Cardiovascular Regulation Profile Predicts Developmental Trajectory of BMI and Pediatric Obesity

By: Paulo A. Graziano, Susan D. Calkins, Susan P. Keane, and Marion O'Brien

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Abstract:

The present study examined the role of cardiovascular regulation in predicting pediatric obesity. Participants for this study included 268 children (141 girls) obtained from a larger ongoing longitudinal study. To assess cardiac vagal regulation, resting measures of respiratory sinus arrhythmia (RSA) and RSA change (vagal withdrawal) to three cognitively challenging tasks were derived when children were 5.5 years of age. Heart period (HP) and HP change (heart rate (HR) acceleration) were also examined. Height and weight measures were collected when children were 5.5, 7.5, and 10.5 years of age. Results indicated that physiological regulation at age 5.5 was predictive of both normal variations in BMI development and pediatric obesity at age 10.5. Specifically, children with a cardiovascular regulation profile characterized by lower levels of RSA suppression and HP change experienced significantly greater levels of BMI growth and were more likely to be classified as overweight/at-risk for overweight at age 10.5 compared to children with a cardiovascular regulation profile characterized by high levels of RSA suppression and HP change. However, a significant interaction with racial status was found suggesting that the association between cardiovascular regulation profile and BMI growth and pediatric obesity was only significant for African-American children. An autonomic cardiovascular regulation profile consisting of low parasympathetic activity represents a significant individual risk factor for the development of pediatric obesity, but only for African-American children. Mechanisms by which early physiological regulation difficulties may contribute to the development of pediatric obesity are discussed.

Article:

INTRODUCTION

Approximately one-third of children are overweight or obese in the United States (1). A significant number of negative health conditions and psychosocial difficulties have been associated with childhood obesity (2,3). Given that pediatric obesity also has a relatively stable course (4), it is important to identify its early predictors. Researchers have recently acknowledged the importance of examining an individual's self-regulation skills as they relate to eating and subsequent obesity (5). This recent focus on self-regulation skills have been a result of observations that the regulation of eating, while generally operates at an automatic level in terms of starting and stopping in response to hunger and satiety cues, can be influenced by stress/negative early experiences and social/emotional factors (6).

Self-regulation generally refers to an individual's conscious or unconscious efforts to alter his/her inner states or responses (5,7). Within the child literature, self-regulation research has mainly focused on children's eating behaviors (e.g., individual differences in energy intake) and response to satiety cues (8,9). More recent research, however, has found that early individual differences in self-regulation outside of the context of food/eating also relate to the development of obesity in children. For example, Graziano, Calkins, and Keane (10) found that individual differences in toddlers' self-regulation skills, in particular, emotion regulation were predictive of both normal variations in BMI development and more significant weight problems (i.e., pediatric obesity).

It has been suggested that self-regulation deficits relate to the development of obesity via an under activated parasympathetic branch of the autonomic nervous system, specifically via the vagus nerve (10). The influence of the vagus nerve on cardiac output (e.g., respiratory sinus arrhythmia (RSA) suppression or vagal regulation) has been conceptualized as a physiological regulation mechanism responsible for facilitating the use of metabolic resources in the service of coping (11). The vagus nerve, however, also enervates the stomach and has a central role in satiety and short-term regulation of food intake (12). In fact, recent adult studies have found that stimulation of the vagus nerve significantly reduces food cravings in obese adults (13).

While empirical studies find conflicting evidence on whether lower or higher sympathetic activity is present in obese individuals (14–18), most studies that have examined autonomic cardiovascular regulation do find a decrease in parasympathetic activity in obese adults (16–18) and in adults who experience weight gain (19). An increase in parasympathetic activity has also been documented in individuals that achieve weight loss (20). However, these autonomic cardiovascular regulation studies have focused mainly on adults and on how chronic patterns of lowered parasympathetic activity relate to obese individuals' increased mortality risk via cardiovascular disease (19). It remains unclear, however, whether similar autonomic cardiovascular regulation difficulties occur in overweight children and whether early cardiovascular regulation difficulties can place children at an increased risk for becoming overweight later in childhood.

Hence, the purpose of the current study was to determine whether early individual differences in cardiovascular regulation constitute a significant risk factor for the development of weight problems. Given the previous findings within the adult literature suggesting a decrease in parasympathetic activity in obese individuals (16–18), we included cardiac reactivity measures of RSA and heart period (HP). Both heart rate (HR) variability (i.e., RSA) and HP are influenced by the vagal system and provide measures of parasympathetic activity (11,21). Higher levels of vagal regulation in the form of greater decreases in RSA during demanding tasks (i.e., RSA suppression) as well as HP change (i.e., HR acceleration) have been associated with better self-regulation skills and positive developmental outcomes (7,22,23). Subsequently, we expected that children with a cardiovascular regulation profile of low parasympathetic activity (i.e., RSA suppression and HP change) at age 5.5 to experience greater BMI gain and be more likely to be classified as overweight/at-risk at age 10.5 compared to children with a cardiovascular regulation profile of high parasympathetic activity.

METHODS AND PROCEDURES

Participants

Participants for this study included 268 children (141 girls) obtained from a larger ongoing longitudinal study which was approved by the governing institutional review board. Four hundred and forty seven participants were initially recruited at 2 years of age through child care centers, the County Health Department, and the local Women, Infants, and Children program. Further details about the recruitment may he found elsewhere (24). The recruitment sample was diverse with 67% of the children classified as European American, 27% were African American, 4% were biracial, and 2% were Hispanic. At age 2, the children were primarily from intact families (77%), and families were economically diverse, with Hollingshead scores, which take into account the families' educational level and occupation (25), ranging from 14 to 66 (M = 39.56). Of the original 447 participants, 365 participated at 5.5 years of age assessment. There were no significant demographic differences between families who did and did not participate at 5.5 years of age. The current study focused on a subgroup of children for whom physiological measures were obtained at the 5.5-years of age assessment along with height/weight measurements which, were obtained at follow-up assessments when children were 7.5 and 10.5 years of age. This subgroup of children were racially (66% white) and economically diverse (Hollingshead scores ranging from 14 to 61, M = 40.1). There were no significant demographic differences between this study's sample and the original recruitment sample.

Procedures

The focus of this study involved the physiological regulation assessment at the 5.5-year visit. Mothers accompanied their child to the laboratory where the child was assessed using several procedures in a laboratory playroom. The electrodes placed on the child's chest were connected to a preamplifier, the output of which was transmitted to a vagal tone monitor (VTM-I, Delta Biometrics, Bethesda, MD) for R-wave detection. The vagal tone monitor displayed ongoing HR and computed and displayed an estimate of RSA (vagal tone) every 30s. A data file containing the interbeat intervals for the entire period of collection was transferred to a laptop computer for later artifact editing. The onset and end of each challenge episode was marked on the computer file of the interbeat interval data through the use of an electronic signal controlled by the experimenter. While connected to the HR collection equipment, the child was observed during a multiepisode sequence derived from the Laboratory Temperament Assessment Battery (26) and methods used in prior work (27).

The baseline episode consisted of a 5-min segment of the videotape "Spot," a short story about a puppy exploring a neighborhood. Following the baseline episode, the child participated in several tasks designed to elicit physiological stress/coping. The first task was a 6-min effortful control task designed to assess the child's ability to slow down gross and fine motor activity. The child was asked to draw some shapes (circles and stars) between boundary lines at varying speeds (regular, slow, and fast). The next task was a 4-min effortful control task similar to a Stroop task. The child was presented with large pictures representing large shapes (animals, geometric figures). Within the larger pictures, smaller shapes were depicted. In half of the trials the small shapes were consistent with the large shape (e.g., a large cat was made up of identical smaller cats), and in the other half the shapes were inconsistent (e.g. large circle made up of small squares). The child was asked to identify only the smaller shapes in the pictures presented and were instructed to answer as fast as they could. The last episode was a 3-min attentional

persistence task, during which the child was asked to sort a large number of beads by color and place them in a container (Laboratory Temperament Assessment Battery (26)). Several studies have shown the reproducibility and reliability of obtaining cardiovascular regulation measures during these Laboratory Temperament Assessment Battery tasks both within subject and across ages (28–30).

Measures

Anthropometrics. Trained research assistants measured children's height and weight during their 5.5, 7.5, and 10.5-year laboratory visit. Degree of overweight was calculated based on age norms from the Centers for Disease Control and Prevention (31).

Physiological measures. Two types of physiological measures were derived from the laboratory assessments: cardiac vagal regulation measures (RSA and RSA change), and HP measures (HP and HP change). To generate measures of cardiac activity and to derive measures of resting RSA (baseline vagal tone) and RSA suppression (baseline vagal tone–challenge vagal tone = vagal regulation), the interbeat interval files were edited and analyzed using MXEDIT software (Delta Biometrics, Bethesda, MD). Data files that required editing of >5% of the data were not included in the analyses *(n* = 13).

Estimates of RSA were calculated using Porges' (32) method to analyze the interbeat interval data. This method applies an algorithm to the sequential HP data. The algorithm uses a moving 21-point polynomial to detrend periodicities in HP slower than RSA. A band-pass filter then extracts the variance of HP within the frequency band of spontaneous respiration in young children, 0.24–1.04 Hz (28,29,33). The estimate of RSA was derived by calculating the natural log of this variance and is reported in units of ln $(ms)^2$. HP and RSA were calculated every 30s for the 5-min baseline period and all other challenge episodes >3 min in length. The mean estimate of HP and RSA of the 30-s epochs within each episode was used in subsequent analyses. Vagal regulation scores indexed by change scores were computed for each challenge episode by subtracting the challenge episode RSA from the baseline RSA. Consistent with previous research methodology (28–30,33), positive change scores indicate a decrease in RSA from baseline to task (i.e., RSA suppression or vagal withdrawal). Likewise, HP change scores were calculated by subtracting the challenge episode HP from baseline HP.

Data analytic strategy

First, preliminary analyses (descriptive statistics/data reduction) were computed. Next, growth curve analyses were conducted to examine the trajectory of children's BMI across early childhood using hierarchical linear modeling (34). An advantage of growth curve modeling and hierarchical linear modeling is the ability to account for missing data longitudinally (32). In the current study, 167 children had physiological data along with BMI data across all visits, 72 children had physiological data along with BMI data across two time points, and 29 children had physiological data along with BMI data across only one time point. Thus, a total of 268 children (141 girls), who had physiological data with at least one wave of BMI data, were included in the analyses. There were no significant demographic differences between children who had physiological data and provided one, two, or three waves of BMI data. Additionally, there were no significant demographic differences between this study's sample and the original recruitment

sample. See Supplementary Appendix 1 online for more details on the procedures employed for the hierarchical linear modeling analyses.

Based on our hypotheses, we expected: (i) growth in BMI across time as evidenced by a significant Unconditional Growth Model and (ii) that children with a cardiovascular regulation profile of low parasympathetic activity (i.e., RSA suppression and HP change) at age 5.5 would have higher initial levels of BMI at age 5.5, as evidenced by a significant initial status effect, and would experience greater BMI gain over time as evidenced by a significant slope effect compared to children with a cardiovascular regulation profile of high parasympathetic activity.

RESULTS

Preliminary analyses

Descriptive statistics. Descriptive statistics for the study variables are presented in Tables 1, 2, and 3. Preliminary analyses found no significant associations between demographic variables and the 5.5-year physiological measures of baseline and task RSA and HP. In terms of the anthropometric data, African-American children had greater levels of BMI across the 5.5-year, (M = 16.82, s.d. = 0.35, $P < 0.08$) 7.5-year (M = 18.58, s.d. =.43, $P< 0.01$), and 10.5-year (M = 22.04, s.d. = 0.63, $P< 0.001$) visits compared to white children (M = 16.10, s.d. = 0.22, M = 17.11, s.d. = 0.27, and M = 19.63, s.d. = 0.39, respectively).

Table 1: Descriptive statistics for 5-year RSA, RSA change, HP, and HP change

	M	s.d.	Min	Max	*N*
5.5-year RSA					
Baseline RSA	6.05	1.16	3.28	9.42	268
Effortful control #1 RSA	6.06	1.13	3.09	9.09	268
Effortful control #2 RSA	5.87	1.18	3.01	8.80	268
Attentional persistence RSA	5.56	1.13	2.72	8.85	268
5.5-year RSA change					
Effortful control #1	-0.01	0.53	-1.62	2.05	268
Effortful control #2	0.18[a]	0.72	-2.08	2.27	268
Attentional persistence	0.49	0.75	-1.77	3.24	268
5.5-year HP					
Baseline HP	640.77[a]	70.22	501.90	913.56	268
Effortful control #1 HP	625.07	67.10	487.45	893.86	268
Effortful control #2 HP	622.05	64.42	489.89	862.02	268
Attentional persistence HP	595.65	59.46	473.35	798.23	268
5.5-year HP change					
Effortful control #1 HP	15.69	23.48	-53.60	79.90	268
Effortful control #2 HP	18.71	33.88	-75.39	174.08	268
Attentional persistence HP	45.11	35.73	-54.30	195.11	268

HP, heart period; man, maximum; min; minimum; RSA, respiratory sinus arrhythmia

[a]Positive change scores indicate a decrease in RSA or HP from baseline to task (i.e., RSA or HP suppression).

Data reduction: cardiovascular regulation profile. To generate profiles of children's physiological regulation abilities, two-step cluster analysis was performed on the measures of RSA suppression and HP change across the three cognitive tasks. In this statistical method, original cases are first grouped into preclusters that are then used instead of the raw data in the hierarchical clustering. Using an Euclidean distance measure, each successive case is then either merged into an existing precluster or added to form a new precluster. In the second step, the preclusters are grouped using the standard agglomerative clustering algorithm which produces a range of solutions. Lastly, on the basis of the Bayesian Information Criterion, an optimal number of clusters are identified (33). The auto-clustering algorithm indicated that a two-cluster solution was the best model. Means and standard deviations for the two clusters are presented in Table 3.

The first cluster was labeled High Cardiovascular Regulation *(n* = 95) as it was characterized by both high RSA suppression and HP change scores while the second cluster was referred to as Low Cardiovascular Regulation (n = 173) as it was characterized by low RSA suppression and low HP change scores. No significant differences among the clusters were found in terms of any demographic variables.

Table 2: Descriptive statistics for BMI variables

	M	s.d.	Min	Max	*N*
5.5-year measures					
Height in inches (L)	46.06	2.46	36	57	274
Weight in pounds (L)	49.63	9.77	32	116	274
BMI (L)	16.38	2.43	12.20	27.45	274
7.5-year measures					
Height in inches (L)	51.09	2.61	45	63	224
Weight in pounds (L)	65.48	15.00	36	116	224
BMI (L)	17.51	3.09	10.63	29.56	224
10.5-year measures					
Height in inches (L)	58.03	3.10	50	69	211
Weight in pounds (L)	99.19	30.06	56	270	211
BMI (L)	20.44	4.75	13.25	39.87	211

L, laboratory measure; max, maximum; min, minimum

Table 3: Physiological regulation profiles

	High cardiovascular regulation (*n* = 95)	Low cardiovascular regulation (*n* = 173)
Sex		
Male	54	73
Female	41	100
Race		
White	66	121
African American	29	52
5.5-year RSA change		
Effortful control #1	0.42[a] (0.41)	-0.24 (0.44)
Effortful control #2	0.70 (0.68)	-0.10 (0.57)
Attentional persistence	1.07 (0.61)	0.17 (0.62)
5.5-year HP change		
Effortful control #1 HP	36.58 (18.58)	4.22 (17.14)
Effortful control #2 HP	44.46 (31.33)	4.58 (26.05)
Attentional persistence HP	73.59 (31.07)	29.47 (27.58)

Values enclosed in parentheses represent standard deviations.
HP, heart period; RSA, respiratory sinus arrhythmia.
[a]Positive change scores indicate a decrease in RSA or HP from baseline to task (i.e., RSA or HP suppression).

Hierarchical linear modeling for BMI

The unconditional means model and unconditional growth model for children's BMI are presented as Models A and B in Tables 4 and and5.5. As indicated in Model A, the grand mean or fixed effect (Table 4) for BMI is significantly different from zero along with the estimated within-person variances (Table 5). The dependent variable also had significant between-person variances (Table 5) that differed from zero, indicating significant individual differences in average BMI. Because both variance components were not zero, additional predictors may improve model fit. The unconditional growth model in Model B shows that both initial status and slope were significantly different from zero (Table 4). Graphically depicted in Figure 1, it is estimated that the average child has a BMI of 16.17 at 5.5-years with a significant increase in BMI of 0.07 per month. Not surprisingly, this indicates that children's BMI show a significant increase from age 5.5 to 10.5. Moreover, 70% of within-person variation in BMI is explained by age. However, as seen in Figure 1, there is significant variability in children's BMI development. Further examination of the significant Level-2 residual variances (Table 5) for BMI, which

summarize the between-person variability in initial status and rate of change, indicate that additional Level-2 predictors may improve model fit. Additionally, to determine whether the addition of time as a Level-1 predictor improved the model, the fit statistics were compared. Because the unconditional means model is nested within the unconditional growth model, the deviance statistic can be used. The reduction in deviance due to the addition of time was statistically significant ($\chi^2(3) = 4459–3902 = 557$, $P < 0.001$).

Table 4: Results of best fitting hierarchical linear models for change in BMI from 5.5 to 10.5 years of age ($N = 286$)

Fixed effects	Par	Model A (UMM)	Model B (UGM)	Model C	Model D
Initial status ∏0i					
Intercept	γ00	17.95*** (0.17)	16.17*** (0.13)	15.02*** (0.66)	13.72*** (1.55)
Racial status	γ01			0.61 (0.32)	1.60 (1.12)
Cardiovascular regulation profile	γ02			0.26 (0.30)	1.05 (0.91)
Racial status x cardiovascular regulation profile	γ03				-0.60 (0.66)
Slope ∏1i (age)					
Intercept	γ10		0.07*** (0.004)	0.01 (0.02)	0.13** (0.04)
Racial status	γ11			0.03** (0.01)	-0.07* (0.03)
Cardiovascular regulation profile	γ12			0.02* (0.01)	-0.05* (0.03)
Racial status x cardiovascular regulation profile	γ13				0.06** (0.02)

UGM, unconditional growth model; UMM, unconditional means model.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Table 5: Variance components and fit statistics for hierarchical linear modeling models for change in BMI from 5.5 to 10.5 years of age ($N = 268$)

	Par	Model A (UMM)	Model B (UGM)	Model C	Model D
Random effects (variance components)					
Level 1					
Within person	σ^2e	9.36*** (0.59)	2.88*** (0.27)	2.96*** (0.30)	2.96*** (0.30)
Level 2					
In initial status	$\sigma^2$0	5.66*** (0.77)	3.12*** (0.48)	3.13*** (0.52)	3.09*** (0.52)
In slope (age)	$\sigma^2$1		0.002*** (0.00)	0.002*** (0.00)	0.002*** (0.00)
Fit statistics					
Deviance		4,459.44	3,902.28	3,191.16	3,181.33
AIC		4,465.44	3,914.28	3,211.50	3,205.33
BIC		4,479.57	3,942.49	3,256.21	3,259.38

AIC, Akaike Information Criterion; BIC, Bayesian Information Criterion; UGM, unconditional growth model; UMM, unconditional means model.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Predicting BMI growth

A series of models were examined to determine the extent to which demographic variables and children's physiological regulation profile predicted initial levels of BMI and BMI growth over time. No initial status or slope effects were observed in regards to sex, socioeconomic level, or maternal education. However, as seen in Table 4, the final mode (D) revealed a significant interaction between children's cardiovascular regulation profile and children's racial status in predicting BMI growth.

As seen in Table 5, comparison of the goodness-of-fit statistics between the final model that included cardiovascular regulation profile, racial status, and their interaction (Model D) and Model B (unconditional growth model) revealed a lower Akaike Information Criterion and Bayesian Information Criterion statistic suggesting a better fit. Thus, the best fitting model for the prediction of children's BMI growth was Model D.

Prototypical plot for BMI

Figure 2 illustrates the interaction between racial status and cardiovascular regulation profile on BMI growth. These plots were created using the equation from Model D (Table 4). Racial status and cardiovascular regulation profiles were dummy coded (1 = white, 2 = African-American and 1 = high cardiovascular regulation, 2 = low cardiovascular regulation). The graph shows that the effect of cardiovascular regulation profiles on BMI growth was particularly important for African-American children, This indicates that African-American children who had a low cardiovascular regulation profile at age 5.5 had significantly greater levels of BMI growth compared to African-American children who had a high cardiovascular regulation profile and white children.

Figure 1: Unconditional growth model. Grey lines indicate individual growth trajectories using ordinary least squares (47). Black line depicts average growth trajectory.

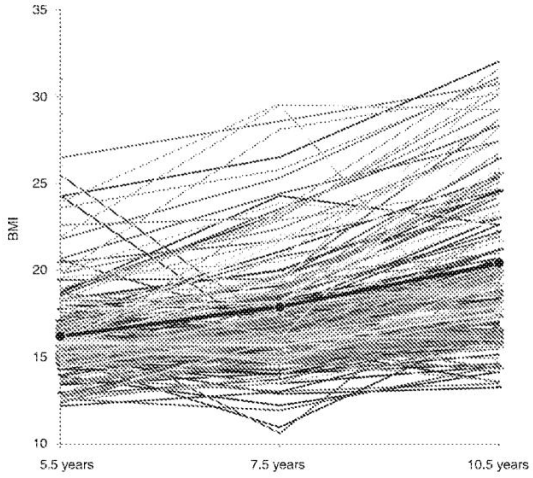
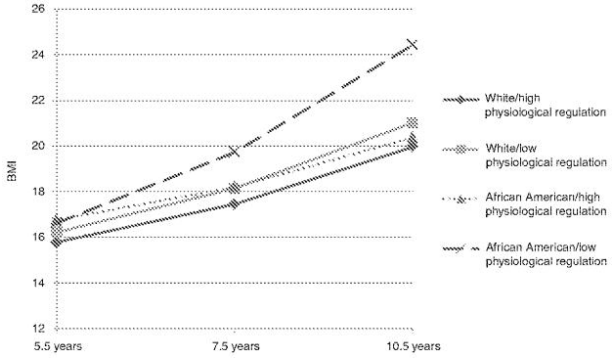


Figure 2: Protypical plot of the interaction between racial status and cardiovascular regulation profile in BMI growth.



Cardiovascular regulation profile as a predictor of pediatric obesity

It was also important to determine whether the cardiovascular regulation profile can differentially predict which children develop more significant weight problems at 10.5 years of age. Hence, based on Centers for Disease Control and Prevention age norms (31), children whose BMI were in the 85th percentile or greater were classified as overweight/at-risk for overweight *(n* = 80) while children between the 6th and 84th percentile were classified as normal

(n = 114). Five children had a BMI <6th percentile and were excluded from the analyses. As expected the overweight/at-risk group had a significantly higher BMI (M = 25.08, s.d. = 3.99) compared to the normal group (M = 17.47, s.d. = 1.57), $P < 0.001$. Children in the overweight/at-risk group and children in the normal weight group did not significantly differ on any demographic variable.

Logistic regressions following the general model were conducted to determine whether children's cardiovascular regulation profile at age 5.5 predicted weight status at age 10.5. Following the hierarchical linear modeling finding indicating an interaction between cardiovascular regulation profile and racial status, separate analyses were conducted for African-American children and white children. Results indicated that cardiovascular regulation profile did not significantly predict weight status for white children (odds ratio = 0.92 (0.39–2.18), $P = 0.85$); however, cardiovascular regulation profile did predict later weight status for African-American children (odds ratio = 7.03 (1.35–36.64), $P = 0.02$, $d = 1.08$), even after controlling for 5.5 year BMI. Hence, African-American children who had a low cardiovascular regulation profile at age 5.5 were over seven times more likely to be classified as overweight/at-risk for overweight at age 10.5 compared to African-American children who had a high cardiovascular regulation profile at age 5.5.

DISCUSSION

The purpose of this study was to determine whether early individual differences in cardiovascular regulation constitute significant risk factors for the development of weight problems in children. Our rationale for creating cardiovascular regulation profiles that included both HP and RSA reactivity measures came from prior research within the adult literature that suggested a decrease in parasympathetic activity in obese individuals (16–18). Given our self-regulation framework and interest in examining individual differences in physiological regulation, it was important to examine change in these cardiac measures during challenging situations where coping or emotional and cognitive regulation is required (7,11). Children with a cardiovascular regulation profile of low parasympathetic activity at age 5.5 experienced greater BMI gain and were more likely to be classified as overweight/at-risk at age 10.5 compared to children with a cardiovascular regulation profile of high parasympathetic activity.

Previous autonomic cardiovascular regulation studies focused mainly on adults and on how chronic patterns of lowered parasympathetic activity relate to obese individuals' increased mortality risk via cardiovascular disease (18,19). Our current findings extend this link to the child population and suggest that poor cardiovascular regulation may be an important risk factor for the development of obesity and not merely a consequence of it. Although the current study cannot fully address the mechanisms by which poor cardiovascular regulation contribute to obesity, recent studies have suggested an important link in terms of its effects on self-regulation skills. For example, there is a substantial literature linking children's cardiovascular regulation, in particular vagal regulation (i.e., RSA suppression), to better self-regulation skills and adaptive functioning (7,23). Self-regulation/executive functioning deficits in overweight/obese individuals have also been recently documented within the adult (35), adolescent (36), and child literature (10,37,38). For example, a recent longitudinal study found that individual differences in toddler's self-regulation skills, in particular emotion regulation, were predictive of both normal variations in BMI development and pediatric obesity (10). Our findings extend this research literature by

highlighting a potential biological mechanism (i.e., cardiovascular regulation) by which self-regulation skills relate to weight gain.

Given the role of the vagus nerve in modulating satiety and short-term regulation of food intake (12), it is also possible that children with lower cardiovascular regulation end up overeating due to inaccurate feelings of hunger and not necessarily due to impulsive or emotional eating. Recent adult studies have found that stimulation of the vagus nerve significantly reduces food cravings in obese adults (13). It remains unclear whether stimulation of the vagus nerve in children would have a similar effect, although future research may be able to investigate whether improvements in children's vagal regulation overtime relate to changes in children's eating behaviors and satiety.

It is important to note that a significant interaction emerged between cardiovascular regulation profile and children's racial status such that the effect of physiological dysregulation on BMI and pediatric obesity was primarily found for African-American children. Higher obesity rates have been documented in ethnic minority groups as well as in families of lower economic backgrounds (39). In terms of cardiovascular functioning, minority groups, especially African American, have been shown to have higher rates of hypertension and cardiovascular disease (40). Some studies have also found that African-American adults display lower cardiac autonomic regulation compared to white adults (41,42). However, unlike our study, these studies did not measure cardiovascular regulation as it relates to modulating stress reactivity (e.g., participants were asked to sit quietly without moving/talking). Consistent with previous physiological regulation research in the child development literature (28–30,43), we did not find any racial differences in terms of children's cardiovascular regulation capabilities during challenging tasks. Rather, it was the link between such regulation capabilities and the development of weight problems that was more prominent in African-American children. It will be essential for future research to investigate why this link was stronger for African-American children.

In terms of this study's limitations, we did not have information on children's eating behaviors as this was not the primary aim of the study design. Future research should examine whether individual differences in cardiovascular regulation relate to observable differences in children's eating behaviors. While there is a well-established literature linking cardiovascular regulation and observable self-regulation behaviors (7), it will also be important for future research to determine the associations between eating behaviors and observable self-regulation measures (e.g., behavioral impulsivity) in order to clarify the mechanisms by which cardiovascular regulation contributes to pediatric obesity. It is also important to acknowledge that we did not have data on children's level of physical activity which not only contributes to obesity (44,45) but has also been shown to affect autonomic function (46). Hence, future research should examine whether the association we found between cardiovascular regulation and obesity remains significant after accounting for children's physical activity levels. Furthermore, our cardiac reactivity measures primarily indexed parasympathetic activity. Given the mixed findings in the adult literature concerning whether higher or lower levels of sympathetic activity relate to obesity (14–18), it will be important for future child research to measure more specific sympathetic linked cardiac activity such as pre-ejection periods. Lastly, it is important to point out that despite our longitudinal design and use of hierarchical linear modeling, we cannot affirm

a causal link between children's cardiovascular regulation and the development of obesity. In particular, it will be important for future research to determine whether changes in children's cardiovascular regulation across time map onto changes in BMI. In other words, do children with initial cardiovascular regulation difficulties who become obese continue to show impaired cardiovascular functioning? Despite these limitations, our results do provide initial evidence for the importance of examining children's physiological regulation skills as it relates to the development of obesity, especially for African-American children. This represents one of the first pediatric studies to identify cardiovascular regulation, as it relates to modulating stress reactivity, as a biological risk factor in the development of pediatric obesity. While there is significant research still to be conducted before any practical applications emerge, there maybe a time when treatment interventions can target children's physiological regulation in order to minimize its influence on weight gain.

SUPPLEMENTARY MATERIAL

Supplementary material is linked to the online version of the paper at http://www.nature.com/oby

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DISCLOSURE

The authors declared no conflict of interest.

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