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The limitations of transforming very high BMIs into z-scores among 8.7 million 2- to 4-year olds

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Abstract

Objective—To examine the associations among several BMI metrics (z-scores, percent of the 95th percentile (%BMI$_{p95}$) and ΔBMIp95 (BMI minus 95th percentile) as calculated in the CDC growth charts. It is known that the widely-used BMI z-scores and percentiles calculated from the growth charts can differ substantially from those that directly observed in the data for BMIs above the 97th percentile (z = 1.88).

Study design Cross-sectional analyses of 8.7 million 2- to 4-year-olds who were examined from 2008 through 2011 in the CDC's Pediatric Nutrition Surveillance System.

Results—Because of the transformation used to calculate z-scores, the theoretical maximum BMIz varied by more than 3-fold across ages. This results in the conversion of very high BMIs into a narrow range of z-scores that varied by sex and age. Among children with severe obesity, levels of BMIz were only moderately correlated (r ~ 0.5) with %BMI$_{p95}$ and ΔBMIp95. Among these children with severe obesity, BMIz levels could differ by more than 1 SD among children who had very similar levels of BMI, %BMI$_{p95}$ and ΔBMIp95 due to differences in age or sex.

Conclusions—The effective upper limit of BMIz values calculated from the CDC growth charts, which varies by sex and age, strongly influences the calculation of z-scores for children with severe obesity. Expressing these very high BMIs relative to the CDC 95th percentile, either as a difference or percentage, would be preferable to using BMI-for-age, particularly when assessing the effectiveness of interventions.

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Keywords

obesity; children

The 2000 Centers for Disease Control and Prevention (CDC) growth charts are widely used to classify obesity (BMI ≥ 95th percentile for a child's sex and age) among children and adolescents (1,2). These growth charts contain 10 smoothed percentile curves (between the 3rd and 97th) of BMI for 2- to 19-year-olds (1,3). These estimates were also used to derive measures that, which are similar to the LMS measures proposed by Cole et al (4,5) that allow for the estimation of other percentiles and z-scores from a child's sex, age and BMI.

However, the use of the LMS measures to calculate percentiles and z-scores above the CDC 97th percentile yields values that do not agree with the estimates based on direct observation of the data (6). This is largely due to the difficulties in estimating extreme values, but also, in part, because the LMS measures in the CDC growth charts were estimated from already smoothed percentiles rather than from the underlying data (1,3). The disagreement between very high BMI-for-age percentiles calculated from the CDC growth charts and those that are directly observed in the data, has led to the use of 120% of the 95th percentile of BMI (%BMIp95) for the classification of classify severe obesity among children (6,7).

Despite the limitations of very high BMIz values estimated from the CDC growth charts, these z-scores have been widely used as a continuous variable in various types of studies, including those focused on interventions (8). This has occurred despite several reports that have emphasized the drawbacks of BMIz and changes in BMIz (9–13) for very high BMIs. Because a wide range of very high BMI values map to similar z-scores, and this range differs substantially by sex and age, a focus on changes in very high values of BMIz may lead to incorrect conclusions. Changes in BMIz values among severely obese children can be more strongly related to differences in the L and S measures than to changes in body size (14).

The objective of the current study is to describe the interrelationships and differences among various BMI metrics (BMI, BMIz, and BMI expressed relative to the 95th percentile) among 8.7 million 2- to 4-year-olds. These analyses extend our previous report concerning these BMI metrics among 2- to 19-year-olds in NHANES (14).

Methods

As previously described (15–17), the Pediatric Nutrition Surveillance System (PedNSS) was a state-based public health system that monitored the nutritional status from birth to age 5 y of low-income children who participated in federally funded maternal/child health and nutrition programs. Over 90% of the enrolled children were in the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). Weight was recorded to the nearest 1/4 pound and height to the nearest 1/8 inch.

There were 14.4 million records (observations) in the database from children between 24.0 and 59.9 months of age from 2008 through 2011. The initial data cleaning excluded (1)

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623,000 records that were missing data on weight or height, (2) 70,000 children for whom the date of birth or sex differed across records, and (4) 151,000 records that had an implausible weight, height or BMI based on the recommended cut-points of modified z-scores (15,18,19).

These exclusions resulted in a sample of 13.5 million records from 8,654,466 children. Based on the assigned ID and birthdate, we determined that 3.6 million had been examined multiple times, and we used data from only the first examination for these children.

Body mass index (BMI) was calculated as kg/m^2. BMIz was calculated by expressing a child's BMI relative to children of the same sex and age in the CDC growth charts (1). The estimated L (power transformation for normalizing the BMI distribution at each sex/age), M (BMI median), and S (BMI coefficient of variation of BMI) measures allow for the estimation (4,20,21) of any z-score based on the following formula:

$$BMIz = \left[\left(\frac{\mathrm{BMI}}{\mathrm{M}} \right)^{\mathrm{L}} - 1 \right] \div (\mathrm{L} \times \mathrm{S})$$

Because values of L are negative, when BMI is large relative to the median BMI, $(\mathrm{BMI} \div \mathrm{M})^{\mathrm{L}}$ approaches 0 and the maximum BMIz that is possible at a specific sex/age is therefore $(-1) \div (\mathrm{L} \times \mathrm{S})$. For example, a 2-year-old boy with a BMI of 30 would have a $(\mathrm{BMI} \div \mathrm{M})^{\mathrm{L}}$ of ~0.3 and a BMIz of 5.1 SDs. Based on the values of L and S in the growth charts for this sex/age, the maximum possible BMIz for this child is 6.3 SDs irrespective of his BMI.

The difference between the LMS method proposed by Cole et al and the methods used in the CDC should also be appreciated (3). Whereas Cole et al proposed estimating the LMS measures from all the data (4,5), the primary emphasis in the CDC growth charts was on creating charts of smoothed percentiles (1). It was subsequently realized that equations describing these percentile curves could be solved to obtain the LMS measures that would allow for the calculation of the z-score and corresponding percentile for any child (1,3). Therefore, the LMS measures in the CDC growth charts were created only from the smoothed percentiles and did not use the underlying data.

Obesity is defined as a BMI-for-age ≥ 95th percentile (BMIz ≥ 1.645) of the CDC growth charts (1,22). We refer to a BMI that is expressed as a percentage of the 95th percentile as %BMIp95, so that a child with a BMI equal to the 95th percentile would have a %BMIp95 of 100. Severe obesity is defined as a %BMIp95 ≥ 120 (6), and we consider children who have a %BMIp95 of 100 to 119 to be have moderate obesity. Several analyses are based on these three categories of BMI status: non-obese (< 95$^{\text{th}}$ percentile), moderately obese, and severely obese (%BMIp95 ≥ 120).

In addition to BMIz and %BMIp95, we the difference (in kg/m^2) of the child's BMI from the 95$^{\text{th}}$ percentile of BMI. This difference (ΔBMIp95), which assessed the distance from the 95$^{\text{th}}$ percentile and does not represent change over time, was calculated by subtracting the sex- and age-specific CDC 95$^{\text{th}}$ percentile from the child's BMI. For example, an 8-year-old boy with a BMI of 22 kg/m^2, would have a ΔBMIp95 of +2 kg/m^2 if the 95$^{\text{th}}$ percentile

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were 20 kg/m^2. ΔBMIp95 values are somewhat like the residuals from a linear model in which BMI is regressed on sex and age, but expresses BMI relative to the 95th percentile rather than to the mean.

BMIz, %BMIp95 and ΔBMIp95 each standardizes BMI values for the differences in BMI levels observed between boys and girls and across ages, but express these standardized BMI values on different scales. In addition to providing z-scores and percentiles, the output of the SAS program for the CDC growth charts (18) includes the 95th BMI percentile, ΔBMIp95 and %BMIp95.

Statistical Analyses

Analyses were performed in R (23). Descriptive characteristics are shown for children who did not have obesity, those with moderate obesity (%BMIp95 of 100 to 119) and those with severe obesity. Pearson correlations among the various BMI metrics (BMIz, ΔBMIp95 and %BMIp95) are shown according to BMI status. Although the truncated range of the BMI metrics within each BMI group would reduce the magnitudes of the correlations, our focus is on differences between the metrics.

The relation of %BMIp95 to levels of BMI and the other BMI metrics are illustrated with violin plots (24), a technique that shows the entire distribution of the data rather than only selected percentiles as do boxplots. The width of each violin is proportional to the density of the sample at that value, and we also show the 10th, 50th and 90th percentile for each characteristic.

Results

Figure 1 shows levels of the median BMI, the 95th percentile of BMI, and the theoretical maximum value of BMIz, in the CDC growth charts. Also shown are the observed, maximum values of BMIz in PedNSS (lower right). Between 24 and 59 months of age, the median BMI (M) decreased by about 1 kg/m^2, and except for small increases after about 50 months, the patterns for the CDC 95th percentile were similar. In contrast, the theoretical maximum BMI-for-age, which is based solely on the L and S measures in the growth charts, showed a very different pattern (lower left), with the maximum possible BMIz decreasing from about 12 to 3.5 over the range of ages among girls. Among boys, the pattern was concave, with the maximum (10 SD) occurring at about 40 months of age. The maximum values of BMIz that were observed in PedNSS (lower right) show trends that were fairly similar to those for the theoretical maximums, but the values were lower. About 32,000 children in the current study had a BMIz ≥ 4 SDs; about two thirds of these children were boys between 30 and 54 months of age.

Table 1 (available at www.jpeds.com) shows levels of various characteristics by BMI status. About 13% of the children had moderate obesity (%BMIp95: 100 to 119), and 2% had severe obesity. Children with severe obesity were older than other children, and were more likely to be Hispanic or American Indian. As compared with children without obesity, those with severe obesity had higher mean levels of ΔBMIp95 (+7.7 kg/m^2), along with higher levels of BMIz. As expected, children with severe obesity also had a higher (3.0 SDs)

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weight-for-age than did children without obesity, but they also had a 0.7 SD higher mean height-for-age.

Figure 2 shows levels of BMIz for various levels of ΔBMIp95 between 0 and +12 kg/m^2. Apart from a ΔBMIp95 of 0 (the 95th percentile), BMIz values for a given ΔBMIp95 varied substantially across ages and between sexes, with the shapes of the curves being somewhat similar to the theoretical maximums for BMIz (Figure 1). The patterns were concave among boys, with a maximum at about 40 months, while among girls, the value of BMIz for a constant ΔBMIp95 decreased with age. For example, a girl who had a ΔBMIp95 of +12 kg/m^2 would have a BMIz of 5.5 SDs at 24 months, but a BMIz of 3.2 at 49 months. The extent of compression of these extreme BMIz values varied by sex, and older girls showed the most compression. For example, the BMIz difference between ΔBMIp95 values of +3 and +12 among girls was 2.5 SDs at 24 months, but only 0.8 SDs at 59 months.

BMIz was strongly correlated with levels of ΔBMIp95, and %BMIp95, but the magnitudes of the associations varied according to BMI status (Table 2; available at www.jpeds.com). Among children without obesity (top rows), BMIz was strongly correlated ($r \geq 0.94$) with levels of the other metrics, but the correlation between BMIz and BMI was somewhat weaker ($r = 0.86$) among children with moderate obesity, and was much weaker ($r = 0.55$) among children with severe obesity (bottom rows). Among children with severe obesity, BMIz also showed only a moderate correlation ($r = 0.54$) with levels of ΔBMIp95 and %BMIp95. Further, because of the age-related decreases in very high BMIz levels, particularly among girls (Figure 1), BMIz levels were inversely associated with age ($r = -0.33$) among children with severe obesity but not among other children.

Figure 3 shows the relation of %BMIp95 (x-axis) to levels of the other BMI metrics; the distributions of BMI, ΔBMIp95 and BMIz within each %BMIp95 category is shown as a violin plot, with the width of each figure proportional to the probability density. Mean levels of BMI (left panel) increased from 16 to 30 kg/m^2 across the 6 categories of %BMIp95, and a similar trend was see for ΔBMIp95. In contrast, the pattern for BMIz (right panel) was curvilinear, with levels showing large differences across the 3 lowest %BMIp95 categories (< 140), but much smaller differences at higher %BMIp95 levels. BMIz levels for the 5832 children in the 2 highest %BMIp95 categories (≥ 150) were, on average, lower than those among children who had a %BMIp95 of 140 to 149 as a result of the strong influence of sex and age on very high BMIz levels. Children who had a %BMIp95 ≥ 150 tended to be older (mean, 46 months) and 75% were girls, characteristics associated with greater compression of very high BMIz values,

Figure 4 shows the relation of BMI levels (x-axis) to BMIz (top) and %BMIp95 (bottom) by sex and year of age among children with severe obesity. These analyses indicated that among 3- and 4-year-olds, BMI levels mapped to substantially higher values of BMIz (but not %BMIp95) among boys than among girls. For example, as seen in the middle, upper panel, the median BMIz among 3-year-old boys who had a BMI of 24.0 to 25.9 kg/m^2 was about 1 SD higher than the corresponding value among girls, while among children with a BMI of 26.0 to 27.9 kg/m^2, the difference was 1.5 SDs. Furthermore, the decrease in the

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range of BMIz values with age among girls, as well as the lack of a sex difference among 2-year-olds, illustrate that BMIz cannot be used to standardize very high BMIs for sex and age.

These sex and age differences in the distributions of BMIz were due to differences in the L (power) and S (coefficient of variation) measures of the CDC growth charts. At 54 months of age, for example, the maximum possible BMIz is 6.5 among boys, but only 3.8 among girls, complicating the interpretation of very high BMIz levels between boys and girls. In contrast to these BMIz differences, the relation of BMI to %BMIp95 (bottom panels) and ΔBMIp95 (not shown) showed little difference between boys and girls with the exception of very high %BMIp95 values among 4-year-olds who had a BMI ≥ 28 (lower right panel). The maximum BMI in this subset of girls was 32 kg/m^2 whereas the corresponding maximum BMI among boys was 28.4 kg/m^2. Despite this difference in BMI levels, values of BMIz in this subset were substantially higher among girls than boys (top right panel).

Discussion

There is interest in the identification and treatment of children and adolescents who have high BMIs (6,7). About 6% of all 2- to 19-year-olds in the United States have severe obesity (25). Although the CDC (1) cautioned about extrapolating beyond the range of the data used to estimate the LMS measures (3rd through 97th percentiles, corresponding to z-scores of ±1.88), BMIz continues to be widely used for children who have extreme BMI values (8,26–31). Our results emphasize that BMIz is a poor BMI metric among these children, as the conversion of very high BMIs to z-scores is strongly influenced by the L and S measures in the CDC growth charts. Like the upper limit of BMI percentiles, BMIz values also have an upper limit resulting in the mapping of a wide range of very high BMIs to similar z-scores. Further, the range of these very high BMIz values varies by sex and age due to differences in the L and S measures. These differences make it very difficult to interpret the high BMIz levels (and changes in these levels) among children with severe obesity, possibly leading to incorrect conclusions.

Several of the limitations of BMIz were most evident in the plots showing the relation of %BMIp95 to the other BMI metrics (Figure 3). Despite the monotonic increases in BMI and ΔBMIp95 with levels of %BMIp95, BMIz levels were, on average, lower among children with a %BMIp95 ≥ 150 than among those with lower levels. This paradoxical result is due to sex and age differences in the attenuation of very high values of BMI-for-age. Our results indicate that for children with severe obesity, the focus should be on ΔBMIp95 or %BMIp95 rather than BMI-for-age. Further, even at very high BMIs, ΔBMIp95 and %BMIp95 values are not attenuated as are levels of BMIz.

These findings in PedNSS extend our previous findings concerning the relation of various BMI metrics to skinfolds, circumferences and fat mass among 2- to 19-year-olds (14). The previous analyses of NHANES data found that BMIz levels were less strongly associated with the other adiposity measures (skinfolds, circumferences and fat mass) than were other BMI metrics. Among children with severe obesity, we found that waist circumference showed almost no association with BMIz (r = 0.10), while correlations with %BMIp95 and ΔBMIp95 were r=0.55 and 0.63.

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Because of the LMS transformation, extreme values of BMIz can differ substantially among children who have similar levels of BMI, %BMIp95 and ΔBMIp95. For example, the median BMIz among girls who had a BMI of ≥ 28 kg/m^2 in the current study was 4.8 SDs at age 2 y, but 3.3 SDs at age 4y. This decrease in BMIz with age among these girls was seen despite age-related increases in both BMI and %BMIp95, and were due to differences in the L and S measures. Several investigators (9–11,13) have concluded that BMIz should not be used to assess changes in body size among children with obesity, and we found that BMIz differences of more than 1 SD among children with severe obesity can reflect differences in sex or age rather than differences in body size.

The attenuation and confounding of very high BMIz values could be particularly problematic in longitudinal studies that focus on children with obesity (8,26–28,32). As these children age during follow-up, the extent of the compression of very high BMIz values will vary based on the values of L and S in the growth charts. Our results indicate that it is possible that even an ineffective intervention program that focused on BMIz levels among 2-year-old girls with severe obesity would find the intervention to be effective. The converse would also be possible if the (effective) intervention followed 2-year-old boys for 1 year as the maximum possible BMIz increases during this period. Results based on changes in BMIz among children who have very high BMIs could lead to erroneous conclusions. Rather than focusing on BMIz, analyses of studies in which a large proportion of children have a BMI ≥ 97^{th} percentile should express BMI relative to the to the 95^{th} percentile in the CDC growth charts as either %BMIp95 or ΔBMIp95. This would be particularly important when assessing BMI changes among children with severe obesity.

Several limitations of our analyses should be considered. The PedNSS dataset is extremely large, but the data were not collected for research purposes and we excluded over 800,000 (of 14.4 million) records that we identified as likely having errors or were missing data. Although it is very likely that errors remained in the data used in the current analyses, they would have influenced the calculations for all the BMI metrics, not only BMIz. It should also be realized that the prevalence of obesity among children in the current study was higher (14.7%) than that observed among 2 to 5-year-olds (12.1%) examined in NHANES 2009–2010 (33). Although it is difficult to make a recommendation concerning the use of ΔBMIp95 or %BMIp95, ΔBMIp95 might be easier to interpret in many analyses as the scale is kg/m^2. However, for analyses that include a wide range of ages over which the mean BMI would differ, the same ΔBMIp95 should likely be interpreted relative to the distribution of BMI values at that age and %BMIp95 might be preferred.

Investigators have continued to use LMS-extrapolated z-scores in analyses that include a high proportion of children who have a BMI ≥ 97^{th} percentile in the CDC growth charts (8,26,32), and some have recommended (34) that ΔBMIz be used for children who have a BMI ≥ 99^{th} percentile. However, BMIz values calculated from the CDC growth charts for children who have a BMI ≥ 97^{th} percentile (z ~ 1.88) can differ substantially from the empirical estimates (6), and the magnitude of these differences increases as the BMI level becomes more extreme. The magnitude of the potential errors associated with the use of BMIz values for very high BMIs will depend upon the age distribution of the sample, the proportion of children with a BMI ≥ 97^{th} percentile, and the distance of the BMI values

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above the 97th percentile. In studies that include a large proportion of children with severe obesity, the analyses of BMIz values and changes in these values could result in incorrect conclusions. Rather than using z-scores, very high BMIs among children with severe obesity should be expressed relative to the CDC 95th percentile, either as a difference or percentage.

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Abbreviations

BMI	body mass index
CDC	Centers for Disease Control and Prevention
PedNSS	Pediatric Surveillance Nutrition Surveillance System
WIC	Women, Infants and Children

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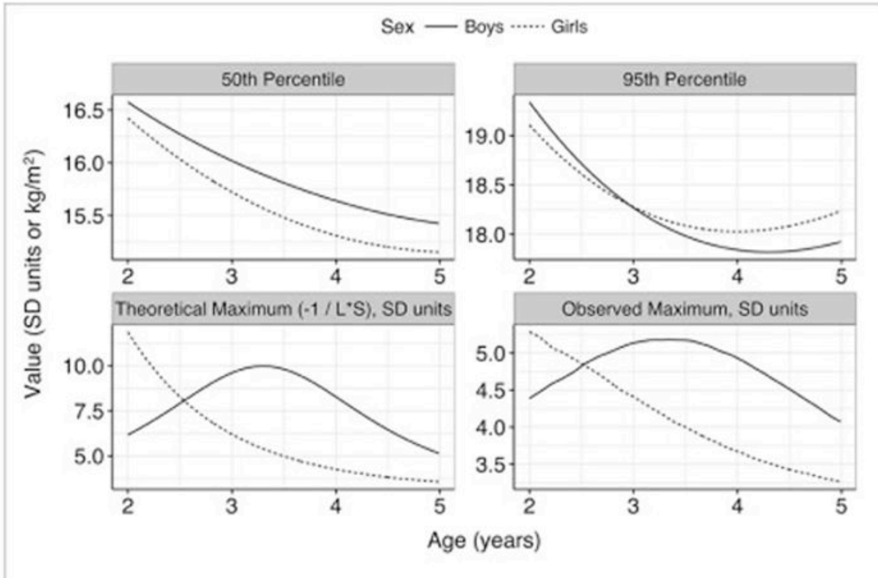

Figure 1.

Levels in the CDC growth charts of the 50th percentile, the 95th percentile, and the theoretical maximum value of BMIz. Levels of the observed maximum BMI in the current study are shown in the lower right panel. Note that the scales and range of values on the y-axes differ across the 4 characteristics.

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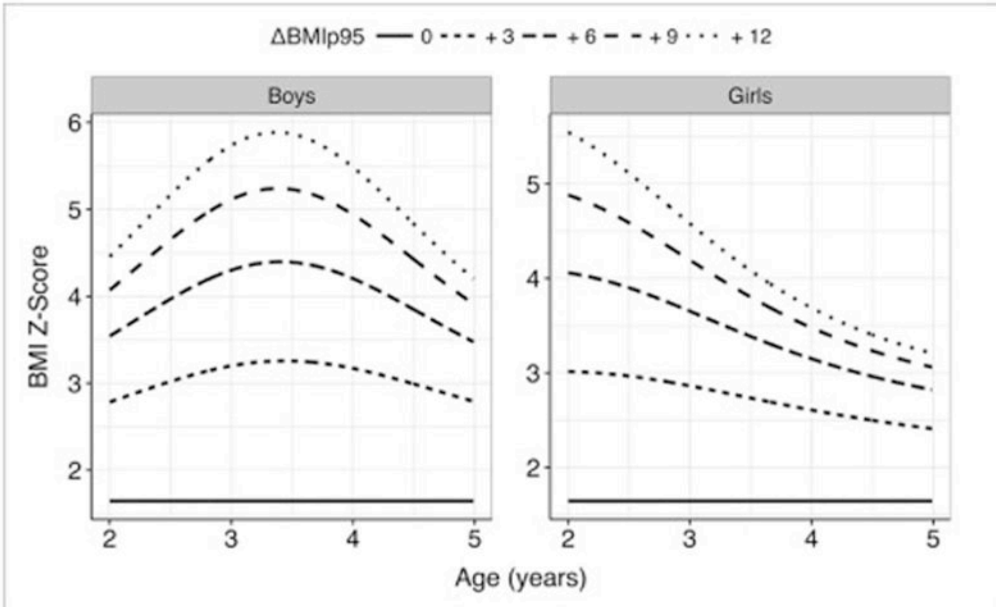

Figure 2.
BMIz values associated with various levels of ΔBMIp95 by sex and age

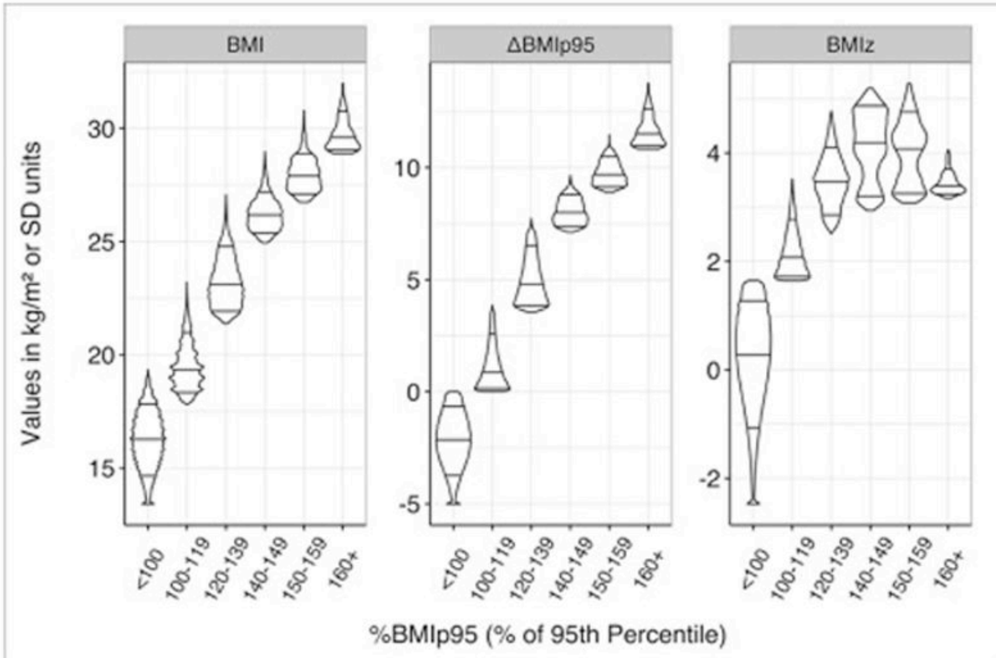

Figure 3.

Violin plots showing the distribution of levels of BMI and various transformation across categories of %BMIp95. The width of each violin is proportional to the density of the sample at that value, and the horizontal lines represent the 10^{th}, 50^{th}, and 90^{th} percentiles. Values below the 1^{st} percentile or greater than the 99^{th} percentile have been set to equal these percentiles.

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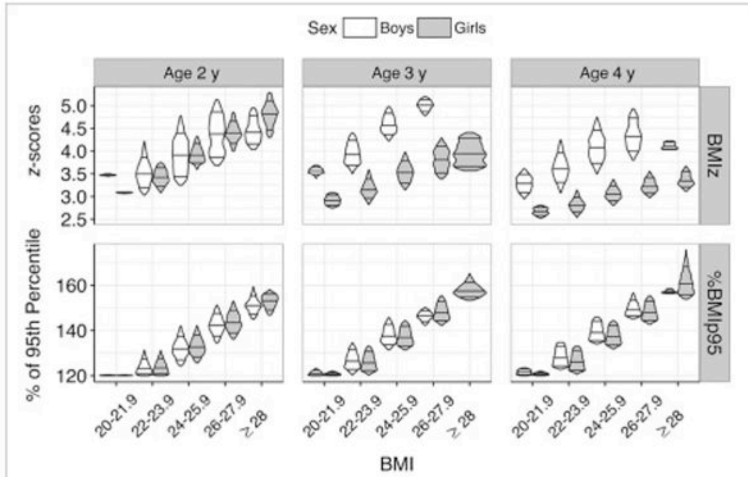

Figure 4.

Violin plots showing the distribution of levels of BMIz and %BMIp95 across categories of BMI, by sex and year of age. None of the 3-year-old boys had a BMI ≥ 28.0 kg/m^2.

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Table 1

Levels of various characteristics stratified by BMI status

	Non-obese	Moderate Obesity (%BMIp95: 100 to 119)	Severe Obesity (%BMIp95 ≥ 120)
N	7,382,740	1,115,349	156,377
Age (months)	37.0 (24, 58)[a]	37.8 (24, 58)	41.9 (25, 59)
Boys	49.7%[b]	46.7%	50.0%
Girls	50.3%	53.3%	50.0%
White	34.4%[b]	29.1%	23.6%
Black	20.1%	16.0%	13.9%
Hispanic	37.4%	47.2%	54.7%
Asian	2.7%	2.2%	2.1%
American Indian/Alaskan	0.7%	1.1%	1.1%
Unknown	4.6%	4.4%	4.6%
BMI (kg/m^2)	16.2 (13.8, 18.4)	19.5 (18.0, 21.8)	23.8 (21.7, 27.9)
BMI z-score (SDs)	0.1 (−2.1, 1.6)	2.2 (1.7, 3.1)	3.6 (2.7, 4.7)
ΔBMIp95 (kg/m^2)	−2.2 (−4.6, −0.2)	1.1 (0.0, 3.3)	5.5 (3.7, 9.6)
%BMIp95 (% of 95th percentile)	88.1 (75.1, 99.0)	106.1 (100.2, 118.1)	130.5 (120.3, 152.8)
Weight-for-age z (SDs)	0.08 (−2.14, 1.91)	1.68 (−0.2, 3.31)	3.1 (0.72, 4.75)
Height-for-age z (SDs)	0.04 (−2.27, 2.33)	0.26 (−2.45, 2.65)	0.73 (−3.83, 3.16)

[a]Values in parentheses represent the inner 95% of data

[b]Percentages are column percents

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Table 2

Intercorrelations between age and the various BMI metrics

%BMIp95 Category		Age	BMI	BMIz	ΔBMIp95	%BMIp95
< 100 (non-obese)	Age	1	−0.26	0.04	0.06	0.02
	BMI	−0.26	1	0.94	0.93	0.95
	BMIz	0.04	0.94	1	0.98	0.98
	ΔBMIp95	0.06	0.93	0.98	1	1
	%BMIp95	0.02	0.95	0.98	1	1
100 –119 (moderate obesity)	Age	1	−0.33	0	0.05	0.08
	BMI	−0.33	1	0.86	0.9	0.89
	BMIz	0	0.86	1	0.96	0.96
	ΔBMIp95	0.05	0.90	0.96	1	1
	%BMIp95	0.08	0.89	0.96	1	1
≥ 120 (severe obesity)	Age	1	−0.13	−0.33	0.07	0.13
	BMI	−0.13	1	0.55	0.97	0.95
	BMIz	−0.33	0.55	1	0.54	0.54
	ΔBMIp95	0.07	0.97	0.54	1	1
	%BMIp95	0.13	0.95	0.54	1	1