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Original Article

Nucleus Accumbens Fractional Anisotropy and Children's Body Mass Index: Moderating Role of Race and Family Income

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Abstract

Background and aims: The nucleus accumbens (NAcc) functional and morphometric features may influence children's body mass index (BMI). Recent evidence, however, suggests that the function and structure of the NAcc may have different predictive abilities for the BMI for the sub-groups of children from different racial and socioeconomic status (SES) backgrounds. Using the Adolescent Brain Cognitive Development data, this study investigated racial and SES differences in the association between NAcc microstructure (i.e., fractional anisotropy) and childhood BMI.

Methods: This cross-sectional study included 9497 children aged 9 and 10. Data were collected from 21 sites across 15 states in the United States. Then, the mixed-effects regression model was applied for data analysis. The predictor variable of interest was NAcc fractional anisotropy measured using diffusion *magnetic resonance imaging* (dMRI). The main outcome of interest was children's BMI values, which were treated as a continuous variable. Covariates included gender, age, and family structure. Race (White, Black, Asian, and Other/mixed) and family income (< USD 50,000, USD 50,000-100,000, and USD100,000+) were the effect modifiers (moderators).

Results: Higher average NAcc fractional anisotropy in dMRI was predictive of lower levels of the BMI, and net of covariates. However, this inverse association between the average intensity of the normalized T2-weighted image and the BMI was stronger in children from Hispanic, low income, and low-educated backgrounds compared to non-Hispanic, high-income, and high-educated backgrounds.

Conclusion: Our findings suggested that although NAcc fractional anisotropy is linked to children's BMI, this link is not invariant across racial and SES groups. The issue of whether or not obesogenic environments alter the implications of NAcc for childhood BMI needs further investigation. For diverse groups, NAcc microstructures may have different magnitudes of associations with childhood BMI.

Keywords: Children, Obesity, Ethnic background, Body mass index, Nucleus accumbens

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Introduction

Distributions of obesity and high body mass index (BMI) in the populations are not random as they follow a social gradient. High BMI and obesity are both more common in individuals from racial minority and low socioeconomic status (SES) backgrounds. As such, Hispanic, Black, low income, and low-educated families have higher BMIs in comparison with non-Hispanic, White, high-income, and high-educated families.[1] Among various racial groups, Latino and Black children have the highest BMIs across various racial groups.[1] Considering that high childhood BMI is one of the gateways to health disparities later in life, researchers have shown interest in underlying mechanisms that explain social inequalities in the BMI due to race and SES.[2]

Given that race and SES differences exist in the social and physical aspects of the social-environmental contexts of populations, we may expect racial and SES variations in how various risk and protective factors contribute to the risk of childhood obesity and high BMI.[3] Although race and SES have direct effects on BMI, some of the effects of race and SES on the BMI are through racial and SES variations in vulnerability and sensitivity to various risk and protective factors on childhood BMI.[3]

Moreover, although high BMI and obesity have many neurological mechanisms such as emotion regulation, impulsivity, attention, and cognition, the brain reward system is regarded as one of the main contributors to the BMI through binge eating and excessive food-seeking behaviors.[4] Accordingly, various structures of the brain reward system have the potential to distinguish obesity-prone from other individuals not prone to it.[5,6] One of such brain structures is the nucleus accumbens (NAcc), which has a role in the regulation of urges for food-seeking behaviors, affecting the risk of obesity.[4]

The overall effect of NAcc on children's BMI is well established, although less is known about racial and SES differences in the implications of NAcc.[7-11] As mentioned above, people live in different food environments, thus the salience of the NAcc on the childhood BMI may depend on race and SES.[7-11] In other words, various neighborhoods and contexts may alter the salience of the brain structure for various population sub-groups. Groups living in obesogenic conditions may be less or more prone to their NAc-related increase in BMI. As mentioned earlier, while a large body of research has connected to the brain structure such as cortical thickness (CT)[7-11] and NAcc,[12-14] very little information is available on the heterogeneity of these effects by racial and SES.

A study was conducted on a racial and SES diverse sample of 9-10-year-old American children to compare the role of the NAcc microstructure (fractional anisotropy) as a correlate of the BMI across the subgroups of children based on race and SES (income). Our first hypothesis is that this microstructure (fractional anisotropy) is associated with childhood BMI.[7-11] Our second hypothesis is that the role of NAcc microstructure (fractional anisotropy) as a predictor of children's BMI is different in economically disadvantaged children who are from underserved backgrounds (Black, Latino, and low-income) compared to socially privileged children from more prosperous economic backgrounds (White, non-Latino, and high-income).

Methods

A secondary analysis of the existing data was conducted in this cross-sectional study. Data were collected from the Adolescent Brain Cognitive Development (ABCD) study.[15,16] The ABCD sample is limited to 9-and-10-year-old children in the US. The ABCD samples are recruited from 15 US states. Children were recruited into the ABCD study from 21 sites. The main place for sampling in the ABCD study was the US schools.[17] A full description of diffusion *magnetic resonance imaging* (dMRI) in the ABCD study is available in previous research.[18]

Baseline BMI at the Time of Entry to the Study (Brain Imaging)

The BMI was estimated using participants' weight and height, which were directly measured for this purpose. The index was treated as a continuous measure. The NAcc microstructure (fractional anisotropy) was defined as diffusion tensor imaging measures (dMRI) in the subcortical automatic segmentation (ASEG) of our region of interest (ROIs). Average fractional anisotropy within ASEG ROI left NAcc was the outcome (continuous measure). Race was a categorical variable (Black, Asian, Other/mixed race, and White). Ethnicity was 1 and 0 for Hispanics and non-Hispanics, respectively. Parents reported their educational attainment as less than high school, high school, some college courses, college graduate, and graduate studies. Family income, reported by parents, was a 3-level categorical variable, including less than USD$ 50,000, USD 50,000-100,000, and USD 100,000 or more. Both parental education and family income were used as categorical variables.

The Data Analysis and Exploration Portal (DEAP) was employed for our data analysis. The DEAP operates based on the R statistical package. Using the DEAP, the mean (standard deviation, SD) and frequency (%) of all variables were reported generally and by race and family income. Then, the analysis of variance and Chi-square tests were applied to compare our racial and income groups.

To conduct our multivariable modeling, mixed-effects regression models were run with some specifications. The left NAcc fractional anisotropy and the BMI were our predictor and outcome, respectively, and age, gender, ethnicity, family structure, and parental education were covariates. Race and income levels were the moderators. All our regression models were estimated in the pooled sample (n = 9497). Our 1st model was without any *interaction terms*, while our 2nd model included the interaction term between race and NAcc fractional anisotropy. In addition, our 3rd model was performed with the presence of interaction terms between family income and NAcc fractional anisotropy (Supplementary file 1). Regression coefficients (b), standard errors (SE), and two-sided *P*-values were reported for our model. Supplementary file 2 depicts the distribution of our predictor (a), outcome (b), residuals (c), and quantiles (d).

The ABCD study protocol received Institutional Review Board (IRB) approval from several institutions, including but not limited to the University of California, San Diego. All participating children provided assent, and all participating parents signed informed consent forms.[19] Our study was exempt from a full IRB review.

Results

Descriptives

Our analysis included an overall number of 9497 children who were all 9-10 years old. In this study, 6411 (67.5%), 1321 (13.9%), 200 (2.1%), and 1565 (16.5%) participants were White, Black, Asian, and other/mixed race, respectively. Table 1 presents the descriptive characteristics of the sample overall and by race. Black and mixed/other race children had higher, while White and Asian children had lower BMIs.

Based on data in Table 2, from all participants, 2638 (27.8%), 4132 (43.5%), and 2727 (28.7%) cases had an annual family income of less than 50 K, between 50 and 100 K, and more than 100 K, respectively. A significant difference was found in NAcc fractional anisotropy (microstructure) across income groups. Children from low- and high-income families were different in their mass index levels.

Overall Effect of NAcc Fractional Anisotropy on BMI

In the pooled sample, NAcc fractional anisotropy was predictive of the BMI (b = 4.81, *P < 0.001)*. However, the association between NAcc fractional anisotropy and the BMI was stronger (i.e., steeper) in Black than White children, as well as low- than high- family income

Table 1. Descriptive Statistics by Race

	Level	All N = 9497 Mean (SD)	White n = 6411 Mean (SD)	Black n = 1321 Mean (SD)	Asian n = 200 Mean (SD)	Other/Mixed n = 1565 Mean (SD)	*P* Value
Age (mon)		119.06 (7.47)	119.13 (7.49)	119.04 (7.23)	119.90 (7.82)	118.67 (7.54)	0.060
BMI		18.62 (3.88)	18.17 (3.51)	20.38 (4.80)	17.57 (3.18)	19.12 (4.05)	< 0.001
NAcc fractional anisotropy (Left)		0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.24 (0.05)	0.24 (0.05)	< 0.001
Gender	Female	4574 (48.2)	3029 (47.2)	668 (50.6)	103 (51.5)	774 (49.5)	0.067
	Male	4923 (51.8)	3382 (52.8)	653 (49.4)	97 (48.5)	791 (50.5)	
Parental education	< High school diploma	334 (3.5)	127 (2.0)	103 (7.8)	4 (2.0)	100 (6.4)	< 0.001
	High school diploma/GED	749 (7.9)	287 (4.5)	294 (22.3)	2 (1.0)	166 (10.6)	
	Some college courses	2399 (25.3)	1338 (20.9)	524 (39.7)	15 (7.5)	522 (33.4)	
	Bachelor	2533 (26.7)	1921 (30.0)	198 (15.0)	52 (26.0)	362 (23.1)	
	Post graduate degree	3482 (36.7)	2738 (42.7)	202 (15.3)	127 (63.5)	415 (26.5)	
Married family	No	2817 (29.7)	1281 (20.0)	929 (70.3)	31 (15.5)	576 (36.8)	< 0.001
	Yes	6680 (70.3)	5130 (80.0)	392 (29.7)	169 (84.5)	989 (63.2)	
Annual family income	< 50K	2638 (27.8)	1141 (17.8)	865 (65.5)	30 (15.0)	602 (38.5)	< 0.001
	≥50K and < 100K	2727 (28.7)	1943 (30.3)	296 (22.4)	47 (23.5)	441 (28.2)	
	≥100K	4132 (43.5)	3327 (51.9)	160 (12.1)	123 (61.5)	522 (33.4)	
Hispanic ethnicity	No	7709 (81.2)	5335 (83.2)	1254 (94.9)	181 (90.5)	939 (60.0)	< 0.001
	Yes	1788 (18.8)	1076 (16.8)	67 (5.1)	19 (9.5)	626 (40.0)	

Note. SD: Standard deviation; BMI, Body mass index; NAcc: Nucleus accumbens

Table 2. Descriptive Statistics by Annual Family Income

	Level	All N = 9497	< 50,000 n = 2638	≥50,000 & < 100,000 n = 2727	≥100,000 n = 4132	*P* Value
Age (mon), Mean (SD)		119.06 (7.47)	118.78 (7.44)	118.83 (7.50)	119.39 (7.46)	0.001
BMI, Mean (SD)		18.62 (3.88)	19.93 (4.47)	18.63 (3.87)	17.78 (3.19)	< 0.001
NAcc fractional anisotropy, Mean (SD)	(Left)	0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.040
Race, No. (%)	White	6411 (67.5)	1141 (43.3)	1943 (71.3)	3327 (80.5)	< 0.001
	Black	1321 (13.9)	865 (32.8)	296 (10.9)	160 (3.9)	
	Asian	200 (2.1)	30 (1.1)	47 (1.7)	123 (3.0)	
	Other/Mixed	1565 (16.5)	602 (22.8)	441 (16.2)	522 (12.6)	
Gender, No. (%)	Female	4574 (48.2)	1300 (49.3)	1311 (48.1)	1963 (47.5)	0.361
	Male	4923 (51.8)	1338 (50.7)	1416 (51.9)	2169 (52.5)	
Parental education, No. (%)	< High school diploma	334 (3.5)	314 (11.9)	18 (0.7)	2 (0.0)	< 0.001
	High school diploma/GED	749 (7.9)	587 (22.3)	134 (4.9)	28 (0.7)	
	Some college courses	2399 (25.3)	1214 (46.0)	836 (30.7)	349 (8.4)	
	Bachelor	2533 (26.7)	344 (13.0)	933 (34.2)	1256 (30.4)	
	Post graduate degree	3482 (36.7)	179 (6.8)	806 (29.6)	2497 (60.4)	
Married family, No. (%)	No	2817 (29.7)	1750 (66.3)	721 (26.4)	346 (8.4)	< 0.001
	Yes	6680 (70.3)	888 (33.7)	2006 (73.6)	3786 (91.6)	
Hispanic, No. (%)	No	7709 (81.2)	1774 (67.2)	2199 (80.6)	3736 (90.4)	< 0.001
	Yes	1788 (18.8)	864 (32.8)	528 (19.4)	396 (9.6)	

Note. SD: Standard deviation; BMI, Body mass index; NAcc: Nucleus accumbens

children (Table 3).

Overall Effect of NAcc Fractional Anisotropy on BMI

Figure 1 shows the positive association between NAcc fractional anisotropy and the BMI in the pooled sample. In the regression model, 1 unit increase in NAcc fractional anisotropy (from 0 to 1; minimum to maximum) is associated with a 4.81 value increase in the childhood BMI.

Overall Effect of NAcc Fractional Anisotropy on BMI

Figure 2 illustrates the positive association between NAcc fractional anisotropy and the BMI in the pooled sample

Table 3. Effects of Left NAcc Fractional Anisotropy on Childhood Body Mass Index Overall and by Race and Income

	Estimate	SE	*P* Value
Model 1			
Left NAcc fractional anisotropy	4.81***	1.04	<0.001
Model 2			
Left NAcc fractional anisotropy	4.25***	1.24	0.001
Race (Black)	0.12	0.60	0.837
Race (Asian)	0.97	1.44	0.501
Race (Other/Mixed)	0.32	0.53	0.542
Race (Black) × Left NAcc fractional anisotropy	5.29*	2.58	0.040
Race (Asian) × Left NAcc fractional anisotropy	-5.98	5.92	0.313
Race (Other/Mixed) × Left NAcc fractional anisotropy	-0.25	2.20	0.911
Model 3			
Left NAcc fractional anisotropy	9.33***	1.76	<0.001
Family income ≥50K &<100K)	1.16*	0.54	0.033
Family income (≥100K)	1.09*	0.51	0.032
Family income (≥50K &<100K) × Left NAcc fractional anisotropy	-5.51*	2.31	0.017
Family income (≥100K) × Left NAcc fractional anisotropy	-6.58**	2.13	0.002

Note. SE: Standard error; NAcc: Nucleus accumbens.
*$P<0.05$, **$P<0.01$, ***$P<0.001$. Covariates: Gender, age, ethnicity, and family structure.

and by race. As shown, the positive association between these two parameters was stronger in Black than White children.

Effect of NAcc Fractional Anisotropy on BMI by Family Income

Figure 3 displays the positive association between NAcc fractional anisotropy and the BMI in the pooled sample based on family income. Based on the results, the positive association between the two above-mentioned variables was stronger (steeper) in low-income than high-income children.

Discussion

In general, our findings showed that higher NAcc fractional anisotropy was associated with a higher BMI in 9-10 years old American children. However, this association was probably weaker for White and high-income than Black and low-income children.

Brain structures such as cerebral cortex[5,20] and NAcc[13,21-24] are correlated with the obesity risk of children, youth, and adults. These correlations are through reward processing and emotion regulation that alter the individual response to food cues and food-seeking behavior. Some other influences on obesity are through inhibitory control and impulsivity. Several other brain influences on obesity risk are through NAcc, a component of the striatum, which is involved in the regulation of feeding and eating, and ion harmony with jointly works with the cerebral cortex.[20,25] In NAcc, GABA may predict hyperphagia and overeating that shape weight gain.[2] NAcc and thalamus structure, microstructure, and function shape appetite[27] and food-seeking behaviors.[13,21-24] NAcc is involved in the regulation of brain reward processing.[28]

The magnitude of the effect of brain circuits on obesity may change by obesity risk factors in the social environment (e.g., access to healthy versus junk food).[28] Long-term exposure to fast food may influence brain pathways (e.g., striatum) that regulate food-seeking behaviors.[29] NAcc characteristics (e.g., microstructure) may interact with the

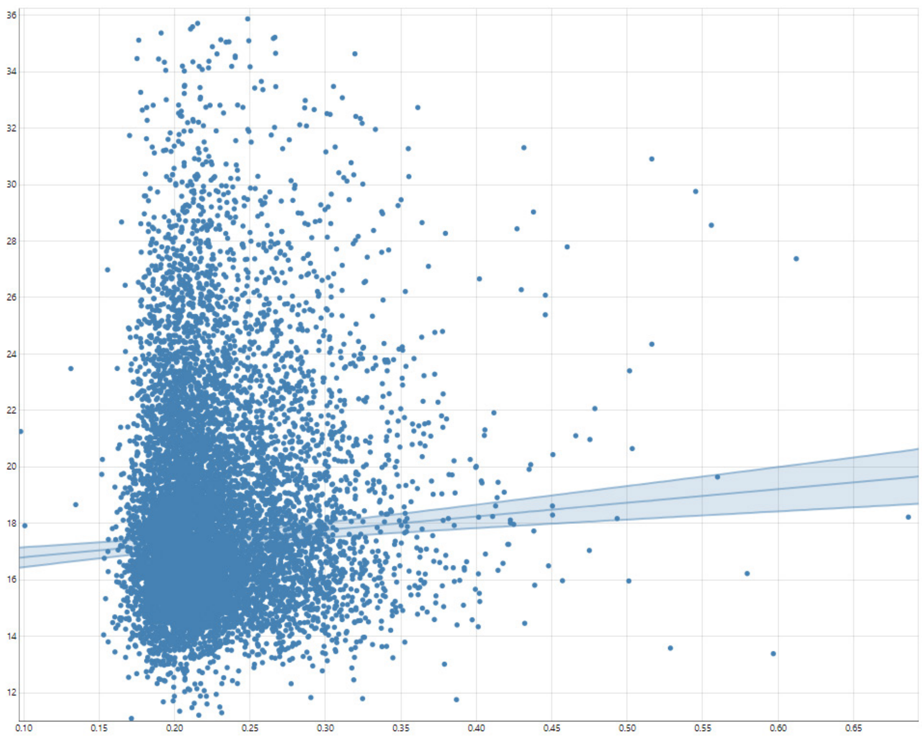

Figure 1. Correlation Between NAcc Fractional Anisotropy and Body Mass Index Overall. *Note*. NAcc: Nucleus accumbens.

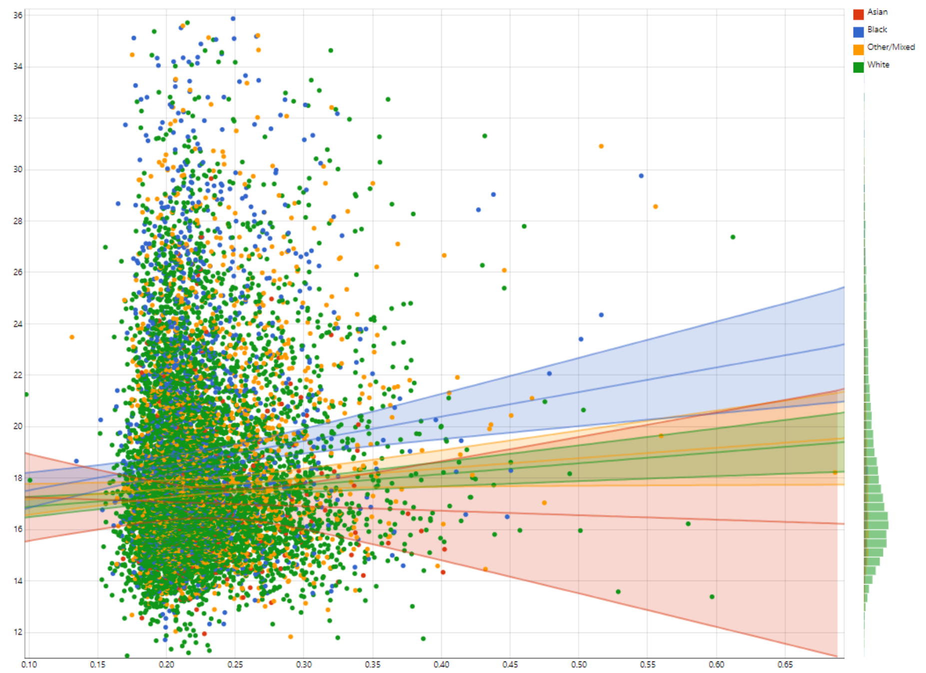

Figure 2. Correlation Between NAcc Fractional Anisotropy and Body Mass Index by Race. *Note*. NAcc: Nucleus accumbens.

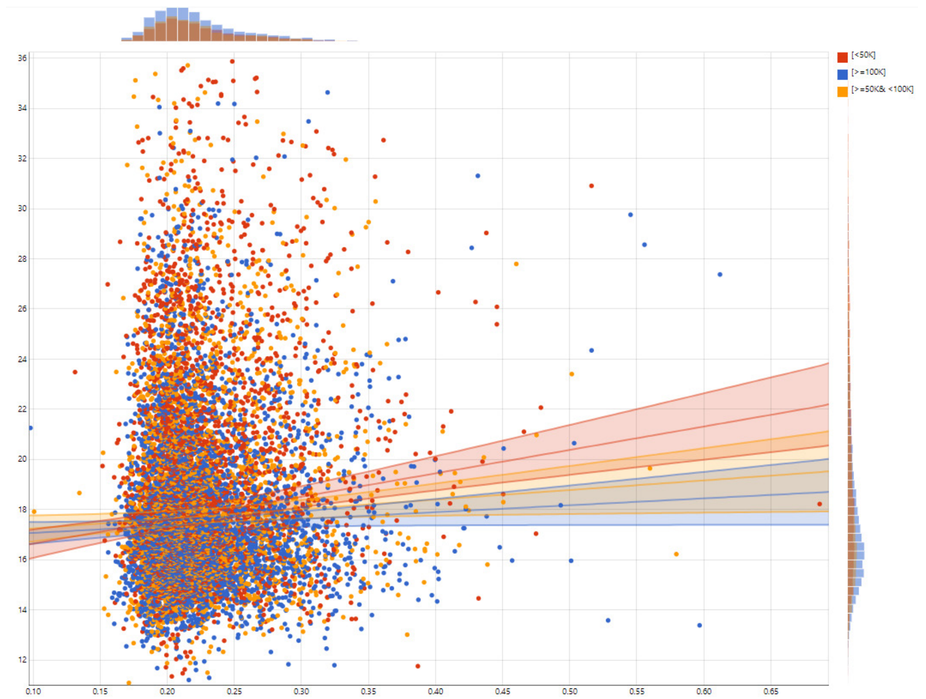

Figure 3. Correlation Between NAcc Fractional Anisotropy and Body Mass Index by Family Income. *Note*. NAcc: Nucleus accumbens.

social environment and predispose individuals to obesity. Some neural and cognitive risk factors may have larger effects on the BMI in obesogenic environments. In contrast, in environments where food options are primarily healthy, calories remain low even when the individual experiences over-eating. In such contexts, food-related cues may result in the consumption of healthier low-calorie food. Thus, susceptibility to obesity is not merely a function of neural pathways but their interaction with the social and food environment.[30] In the US, group membership reflects the physical and social environment.

A vast array of brain structures such as NAcc, thalamus, and cortex are involved in the regulation of food-seeking behaviors.[29] A wide range of social factors such as family and the neighborhood food environment may alter the influence of NAcc on the BMI through changes in calorie intake. There is a need for the investigation of the interactions between social group membership, food environment, and brain structures such as NAcc, prefrontal cortex, and thalamus as the determinants of obesity risk through food-seeking behaviors.[31-35]

Conclusion

In this study, NAcc fractional anisotropy was positively associated with the BMI among 9-10-year old children. Nonetheless, this positive association may not be identical across racial and SES groups. The steeper slope of the effect of NAcc fractional anisotropy on childhood BMI may be due to the variation of food options for various social groups. NAcc fractional anisotropy may have stronger implications for the childhood BMI in obesogenic environments where available food is high calory and unhealthy. As such, the brain-obesity link may vary for high SES, low SES, Black, and White families. More research is needed on this topic.

Ethical Approval
Our study was exempt from a full IRB review.

Conflict of Interest Disclosures
None.

Supplementary Materials
Supplementary file 1. Formula Used for Modeling.
Supplementary file 2. Distribution of our Predictor (a), Outcome (b), Residuals (c), and Quantiles (d).

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