ARTICLE

PEDIATRICS

Added sugars mediate the relation between pre-pregnancy BMI and infant rapid weight gain: a preliminary study

Brenda Burgess[1], Katherine S. Morris[1], Myles S. Faith[2], Rocco A. Paluch[1] and Kai Ling Kong[3,4,5]✉

BACKGROUND: Parental obesity is linked to offspring obesity, though little research has explored factors that might influence this relationship during the complementary feeding period. This study investigated whether infant intakes of added sugars mediate the relationship between a mother's pre-pregnancy body mass index (BMI) and infant rapid weight gain (defined as upward weight-for-age percentile crossing).

METHODS: This study was of a cross-sectional design. Anthropometrics for 141 mother-infant dyads (mean age [standard deviation]: 32.6 [4.4] year for mothers, 11.9 [1.9] months for infants) were obtained. Data from three 24-h recalls pertaining to the infants' diets were collected and analyzed. Pearson product-moment correlations and multivariable regressions assessed bivariate relationships between pre-pregnancy BMI, infant added sugar intakes and upward weight-for-age percentile crossing. Mediation models evaluated the effects of added sugars and breastfeeding duration.

RESULTS: Pre-pregnancy BMI correlated positively with infants' added sugar intakes ($r = 0.230$, $p = 0.006$). Added sugar intakes mediated the impact of pre-pregnancy BMI on upward weight-for-age percentile crossing (indirect effect = 0.007, 95% CI = 0.0001, 0.0197, indirect/total effect ratio = 0.280). Breastfeeding duration also moderated the relationship, with infants who were breastfed for a shorter duration experiencing a greater mediating effect (indirect effect = 0.010, 95% CI = 0.0014, 0.0277, indirect/direct effect ratio = 0.7368).

CONCLUSIONS: Mothers who were overweight or obese prior to pregnancy were significantly more likely to give their infants foods and beverages with added sugars, and this practice was found to mediate the relationship between maternal and infant obesity. Breastfeeding duration moderated the mediating effect of added sugars between pre-pregnancy BMI and infant rapid weight gain.

International Journal of Obesity (2021) 45:2570–2576; https://doi.org/10.1038/s41366-021-00936-w

INTRODUCTION

Current estimates from the Centers for Disease Control indicate that nearly a tenth of Americans under the age of 2 are experiencing rapid weight gain [1], defined as an upward centile crossing in weight growth charts [2]. Studies show that rapid weight gain during infancy elevates the risk of chronic conditions like obesity, type 2 diabetes, and cardiovascular disease [3]; therefore, understanding factors that are implicated in its development is imperative for creating effective treatment strategies. To this point, it is well known that parental obesity is highly predictive of offspring obesity. Accumulating evidence has found this relationship to be attributed both to genetics and environmental factors [4, 5]. The latter, being modifiable, however, is of particular interest to prevention researchers and includes poor maternal eating behaviors and feeding practices as among the most consistent determinants of unhealthy weight gain in infants [5].

Investigations delving deeper into environmental influences have noted that mothers who were overweight or obese prior to pregnancy tended to cease breastfeeding sooner [6–8], introduce complementary foods earlier [7, 8], and feed their infants more sweets [9, 10] relative to lean mothers. In view of such findings, it's conceivable that this shared weight status is partially rooted in infants' low dietary quality. Consumption of added sugars (i.e., sugars or sweeteners added to a food or beverage during the manufacturing process, including but not limited to: sucrose, dextrose, honey, syrup, and fruit and vegetable concentrates [11]) during early childhood is an appreciable concern as of late [12, 13]. The 2020 Dietary Guidelines for Americans advise against any intake of added sugars up through 24 months because they are linked to obesity in children and adults [14–16], and a recent study by our group discovered that they also associate with rapid weight gain in infancy [17].

[1]Division of Behavioral Medicine, Department of Pediatrics, Jacobs School of Medicine and Biomedical Sciences, University at Buffalo, Buffalo, NY, USA. [2]Department of Counseling, School, and Educational Psychology, Graduate School of Education, State University of New York at Buffalo, Buffalo, NY, USA. [3]Baby Health Behavior Lab, Division of Health Services and Outcomes Research, Children's Mercy Research Institute, Children's Mercy Hospital, Kansas City, MO, USA. [4]Department of Pediatrics, University of Missouri-Kansas City, Kansas City, MO, USA. [5]Department of Pediatrics, University of Kansas Medical Center, Kansas City, KS, USA. ✉email: kkong@cmh.edu

Received: 9 July 2020 Revised: 21 July 2021 Accepted: 4 August 2021
Published online: 18 August 2021

For the present study, we examined whether added sugar intakes might mediate the link between maternal pre-pregnancy body mass index (BMI) and infant rapid weight gain. As an ancillary aim, we examined the moderating effect of breastfeeding on this mediational pathway. Breastfeeding is known to correlate with healthier BMIs and reduced obesity rates across the lifespan [18–24]; however, some research suggests it may be uniquely beneficial for persons of high risk. For example, one prospective study conducted by Carling et al. [25] discovered that infants born to mothers with high body weights and little education received greater protection from overweight and obesity than lower-risk counterparts when they were breastfed for a long duration. From this, the objectives of our study were to assess: (1) the relationship between pre-pregnancy BMI and infant added sugar intakes during the complementary feeding period, (2) whether added sugar intakes mediate the relationship between pre-pregnancy BMI and infant rapid weight gain, and (3) the role of breastfeeding duration on this potential mediation model.

SUBJECTS AND METHODS

Participants

Our participants were a convenience sample of individuals aged 9–15 months ($n = 141$) at baseline who were recruited for involvement in an ongoing longitudinal study from 2017 to 2019. To ensure our sample was fairly representative of a healthy demographic, exclusion criteria consisted of being born: (1) prematurely (<37 weeks), (2) with a low birth weight (<2500 g), (3) needing a special diet, (4) with congenital defects, developmental delays or disabilities, (5) to a mother <18 years who smoked, consumed excess alcohol, used controlled substances during pregnancy or had gestational diabetes, or (6) not as a singleton. Of note, data from three individuals with estimated daily energy intakes ±2 standard deviations (SD) from their requirements, per the equation by the Institute of Medicine's Food and Nutrition Board [26], were not included in statistical analyses.

Preliminary screening

Eligibility assessments first occurred with mothers over the phone, and then those whose infants fulfilled inclusion criteria were emailed study questionnaires to complete and invited to attend a 1-h appointment at the Division of Behavioral Medicine. Subsequent to arrival, the heights and weights of the dyads were measured by laboratory staff, and then mothers received a packet detailing how to capture their infant's dietary intakes. The Institutional Review Board at the University at Buffalo approved the study's protocol; all mothers provided written, informed consent.

Questionnaires on infant feeding practices and pregnancy history

The Infant Feeding Practices Study II [27] questionnaire was distributed to mothers to collect data pertaining to the introduction of solid foods, as well as breastfeeding initiation, duration, and cessation. This questionnaire has previously been utilized and validated to confirm the relationship between maternal education and infant feeding practices [27]. Another questionnaire sent through SurveyMonkey inquired about the mother's pre-pregnancy BMI, gestational weight gain, and birthing experience.

Anthropometric measurements

Weights and lengths (in the supine position) were measured independently by two research staff using a Seca 374 Digital Baby Scale and Seca 416 Infantometer, respectively, per the World Health Organization (WHO) Multicentre Growth Reference Study's protocols [28]. If the difference in recorded values by the two staff members was greater than 7.0 mm, measurements were obtained again and averaged [28]. Z-scores for weight-for-length (zWFL), weight-for-age, and length-for-age were calculated using the WHO's infant growth chart (0 to 5 years) [29]. Birth weights for all infants were reported by their mothers.

In this study, rapid weight gain was classified specifically as upward weight-for-age percentile (WFA percentile) crossing according to methods established by Ekelund et al. [30]. This variable was calculated by determining how many major percentile thresholds (5th, 10th, 25th, 50th, 75th, 90th, and 95th) were crossed from birth to the time of assessment per the WHO growth chart of sex-specific WFA. The variable of upward WFA percentile crossing is a more sensitive measure that quantifies the degree of rapid weight gain, and thus it can generate more meaningful results compared to using a dichotomous variable of rapid weight gain (change in weight SD score > 0.67). Participants who crossed a lower threshold or remained within the same band of major percentiles were classified as having no upward crossings [30].

Infant dietary collection

The procedure for obtaining 24-h dietary recalls followed a modified version of that employed in the Feeding Infants and Toddlers Study [31]. Briefly, mothers were instructed for two weekdays and one weekend day (all within 10 days of their initial laboratory visit) to record the foods and beverages consumed by their infant, and if still breastfeeding, the duration at the breast. Next, research staff, extensively trained by a registered dietitian (RD), telephoned the mothers 24 h after each prescribed day to see whether the infant displayed a normal day of eating. If not, a new day to complete the recall would be scheduled, but if so, the staff would proceed to ask detailed questions using the United States Department of Agriculture's Automated Multiple-Pass Method [32]. Here, mothers were prompted to list everything the infant had eaten the day before, and then the research member would inquire about any major discrepancies and read the list aloud. If mothers wanted to modify or add anything, they could do so at that time. Upon completion of this run-through, the research member would then ask more detailed questions about each item on the list and point the mother to the serving size guide in their handout packet if they had difficulty estimating the amount of a food or beverage. At the conclusion of the phone call, information on supplements and medications was gathered, although this was not included in the final analyses since it was not related to our primary aims.

Nutritional analyses

Nutrition Data System for Research software (v. 2019; Nutrition Coordinating Center, University of Minnesota, Minneapolis, MN) was utilized to analyze the 24-h dietary recalls. This software has a database consisting of over 18,000 items, 7500 being brand-specific and over 1000 that were baby foods. When a certain item was found not to exist in the database during entry of the dietary information, the research staff would choose a generic product with a nutrient profile closely aligned to that of the item of interest. Failing to locate a suitable approximation, they would contact the Nutrition Coordinating Center to have them add the item to their database. From the present investigation, 15 foods were added to the database.

If individuals were still being breastfed, intake of breastmilk was estimated per the method outlined by the Feeding Infants and Toddlers Study [33]. Briefly, for individuals 7–12 months of age, research members would input 600 mL of breastmilk into the calculation for those breastfed exclusively or subtract their formula volume from 600 mL and enter the remaining amount as breastmilk for individuals receiving formula and breastmilk. Among participants >12 months of age, one fluid ounce (29.6 mL), per every 5 min of feeding, was entered into the calculation.

After all of the dietary data were entered, an RD combed through everything thoroughly in order to identify and remove anything amiss. Information that was extracted from the database included calorie, carbohydrate, protein, fat, total, and added sugar intakes. The sources of added sugars consumed by the infants and toddlers were grouped into 16 categories as described by Herrick et al. [34]: yogurt, baby snacks and sweets, quick bread, savory snacks, sweet bakery products, flavored milk and dairy drinks, fruits, fruit drinks, sugar and candy, ready-to-eat cereals, bread/rolls/tortillas, ice cream/pudding/gelatin, mixed dishes, protein foods, baby and cooked cereals, and sweetened beverages.

Statistical analysis

Bivariate relationships between pre-pregnancy BMI, infant added sugar intakes, current zWFL, and upward WFA percentile crossing were evaluated using Pearson product-moment correlations. Multivariable regressions were performed when significant correlations were detected between any of the aforementioned variables after controlling for covariates (sex, age, timing of solid food introduction, maternal education, household income, and parity).

Pre-pregnancy BMI was found to relate to both upward WFA percentile crossing and added sugar intakes across all participants, so these were tested using a mediation analysis (i.e., pre-pregnancy BMI was employed as the predictor variable (x), upward WFA percentile crossing was the dependent variable (y), added sugar intakes was the mediator (m)) [35, 36]. To test aim 2, models used 10,000 bootstrapped simulations to estimate: (1) indirect effects of pre-pregnancy BMI on upward WFA percentile crossing mediated by added sugar intakes, (2) direct effects of pre-pregnancy BMI on added sugar intakes (path a), (3) direct effects of added sugar intakes on upward WFA percentile crossing (path b), and (4) direct and total effects of pre-pregnancy BMI on upward WFA percentile crossing (paths c and c'). Mediation was established if the confidence interval for the indirect effect did not contain zero. The proportion of the total effect explained by the indirect effect was quantified upon dividing the indirect effect by the total effect [37].

In our previous analysis [17], breastfeeding for ≥12 months buffered rapid weight gain in infants consuming added sugars. For the current investigation, we tested aim 3 using a conditional mediation analysis to explore breastfeeding duration as a moderator (v) of the indirect effect of pre-pregnancy BMI (x) on infant rapid weight gain (y) through added sugars (m). This conditional mediation analysis not only tests to see if a conditional effect is present, but also estimates the indirect effect at low, medium, and high values. In other words, the Process Macro illustrates the nature of moderating effects automatically by providing the indirect effects at multiple levels of the moderator (i.e., −1 SD, mean/zero SD, and +1 SD) [36]. They are snapshots of the indirect effects at various levels and are selected based on the distribution of the data included in the analyses.

Lastly, a sensitivity analysis was conducted by replicating mediation models controlling for sex, age, timing of solid food introduction, maternal education, household income, parity, and healthy gestational weight gain (calculated according to recommendations by the Institute of Medicine [38]). All data were analyzed using SYSTAT 11 (Systat Software, 2004) and SAS 9.4 (SAS Institute Inc., Cary NC). Mediational and conditional mediation analyses were completed using Hayes Process Macro [36].

RESULTS

Characteristics of the mother-infant dyads are presented in Table 1. Overall, the sample consisted of highly educated families (≥ college graduates = 87.1%) with Caucasian ethnicity (78.0%). The mean (standard deviation) age and pre-pregnancy BMI for the mothers were 32.6 (4.4) y and 28.3 (7.2) kg/m^2, respectively. The top 5 sources of added sugars consumed by infants were baby snacks and sweets (5.69%), sweet bakery products (5.44%), yogurt (4.08%), mixed dishes (3.16%), and ready-to-eat cereals (2.83%). The top 5 sources of added sugars consumed by toddlers were sweet bakery products (20.6%), yogurt (16.8%), mixed dishes (11%), cooked and baby cereals (7.47%), sugar and candy (6.06%). Of note, the percentages in parentheses represent the amount of added sugars present in a specific category divided by the total amount of added sugars consumed by children in our cohort.

Pertaining to aim 1, Pearson's analysis showed that pre-pregnancy BMI was positively correlated with infants' added sugar intakes ($r = 0.230$, $p = 0.006$), and this association remained significant after controlling for sex, age, timing of solid food introduction, maternal education, household income, and parity ($\beta = 0.352$, 95% CI = 0.054, 0.649, $p = 0.021$). We also found that consumption of added sugars was positively correlated with upward WFA percentile crossing ($r = 0.280$, $p < 0.001$), and this association remained significant after controlling for the same covariates ($\beta = 0.020$, 95% CI = 0.008, 0.032, $p = 0.001$). Cross-sectionally, infant zWFL was not correlated to added sugar intakes or pre-pregnancy BMI.

Pertaining to aim 2, the mediation analysis revealed that the influence of pre-pregnancy BMI on infant upward WFA percentile crossing was mediated by added sugar intakes (indirect effect = 0.007, 95% CI = 0.0001, 0.0197, indirect/total effect ratio = 0.280, see Table 2, and Fig. 1).

Pertaining to aim 3, the exploratory analysis further demonstrated that breastfeeding duration was found to moderate this relationship. Hayes Process Macro classified our data as low breastfeeding duration (−1SD) ≤ 3.4 months; average breastfeeding duration = 8.0 months; and high breastfeeding duration (+1 SD) ≥ 12.0 months. The mediating effect of added sugars was significant for infants breastfed ≤ 3.4 months (indirect effect = 0.010, 95% CI = 0.0014, 0.0277, indirect/direct effect ratio = 0.7368), but the effect gradually dissipated for those who experienced a longer breastfeeding duration (see Table 3, and Fig. 2). This implied that the mediating effect of added sugars on the relationship between pre-pregnancy BMI and rapid weight gain was moderated by breastfeeding

Table 1. Participant characteristics ($n = 141$).

	Mean (SD)	*N* (%)	Range
Child			
Sex, male		63 (44.7)	
Age, months	11.9 (1.9)		9.1–15.8
Race, Caucasian		110 (78.0)	
Refuse to answer		4 (2.8)	
Gestational age, weeks	39.4 (1.3)		37–43
Birth weight, kg	3.5 (0.5)		2.5–5.2
Weight-for-length z-score[a]	0.6 (0.9)		−1.3–3.1
Weight-for-age z-score[a]	0.2 (0.9)		−2.4–2.9
Length-for-age z-score[a]	−0.4 (1.1)		−3.1–2.9
Upward weight-for-age (WFA) percentile crossing[b]	0.5 (0.8)		0–4.0
Breastfeeding duration	7.7 (4.6)		0–15.8
<6 months		45 (31.9)	
≥6 months		96 (68.1)	
First introduction to solid foods	5.3 (1.0)		2.0–9.0
<4 months		5 (3.5)	
4–5 months		62 (44.0)	
≥ 6 months		74 (52.5)	
Mother			
Age, years	32.6 (4.4)		23.6–46.3
Education level			
Some college or below		36 (25.5)	
College graduate or higher		103 (87.1)	
Refuse to answer		2 (1.4)	
Parity			
Nulliparous		79 (56.0)	
Parous ≥1		62 (44.0)	
Pre-pregnancy BMI, kg/m²	28.3 (7.2)		19.0–52.9
Normal weight		54 (38.3)	
Overweight/obese (≥25 BMI)		86 (61.0)	
Missing		1 (0.7)	
Current BMI, kg/m²	30.0 (7.7)		18.9–51.3
Normal weight		47 (33.3)	
Overweight/obese (≥25 BMI)		94 (66.7)	
Household total income			
<$30,000		13 (9.2)	
$30,000–69,999		35 (24.8)	
$70,000–109,999		53 (37.6)	
≥$110,000		33 (23.4)	
Refuse to answer		7 (5.0)	

SD standard deviation.
[a]Calculated using the WHO growth charts.
[b]Calculated using methods described by Ekelund et al. [30].

Table 2. Summary of mediation models assessing the indirect effect of infant added sugar intakes on the relationship between pre-pregnancy BMI and infant rapid weight gain.

Parental weight (x)	Mediator (m)	Direct effect c′ (SE)	Total effect c (SE)	Path a (SE)	Path b (SE)	Indirect effect (SE)	Bootstrap adjusted 95% CI		Effect ratio
Model 1									
Pre-pregnancy BMI	Added sugars	0.019(0.01)	0.025(0.01)*	0.393(0.14)**	0.017(0.01)**	0.007(0.00)[a]	0.0001	0.0197	0.280
Model 2									
Pre-pregnancy BMI	Added sugars	0.014(0.01)	0.020(0.01)	0.32(0.15)*	0.017(0.01)*	0.006(0.00)[a]	0.0002	0.0180	0.300

Model 1 = no covariates; Model 2 = Model 1 + covariates (infant sex, age, timing of solid food introduction, maternal education, household income, parity, and healthy gestational weight gain—calculated according to the Institute of Medicine's recommendations [40]).
*$p < 0.05$, **$p < 0.01$.
[a]Confidence intervals (CI) not crossing zero indicate the significance of the indirect effect at the 0.95 level.

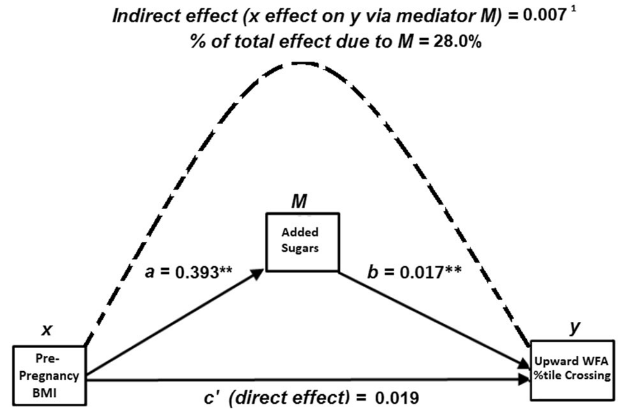

Fig. 1 The relationship between pre-pregnancy BMI and infant rapid weight gain was mediated by infant added sugar intakes. Our analysis showed that the relationship between pre-pregnancy BMI and rapid weight gain (upward WFA percentile crossing) was mediated, in part, by added sugar intakes (indirect effect = 0.007, 95% CI = 0.0001, 0.0197, indirect/total effect ratio = 0.280).

duration with a larger mediation effect when the duration was shorter.

Sensitivity analyses revealed similar findings when covariates (sex, age, timing of solid food introduction, maternal education, household income, parity, and healthy gestational weight gain) were added to the mediation and conditional mediation models (Tables 2 and 3).

DISCUSSION

Results from this study demonstrated that pre-pregnancy BMI positively predicts intakes of added sugars among 9–15-month-olds, and this dietary practice mediates the relationship between a high pre-pregnancy BMI and infant rapid weight gain. We further demonstrated that breastfeeding duration moderates this relationship, with infants who were breastfed for a shorter duration experiencing a greater mediating effect.

According to a contemporary survey of more than 4000 infants and toddlers, ~85% consume added sugars on a daily basis. Estimates indicate these constitute 1.5–7.6% of their average energy intakes, and trends show these figures increase both in amount and prevalence over time [34]. Mothers play a pivotal, if not primary, role in the selection of food items given to infants. Unveilings by our data showed that mothers with overweight or obesity prior to conception were prone to give their infants foods and beverages with added sugars. Future research inquiring about the reasons behind the decision to offer sweetened foods and beverages at such a young age will provide additional insight into factors influencing their feeding practices and thus, the accelerated weight gain of infants and toddlers.

In our investigation, intake of added sugars mediated almost one-third (~28%) of the connection between pre-pregnancy BMI and infant rapid weight gain. We believe this preliminary analysis is the first to demonstrate the unique mediating effect of a nutritional factor on infant rapid weight gain. To date, birth anthropometrics have been found to account for a modest portion of the impact of maternal obesity on offspring body weight. Liu et al. [39] calculated that infant birth zWFL explained 30% of the relationship at one year of age, while Adane et al. [40] and Stevens et al. [41] discovered that individual parameters like weight, height, and head circumference were responsible for 2–15% of the mediation. In addition, gut microbiota (specifically a preponderance of Firmicutes) were found to contribute to this association up through toddlerhood [42]. Future research is necessary to ascertain how the quality and quantity of the various

Table 3. Breastfeeding duration moderated the indirect effect of infant added sugar intakes on the relationship between pre-pregnancy BMI and infant rapid weight gain.

Parental weight (*x*)	Mediator (*m*)	Level of moderator	Indirect effect (SE)	Bootstrap adjusted 95% CI	
Model 1					
Pre-pregnancy BMI	Added sugars	Low breastfeeding duration	0.010(0.01)[a]	0.0014	0.0277
Pre-pregnancy BMI	Added sugars	Average breastfeeding duration	0.001(0.00)	−0.0035	0.0101
Pre-pregnancy BMI	Added sugars	High breastfeeding duration	−0.006(0.01)	−0.0218	0.0005
Model 2					
Pre-pregnancy BMI	Added sugars	Low breastfeeding duration	0.009(0.01)[a]	0.002	0.0259
Pre-pregnancy BMI	Added sugars	Average breastfeeding duration	0.001(0.00)	−0.0038	0.0093
Pre-pregnancy BMI	Added sugars	High breastfeeding duration	−0.006(0.01)	−0.0229	0.0012

[a]Confidence Intervals (CI) not crossing zero indicate the significance of the indirect effect at the 0.95 level.
Low breastfeeding duration (−1SD) = 3.4 months, Average breastfeeding duration = 8.0 months, High breastfeeding duration (+1 SD) = 12.0 months. Model 1 = moderated mediation; Model 2 = Model 1 + covariates (infant sex, age, timing of solid food introduction, maternal education, household income, parity, and healthy gestational weight gain—calculated according to the Institute of Medicine's recommendations [40]).

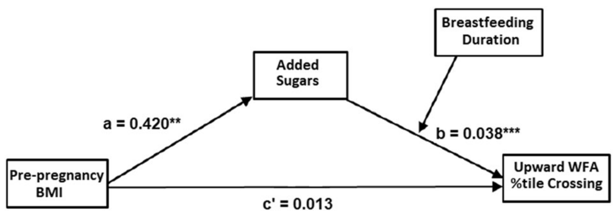

Fig. 2 Breastfeeding duration moderated the mediating effect of added sugar intakes on infant rapid weight gain linked to pre-pregnancy BMI. Our analysis showed that the mediating effect of added sugars on the relationship between pre-pregnancy BMI and rapid weight gain (upward WFA percentile crossing) was moderated by breastfeeding duration, with infants who were breastfed for a shorter duration experiencing a greater mediating effect (indirect effect = 0.010, 95% CI = 0.0014, 0.0277, indirect/direct effect ratio = 0.7368).

micro- and macronutrients introduced during the complementary feeding period modulate childhood obesity risk.

We observed earlier that breastfeeding ≥12 months was protective against rapid weight gain among those consuming added sugars [17]. Analyses in the current study showed that a mother's pre-pregnancy BMI was strongly linked to infant rapid weight gain, and this relationship was partially mediated by intakes of added sugars for infants experiencing a short breastfeeding duration. This finding is compatible with data obtained by Carling et al. [25] showing that high-risk infants (i.e., those born to mothers with a high pre-pregnancy BMI and lower education level who smoked during the gestational period) breastfed >4 months received the greatest protection against a higher weight gain trajectory when compared to low-risk infants. Results from this collective line of research suggest that the ability to breastfeed to lower obesity risk is context-dependent or relies upon a combination of factors. Going forward, women with a high pre-pregnancy BMI should be encouraged to breastfeed for a minimum of 12 months but if that is not an option, at least strive to avoid introducing added sugars to their infants during the first 2 years.

Given emerging evidence that the early home environment is a particularly robust predictor of weight outcomes later in life, we wanted to advance understanding of the origins of maladaptive feeding and eating behaviors. A strong genetic influence on a child's obesity risk has been previously detected [43–45], and so there has been growing interest in the genetic-environmental architecture of obesity—especially at a time when eating behaviors are still malleable. This study set out to characterize highly predictive biobehavioral variables (i.e., biological plus environmental factors such as maternal pre-pregnancy BMI and infants' intake of added sugars) that emerge during early childhood that underlie individual susceptibility to obesity, which could help inform more targeted prevention strategies. As noted by Frick et al. [46], "promising" interventions are those that focus directly on mechanisms implicated in the development of health disorders.

This study had several strengths. One major strength was that we captured infants' dietary intakes during the transitional period to solid foods via three 24-h dietary recalls, which are superior to food frequency questionnaires and other assessment tools [47]. Moreover, registered dietitians created supplementary materials and trained research staff to instruct mothers on how to accurately detail their infant's food and beverage intakes. In addition, we quantified the amount of energy that added sugars contribute to infants' overall intakes, thereby going beyond the customary nutrients of interest examined in similar studies in an attempt to better determine what drives rapid weight gain. Finally, the research-grade software utilized for the nutritional analyses is supremely comprehensive, being comprised of a database with more than 18,000 items (1000 which are baby foods) that is continuously updated.

Our study was also not without limitations. One shortcoming was that infants' dietary intakes were collected retrospectively and examined subjectively (i.e., per the mothers' observations) since it was not feasible to observe this within a laboratory setting given the number of participants and measurements needed. Thus, it is possible their intakes may have been overestimated [48]. Pre-pregnancy BMI was also reported by the mothers and though this value has been perceived to be imprecise [49], contemporary research indicates mothers' recalls are quite accurate in this instance [50, 51]. Upon examining the distribution of z-scores for infants' reported birthweights and birth lengths, the latter was skewed to the right as nearly half had a birth length ≥95 percentile. To overcome this apparent overestimation, we chose to classify rapid weight gain according to Ekelund et al. [30], rather than Taveras et al. [52]. In this sample, the size was small and the majority of families in our study were Caucasian, of high socioeconomic status, breastfed beyond 6 months, and did introduce solids prior to 4 months of age. Therefore, results from larger cohorts with broader demographics may differ. Lastly, we did not collect data on exclusive breastfeeding, which may deepen knowledge of our present findings. It is estimated that ~25% of babies are breastfed exclusively up through 6 months of age [53] and considering that most participants in our cohort came from high socioeconomic backgrounds, this percentage is likely to be higher and warrants further research.

In conclusion, mothers who were overweight or obese prior to pregnancy were likely to give their infants foods and beverages with added sugars, and this practice was found to be a mediator of the relationship between maternal and infant weight status, while breastfeeding duration moderated this mediational effect. These findings shed light, for the first time, on exactly how intergenerational obesity can be explained by unhealthful feeding practices and underscore the efficacy of breastfeeding duration for high-risk individuals. Interventions educating expecting mothers with excess weight on the contribution of added sugars toward infant rapid weight gain and the protective effects of breastfeeding may enhance treatments aimed at curbing childhood obesity.

REFERENCES

1. Fryar CD, Carroll MD, Afful J. Prevalence of high weight-for-recumbent length among infants and toddlers from birth to 24 months of age: United States, 1971–1974 through 2017–2018. NCHS Health E-Stats. 2020.
2. Zheng M, Lamb KE, Grimes C, Laws R, Bolton K, Ong KK, et al. Rapid weight gain during infancy and subsequent adiposity: a systematic review and meta-analysis of evidence. Obes Rev. 2018;19:321–32.
3. Leunissen RWJ, Kerkhof GF, Stijnen T, Hokken-Koelega A. Timing and tempo of first-year rapid growth in relation to cardiovascular and metabolic risk profile in early adulthood. JAMA. 2009;301:2234–42.
4. Kramer MS, Barr RG, Leduc DG, Boisjoly C, McVey-White L, Pless IB. Determinants of weight and adiposity in the first year of life. J Pediatr. 1985;106:10–4.
5. Kral TVE, Rauh EM. Eating behaviors of children in the context of their family environment. Physiol Behav. 2010;100:567–73.
6. Li R, Jewell S, Grummer-Strawn L. Maternal obesity and breast-feeding practices. Am J Clin Nutr. 2003;77:931–6.
7. Mäkelä J, Vaarno J, Kaljonen A, Niinikoski H, Lagström H. Maternal overweight impacts infant feeding patterns-the STEPS Study. Eur J Clin Nutr. 2014;68:43–9.
8. Baker JL, Michaelsen KF, Rasmussen KM, Sørensen TI. Maternal prepregnant body mass index, duration of breastfeeding, and timing of complementary food introduction are associated with infant weight gain. Am J Cin Nutr. 2004;80:1579–88.
9. Rising R, Lifshitz F. Relationship between maternal obesity and infant feeding-interactions. Nutr J. 2005;4:17.
10. Brekke HK, van Odijk J, Ludvigsson J. Predictors and dietary consequences of frequent intake of high-sugar, low-nutrient foods in 1-year-old children participating in the ABIS study. Br J Nutr. 2007;97:176–81.
11. United States Food and Drug Administration. Added sugars on the new nutrition facts label: U.S. Department of Health and HumanServices. 2020. https://www.fda.gov/food/new-nutrition-facts-label/added-sugars-new-nutrition-facts-label.
12. Lumeng JC, Taveras EM, Birch L, Yanovski SZ. Prevention of obesity in infancy and early childhood: a National Institutes of Health workshop. JAMA Pediatr. 2015;169:484–90.
13. Food and Nutrition Service. Pregnancy and Birth to 24 Months: U.S. Department of Agriculture. 2019. https://www.fns.usda.gov/resource/pregnancy-and-birth-24-months.
14. Te Morenga L, Mallard S, Mann J. Dietary sugars and body weight: systematic review and meta-analyses of randomised controlled trials and cohort studies. Br Med J. 2013;346:e7492.
15. Malik VS, Pan A, Willett WC, Hu FB. Sugar-sweetened beverages and weight gain in children and adults: a systematic review and meta-analysis. Am J Clin Nutr. 2013;98:1084–102.
16. Luger M, Lafontan M, Bes-Rastrollo M, Winzer E, Yumuk V, Farpour-Lambert N. Sugar-sweetened beverages and weight gain in children and adults: a systematic review from 2013 to 2015 and a comparison with previous studies. Obes Facts. 2017;10:674–93.
17. Kong K, Burgess, B, Morris, KS, Faith, MS, Paluch, RA. High intake of added sugars is linked to rapid weight gain in infancy, breastfeeding ≥12 months may protect against this: a preliminary investigation. Pediatr Obes. 2021;16:e12728.
18. Bell KA, Wagner CL, Feldman HA, Shypailo RJ, Belfort MB. Associations of infant feeding with trajectories of body composition and growth. Am J Clin Nutr. 2017;106:491–8.
19. von Kries R, Koletzko B, Sauerwald T, von Mutius E, Barnert D, Grunert V, et al. Breast feeding and obesity: cross sectional study. BMJ. 1999;319:147–50.
20. Li C, Goran MI, Kaur H, Nollen N, Ahluwalia JS. Developmental trajectories of overweight during childhood: role of early life factors. Obesity. 2007;15:760–71.
21. Yan J, Liu L, Zhu Y, Huang G, Wang PP. The association between breastfeeding and childhood obesity: a meta-analysis. BMC Public Health. 2014;14:1267.
22. Harder T, Bergmann R, Kallischnigg G, Plagemann A. Duration of breastfeeding and risk of overweight: a meta-analysis. Am J Epidemiol. 2005;162:397–403.
23. Owen CG, Martin RM, Whincup PH, Smith GD, Cook DG. Effect of infant feeding on the risk of obesity across the life course: a quantitative review of published evidence. Pediatrics. 2005;115:1367–77.
24. Dewey KG. Is breastfeeding protective against child obesity? J Hum Lact. 2003;19:9–18.
25. Carling SJ, Demment MM, Kjolhede CL, Olson CM. Breastfeeding duration and weight gain trajectory in infancy. Pediatrics. 2015;135:111–9.
26. Institute of Medicine. Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids. Washington (DC): National Academy Press. 2005. https://doi.org/10.17226/10490.
27. Fein SB, Labiner-Wolfe J, Shealy KR, Li R, Chen J, Grummer-Strawn LM. Infant feeding practices study II: Study methods. Pediatrics. 2008;122:S28–S35. Suppl 2
28. de Onis M, Onyango AW, Van den Broeck J, Chumlea WC, Martorell R. Measurement and standardization protocols for anthropometry used in the construction of a new international growth reference. Food Nutr Bull. 2004;25:s27–36.
29. WHO Multicentre Growth Reference Study Group. WHO child growth standards based on length/height, weight and age. Acta Paediatr Suppl. 2006;450:76–85.
30. Ekelund U, Ong K, Linne Y, Neovius M, Brage S, Dunger DB, et al. Upward weight percentile crossing in infancy and early childhood independently predicts fat mass in young adults: the Stockholm Weight Development Study (SWEDES). Am J Clin Nutr. 2006;83:324–30.
31. Anater AS, Catellier DJ, Levine BA, Krotki KP, Jacquier EF, Eldridge AL, et al. The feeding infants and toddlers study (FITS) 2016: study design and methods. J Nutr. 2018;148:1516S–24S. suppl_3
32. Raper N, Perloff B, Ingwersen L, Steinfeldt L, Anand J. An overview of USDA's dietary intake data system. J Food Compos Anal. 2004;17:545–55.
33. Ziegler P, Briefel R, Clusen N, Devaney B. Feeding infants and toddlers study (FITS): development of the FITS survey in comparison to other dietary survey methods. J Am Diet Assoc. 2006;106:12. e1–e50.
34. Herrick KA, Fryar CD, Hamner HC, Park S, Ogden CL. Added sugars intake among US infants and toddlers. J Acad Nutr Diet. 2020;120:23–32.
35. Preacher KJ, Hayes AF. SPSS and SAS procedures for estimating indirect effects in simple mediation models. Behav Res Methods Instrum Comput. 2004;36:717–31.
36. Hayes AF. Methodology in The Social Science: Introduction to mediation, moderation, and conditional process analysis: a regression-based approach. New York, NY, US: Guilford Press, 2013.
37. Ezzati M, Vander Hoorn S, Lawes CM, Leach R, James WPT, Lopez AD, et al. Rethinking the "diseases of affluence" paradigm: global patterns of nutritional risks in relation to economic development. PLoS Med. 2005;2:e133.
38. Institute of Medicine (US) and National Research Council (US) Committee to Reexamine IOM Pregnancy Weight Guidelines. The National Academies Collection: reports funded by National Institutes of Health. In: Rasmussen KM, Yaktine AL (eds). Weight Gain During Pregnancy: Reexamining the Guidelines. Washington (DC): National Academy of Sciences. 2009.
39. Liu T, Mueller N, Benjamin-Neelon S. Identifying mediators underlying the intergenerational cycle of obesity: a causal mediation analysis. Curr Dev Nutr. 2020;4:1655.
40. Adane AA, Tooth LR, Mishra GD. The role of offspring's birthweight on the association between pre-pregnancy obesity and offspring's childhood anthropometrics: a mediation analysis. J Dev Orig Health Dis. 2019;10:570–7.
41. Stevens DR, Neelon B, Roberts JR, Taylor SN, Newman RB, Vena JE, et al. Mediation of the association between maternal pre-pregnancy overweight/obesity and childhood overweight/obesity by birth anthropometry. J Dev Orig Health Dis. 2021;12:71–8.
42. Tun HM, Bridgman SL, Chari R, Field CJ, Guttman DS, Becker AB, et al. Roles of birth mode and infant gut microbiota in intergenerational transmission of overweight and obesity from mother to offspring. JAMA Pediatr. 2018;172:368–77.
43. Llewellyn C, Wardle J. Behavioral susceptibility to obesity: gene-environment interplay in the development of weight. Physiol Behav. 2015;152:494–501.
44. Llewellyn CH, Fildes A. Behavioural susceptibility theory: professor jane wardle and the role of appetite in genetic risk of obesity. Curr Obes Rep. 2017;6:38–45.
45. Carnell S, Wardle J. Appetitive traits in children. New evidence for associations with weight and a common, obesity-associated genetic variant. Appetite. 2009;53:260–3.
46. Frick PJ, Ray JV, Thornton LC, Kahn RE. Annual research review: a developmental psychopathology approach to understanding callous-unemotional traits in children and adolescents with serious conduct problems. J Child Psychol Psychiatry. 2014;55:532–48.
47. Ma Y, Olendzki BC, Pagoto SL, Hurley TG, Magner RP, Ockene IS, et al. Number of 24-hour diet recalls needed to estimate energy intake. Ann Epidemiol. 2009;19:553–9.
48. Fisher JO, Butte NF, Mendoza PM, Wilson TA, Hodges EA, Reidy KC, et al. Overestimation of infant and toddler energy intake by 24-h recall compared with weighed food records. Am J Clin Nutr. 2008;88:407–15.
49. Rowland ML. Self-reported weight and height. Am J Clin Nutr. 1990;52:1125–33.
50. Natamba BK, Sanchez SE, Gelaye B, Williams MA. Concordance between self-reported pre-pregnancy body mass index (BMI) and BMI measured at the first prenatal study contact. BMC Pregnancy Childbirth. 2016;16:187.

51. Han E, Abrams B, Sridhar S, Xu F, Hedderson M. Validity of self-reported pre-pregnancy weight and body mass index classification in an integrated health care delivery system. Paediatr Perinatal Epidemiol. 2016;30:314–9.
52. Taveras EM, Rifas-Shiman SL, Sherry B, Oken E, Haines J, Kleinman K, et al. Crossing growth percentiles in infancy and risk of obesity in childhood. Arch Pediatr Adolesc Med. 2011;165:993–8.
53. Kuehn B. Breastfeeding report card. JAMA. 2018;320:1426.

ACKNOWLEDGEMENTS

All authors thank the families who participated in this study and the research staff responsible for the data collection and nutritional analyses.

AUTHOR CONTRIBUTIONS

BB initiated the research question, assisted with the results' interpretation, drafted the manuscript, and approved the final manuscript as submitted; KM assisted with all aspects of the data collection, conducted training for all the research staff members and dietetic interns, quality-controlled all dietary recalls and nutritional analyses, and revised and approved the final manuscript as submitted; MF assisted with the research question, interpreted the results, revised the manuscript, and approved the final manuscript as submitted; RP contributed to the data analyses, interpreted the results, and revised and approved the final manuscript as submitted; KK initiated and developed the research question and study design, led the analytic plan, drafted the manuscript, and approved the final manuscript as submitted.

FUNDING

This work was funded by the National Institute on Child Health and Human Development of the National Institutes of Health, grant number R01 HD087082-01 (awarded to Kai Ling Kong). The sponsor had no role in the study design, data collection, analysis and interpretation, writing of the report, or decision to submit the manuscript for publication.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41366-021-00936-w.

Correspondence and requests for materials should be addressed to K.L.K.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.