium and serum vitamin C and carotenoids as biomarkers. *Int J Epidemiol* 1997; **26**(Suppl 1): S137–S151.
12 Harrington J. *Validation of a Food Frequency Questionnaire as a tool for assessing nutrient intake (MA Thesis)*. National University of Ireland Galway: Galway, 1997.
13 Morgan K, McGee H, Watson D, Perry I, Barry M, Shelley E *et al. SLÁN 2007: Survey of Lifestyle, Attitudes & Nutrition in Ireland. Main Report*. Department of Health and Children: Dublin, 2008.
14 Kelleher CC, Nic Gabhainn S, Friel S, Corrigan H, Nolan G, Sixsmith J *et al. The National Health and Lifestyle Surveys: Survey of lifestyle, Attitudes and Nutrition (SLAN) and the Irish Health Behaviours in School-aged Children Survey (HBSC)*. National University of Ireland: Galway, 2003.
15 Friel S, Nic Gabhainn S, Kelleher CC. *The National Health and Lifestyle Surveys: Survey of lifestyle, attitudes and nutrition (SLAN) and the Irish health behaviour in school-aged children survey (HBSC)*. National University of Ireland: Galway, 1999.
16 Murrin CM. *Maternal factors during pregnancy contributing to early life risk of childhood obesity (PhD Thesis)*. University College Dublin: Dublin, 2011.
17 Food Standards Agency. *Mc Cance and Widdowson's The Composition of Foods*. Royal Society of Chemistry: Cambridge, 2002.
18 Schofield WN. Predicting basal metabolic rate, new standards and review of previous work. *Hum Nutr Clin Nutr* 1985; **39**(Suppl 1): 5–41.
19 Prentice AM, Spaaij CJ, Goldberg GR, Poppitt SD, Van Raaij JM, Totton M *et al.* Energy requirements of pregnant and lactating women. *Eur J Clin Nutr* 1996; **50**: S82–S110, discussion S110–111.
20 Black AE. Critical evaluation of energy intake using the Goldberg cut-off for energy intake:basal metabolic rate. A practical guide to its calculation, use and limitations. *Int J Obes Relat Metab Disord* 2000; **24**: 1119–1130.
21 Black AE, Goldberg GR, Jebb SA, Livingstone MB, Cole TJ, Prentice AM. Critical evaluation of energy intake data using fundamental principles of energy physiology: 2. Evaluating the results of published surveys. *Eur J Clin Nutr* 1991; **45**: 583–599.
22 Goldberg GR, Black AE, Jebb SA, Cole TJ, Murgatroyd PR, Coward WA *et al.* Critical evaluation of energy intake data using fundamental principles of energy physiology: 1. Derivation of cut-off limits to identify under-recording. *Eur J Clin Nutr* 1991; **45**: 569–581.
23 Cogill B. *Anthropometric Indicators Measurement Guide*. Food and Nutrition Technical Assistance Project: Washington, D.C., 2003.
24 World Health Organisation. STEPwise approach to chronic disease risk factor surveillance (STEPS). *WHO Non-communicable Diseases and Mental Health; Training and Practical Guide. Section 3. Guide to Physical Measurements (Step 2)* 2006: 1–14.
25 Cole T, Bellizzi M, Flegal K, Dietz W. Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ* 2000; **320**: 1240–1243.
26 Shrivastava A, Murrin C, Sweeney MR, Heavey P, Kelleher CC. Familial intergenerational and maternal aggregation patterns in nutrient intakes in the Lifeways Cross-Generation Cohort Study. *Public Health Nutr* 2012; **13**: 1–11.
27 Khan IY, Dekou V, Douglas G, Jensen R, Hanson MA, Poston L *et al.* A high-fat diet during rat pregnancy or suckling induces cardiovascular dysfunction in adult offspring. *Am J Physiol Regul Integr Comp Physiol* 2005; **288**: R127–R133.
28 Tamashiro KLK, Terrillion CE, Hyun J, Koenig JI, Moran TH. Prenatal stress or high fat diet increases susceptibility to diet-induced obesity in rat offspring. *Diabetes* 2009; **58**: 1116–1125.
29 Howie GJ, Sloboda DM, Kamal T, Vickers MH. Maternal nutritional history predicts obesity in adult offspring independent of postnatal diet. *J Physiol* 2009; **587**: 905–915.
30 Das UN. Perinatal nutrition and obesity. *Br J Nutr* 2008; **99**: 1391–1392.
31 Dabelea D, Hanson RL, Lindsay RS, Pettit DJ, Imperatore G, Gabir MM *et al.* Intrauterine exposure to diabetes conveys risks for type 2 diabetes and obesity: a study of discordant sibships. *Diabetes* 2000; **49**: 2208–2211.
32 Hillier TA, Pedula KL, Schmidt MM, Mullen JA, Charles MA, Pettitt DJ. Childhood obesity and metabolic imprinting: the ongoing effects of maternal hyperglycemia. *Diabetes Care* 2007; **30**: 2287–2292.
33 HAPO. Hyperglycemia and Adverse Pregnancy Outcome (HAPO) Study: associations with neonatal anthropometrics. *Diabetes* 2009; **58**: 453–459.
34 Pirkola J, Pouta A, Bloigu A, Hartikainen AL, Laitinen J, Jarvelin MR *et al.* Risks of Overweight and abdominal obesity at age 16 years associated with prenatal exposures to maternal prepregnancy overweight and gestational diabetes mellitus. *Diabetes Care* 2010; **33**: 1115–1121.
35 Lawlor D, Fraser A, Lindsay R, Ness A, Dabelea D, Catalano P *et al.* Association of existing diabetes, gestational diabetes and glycosuria in pregnancy with macrosomia and offspring body mass index, waist and fat mass in later childhood: findings from a prospective pregnancy cohort. *Diabetologia* 2010; **53**: 89–97.
36 Sermer M, Naylor CD, Gare DJ, Kenshole AB, Ritchie JW, Farine D *et al.* Impact of increasing carbohydrate intolerance on maternal-fetal outcomes in 3637 women without gestational diabetes. The Toronto Tri-Hospital Gestational Diabetes Project. *Am J Obstet Gynecol* 1995; **173**: 146–156.
37 Scholl TO, Sowers M, Chen X, Lenders C. Maternal glucose concentration influences fetal growth, gestation, and pregnancy complications. *Am. J. Epidemiol* 2001; **154**: 514–520.
38 Mello G, Parretti E, Cioni R, Lucchetti R, Carignani L, Martini E *et al.* The 75-gram glucose load in pregnancy. *Diabetes Care* 2003; **26**: 1206–1210.
39 Langley-Evans S. Pregnancy. In: Langley-Evans S (ed). *Nutrition: A Lifespan Approach*. 1st edn. Wiley-Blackwell: Oxford, pp 66–67, 2009.

40 Fraser RB, Ford FA, Lawrence GF. Insulin sensitivity in third trimester pregnancy. A randomized study of dietary effects. *Br J Obstet Gynaecol* 1988; **95**: 223–229.
41 Deierlein AL, Siega-Riz AM, Herring A. Dietary energy density but not glycemic load is associated with gestational weight gain. *Am J Clin Nutr* 2008; **88**: 693–699.
42 Bayol SA, Farrington SJ, Stickland NC. A maternal 'junk food' diet in pregnancy and lactation promotes an exacerbated taste for 'junk food' and a greater propensity for obesity in rat offspring. *Br J Nutr* 2007; **98**: 843–851.
43 McGowan CA, McAuliffe FM. The influence of maternal glycaemia and dietary glycaemic index on pregnancy outcome in healthy mothers. *Br J Nutr* 2010; **104**: 153–159.
44 Lutomski JE, van den Broeck J, Harrington J, Shiely F, Perry IJ. Sociodemographic, lifestyle, mental health and dietary factors associated with direction of misreporting of energy intake. *Public Health Nutr* 2011; **14**: 532–541.
45 Rogers I, Emmett P. Diet during pregnancy in a population of pregnant women in South West England. ALSPAC Study Team. Avon Longitudinal Study of Pregnancy and Childhood. *Eur J Clin Nutr* 1998; **52**: 246–250.
46 Nelson M. The validation of dietary questionnaire. In: Margretts BM, Nelson M (eds). *Design Concepts in Nutritional Epidemiology*. Oxford University Press: New York, pp 266–297, 1997.