ORIGINAL ARTICLE

Simulation of Growth Trajectories of Childhood Obesity into Adulthood

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ABSTRACT

BACKGROUND

Although the current obesity epidemic has been well documented in children and adults, less is known about long-term risks of adult obesity for a given child at his or her present age and weight. We developed a simulation model to estimate the risk of adult obesity at the age of 35 years for the current population of children in the United States.

METHODS

We pooled height and weight data from five nationally representative longitudinal studies totaling 176,720 observations from 41,567 children and adults. We simulated growth trajectories across the life course and adjusted for secular trends. We created 1000 virtual populations of 1 million children through the age of 19 years that were representative of the 2016 population of the United States and projected their trajectories in height and weight up to the age of 35 years. Severe obesity was defined as a body-mass index (BMI, the weight in kilograms divided by the square of the height in meters) of 35 or higher in adults and 120% or more of the 95th percentile in children.

RESULTS

Given the current level of childhood obesity, the models predicted that a majority of today's children (57.3%; 95% uncertainly interval [UI], 55.2 to 60.0) will be obese at the age of 35 years, and roughly half of the projected prevalence will occur during childhood. Our simulations indicated that the relative risk of adult obesity increased with age and BMI, from 1.17 (95% UI, 1.09 to 1.29) for overweight 2-year-olds to 3.10 (95% UI, 2.43 to 3.65) for 19-year-olds with severe obesity. For children with severe obesity, the chance they will no longer be obese at the age of 35 years fell from 21.0% (95% UI, 7.3 to 47.3) at the age of 2 years to 6.1% (95% UI, 2.1 to 9.9) at the age of 19 years.

CONCLUSIONS

On the basis of our simulation models, childhood obesity and overweight will continue to be a major health problem in the United States. Early development of obesity predicted obesity in adulthood, especially for children who were severely obese. (Funded by the JPB Foundation and others.)

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In the United States, the prevalence of obesity has declined recently among children between the ages of 2 and 5 years and has stabilized among those between the ages of 6 and 11 years of age but continues to rise among adolescents and adults.[1,2] Although the obesity epidemic has been well characterized at a population level, less is known about the individual-level risk of adult obesity for a given child on the basis of current weight and age. Cohort studies indicate that excess weight during childhood is a predictor of future obesity,[3-13] with high correlations with body-mass index (BMI, the weight in kilograms divided by the square of the height in meters) over time.[14-16]

A number of epidemiologic cohort studies provide insight into growth trajectories, but they often do not follow children into adulthood. For example, the sample-weighted average follow-up period among 16 international cohorts was 12 years[3-13,15-18] and was only 7 years among U.S. studies.[3-10] Although obesity has health effects in children,[19-22] obesity-related death and complications generally affect adults who are 35 years of age or older.[23,24] Longitudinal data linking trajectories of childhood BMI with health risks in adulthood are needed to characterize the long-term consequences of childhood obesity more precisely.[25-27]

Although a few studies do follow children into midadulthood, such studies are necessarily based on cohorts that were initiated decades earlier.[5,16,18] Given the changes in obesity prevalence and environmental influences,[28,29] it is not clear how applicable the results of these studies are for today's children. For example, a comparison of two British cohorts born 12 years apart showed significant differences in BMI trajectories,[18] which raises questions about the use of past cohort studies to predict risks for today's youth. Although previous studies have used statistical methods to forecast the population-level prevalence of obesity in the United States,[30-34] they have not incorporated individual-level longitudinal data.

To address such concerns, we developed a method to simulate individual-level height and weight trajectories over the life course while accounting for secular trends. For this study, we simulated such trajectories from childhood until the age of 35 years, at which point the health risks of obesity are well established, in order to analyze the effect of a child's current weight on the risk of adult obesity.

Methods

Data Sources

We pooled five nationally representative U.S. data sets that contain repeated measures of individual-level height and weight: the National Longitudinal Survey of Youth, the National Longitudinal Study of Adolescent to Adult Health, the Early Childhood Longitudinal Study–Kindergarten, the Panel Study of Income Dynamics, and the Epidemiologic Follow-up Study of the National Health and Nutrition Examination Survey (NHANES). After removing participants who had fewer than 2 recorded observations, the pooled data set contained 176,720 observations from 41,567 children and adults, a mean (±SD) of 4.3±1.6 observations per person. Participants with 2 or more observations were on average younger and more likely to be female and white. (Details regarding data sources and exclusion criteria are provided in Section 1.1 in the Supplementary Appendix, available with the full text of this article at NEJM.org.)

Trajectory Simulation

Using these data, we developed a simulation model to predict growth trajectories on the basis of individual-level weight and height information. We interpolated childhood trajectories on the basis of growth curves developed by the Centers for Disease Control and Prevention (CDC) after adjustment for secular trends in weight using NHANES data from 1976 through 2014. We obtained the parameters that were used to adjust for these trends by means of a model-fitting procedure that aligned trends in our simulated BMI categories with recently observed trends, using data from the Census, the American Community Survey, the Behavioral Risk Factor Surveillance System, the National Survey of Children's Health, and NHANES. We estimated trends for four BMI categories: underweight or normal weight, overweight, moderate obesity, and severe obesity. Once these steps were completed, we used the simulation model to predict the risk of obesity. (Details regarding these steps are provided in Sections 1 through 3 in the Supplementary Appendix.)

SIMULATION PREDICTIONS

To predict the risk of obesity at the age of 35 years, we created virtual populations of 1 million children who were 19 years of age or younger using statistical matching techniques to produce nationally representative, open populations beginning in 2016, as described previously.[35,36] (In an open population, new participants are being born into the simulation model, so the population structure changes over time, whereas in a closed population, no new participants are entering the model.) We estimated the conditional probability of obesity at the age of 35 years given BMI status at each age in childhood and then calculated the associated relative risks. We also calculated the risks of future obesity at 5-year intervals for each BMI group, according to age and sex. We repeated this process with 1000 independently generated populations, each time randomly sampling a set of good-fitting parameters for secular trends.

This approach allowed us to incorporate the individual-level (first-order) uncertainty that arises from the simulation of trajectories and also to incorporate uncertainty about the parameters (second-order) that we used to adjust for secular trends.[37] Because the effect of first-order uncertainty on aggregate estimates decreases as the sample size increases, most of the uncertainty in our estimates reflects the previously described second-order issues. We report means and 95% uncertainty intervals (i.e., the 2.5 and 97.5 percentiles). We also performed sensitivity analyses for secular trends by performing 100 iterations of the model, assuming there were actually no secular trends. By not incorporating uncertainty about the various parameters into our sensitivity analysis, we could estimate the relative contribution of individual-level uncertainty to our prediction intervals.

To evaluate the convergent validity (the extent to which different models that address the same problem calculate similar results) of our approach,[38] we compared the simulated prevalence of obesity at the age of 35 years with logistic-regression predictions on the basis of NHANES data from 1999 through 2014 for persons between the ages of 34 and 36 years.

We also performed extensive cross-validation analyses in which we predicted values for participants in our data set.[39] We removed a participant from our data set one at a time and then predicted his or her height and weight over the length of the observed trajectory. We then compared our predictions with the actual values to evaluate the accuracy of our algorithm. We conducted cross-validation analyses for participants whose last age was between 34 and 36 years and calculated the coverage probability of our estimates — that is, we calculated the probability that the actual values for this cohort fell within our predicted uncertainty intervals. In addition, we ran prospective cross-validation analyses for younger cohorts starting from the age of 2 years to 29 years and calculated the number of times that our predictions fell within the bootstrapped 95% confidence intervals (Section 4 in the Supplementary Appendix).

Our model was coded in Java as part of the Childhood Obesity Intervention Cost-Effectiveness Study (CHOICES).[40,41] Statistical analyses were performed with the use of R software. BMI categories were calculated on the basis of CDC standards, with severe obesity defined as a BMI of 35 or higher for adults[42] and 120% or more of the 95th percentile for children.[43] Data and R code are available from the authors on request.

RESULTS

ACCURACY OF THE SIMULATION MODEL

Our simulated projections of BMI categories from 2010 to 2030 corresponded well to trends observed in NHANES and captured differences according to age, sex, and race or ethnic group (Fig. 1, and Section 3.4 in the Supplementary Appendix). Our simulated trajectories also showed correlations between BMI during childhood and BMI at the age of 35 years that were similar to correlations that have been shown in previous studies. Such correlations range from approximately 0.2 at the age of 2 years to 0.5 by 10 years and to more than 0.6 by 15 years. BMI correlations for periods of 5 years and 10 years ranged from approximately 0.4 at the age of 2 years to more than 0.8 by 15 years (Section 3.5 in the Supplementary Appendix). Our cross-validation analyses showed coverage estimates of 100% for predicted obesity prevalence and mean BMI values between the ages of 34 and 36 years; 94% of our obesity predictions for younger ages fell within the 95% confidence intervals of the actual values (Section 4 in the Supplementary Appendix).

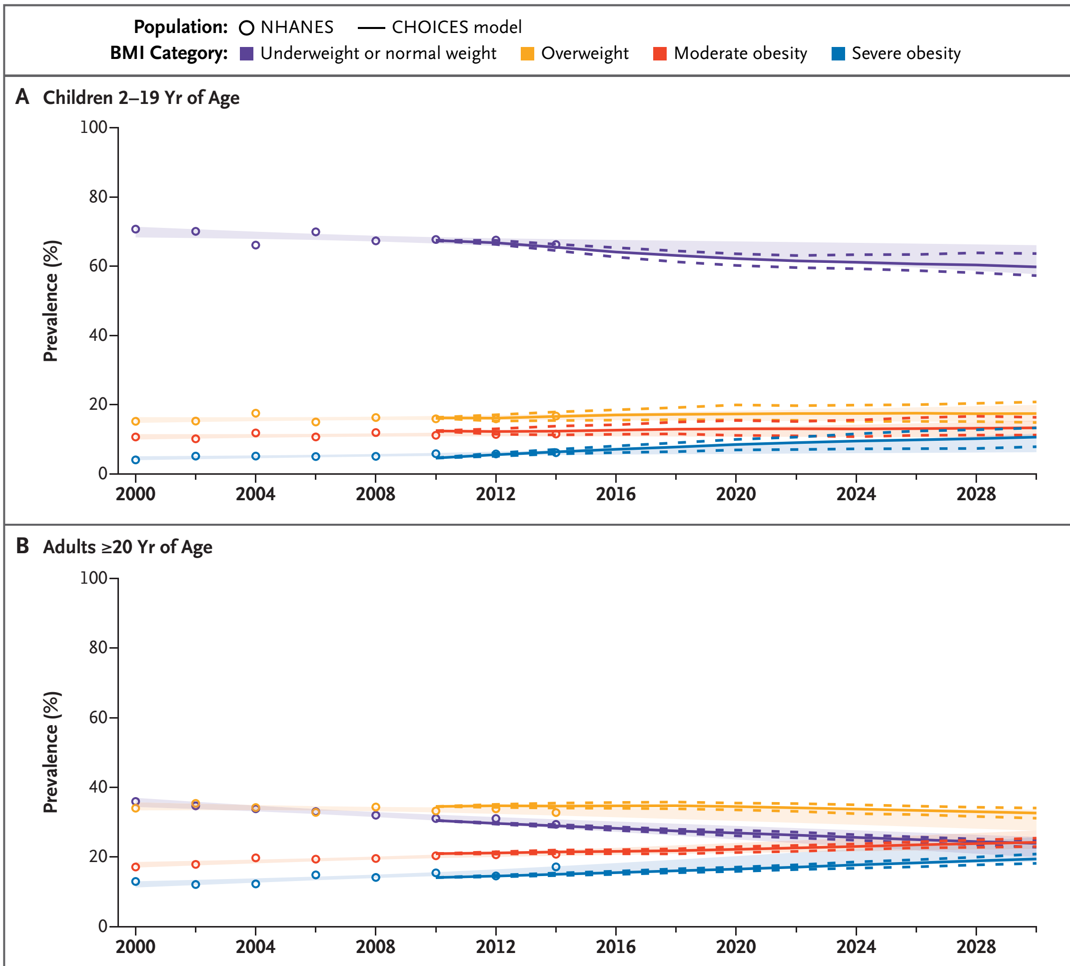

Figure 1. Predicted Prevalence of BMI Categories through 2030 for Children and Adults.

Shown is a comparison of the predicted prevalence of categories of body-mass index (BMI) from the Childhood Obesity Intervention Cost-Effectiveness Study (CHOICES) model and logistic-regression predictions that are based on data from the National Health and Nutrition Examination Survey (NHANES) from 1999 through 2014 for children between the ages of 2 and 19 years (Panel A) and adults 20 years of age or older (Panel B). The shaded areas indicate 95% uncertainty intervals for the logistic-regression predictions, and the dashed lines, ranges for simulated prevalence. BMI categories were calculated on the basis of standards of the Centers for Disease Control and Prevention (CDC), with severe obesity defined as a BMI of 35 or higher for adults and 120% or more of the 95th percentile for children.

PROJECTIONS FOR ALL CHILDREN

On the basis of current trends for BMI and obesity, our projections for children between the ages of 2 years and 19 years showed that the majority of today's youth (57.3%; 95% uncertainty interval [UI], 55.2 to 60.0) will be obese at the age of 35 years (Fig. 2A, and Section 5.1 in the Supplementary Appendix). For a cohort of current 2-year-olds, we found that the prevalence of obesity increased until adolescence, at which point it stabilized, with about half of the projected prevalence reached by this point (Fig. 2B, and Section 5.2 in the Supplementary Appendix). The prevalence then continued to increase after adolescence. Similar patterns were observed according to race or ethnic group but with significant disparities in obesity prevalence already present by the age of 2 years (Fig. 3).

PROJECTIONS ACCORDING TO OBESITY STATUS

Among obese children, we found that the probability that they will still be obese at the age of

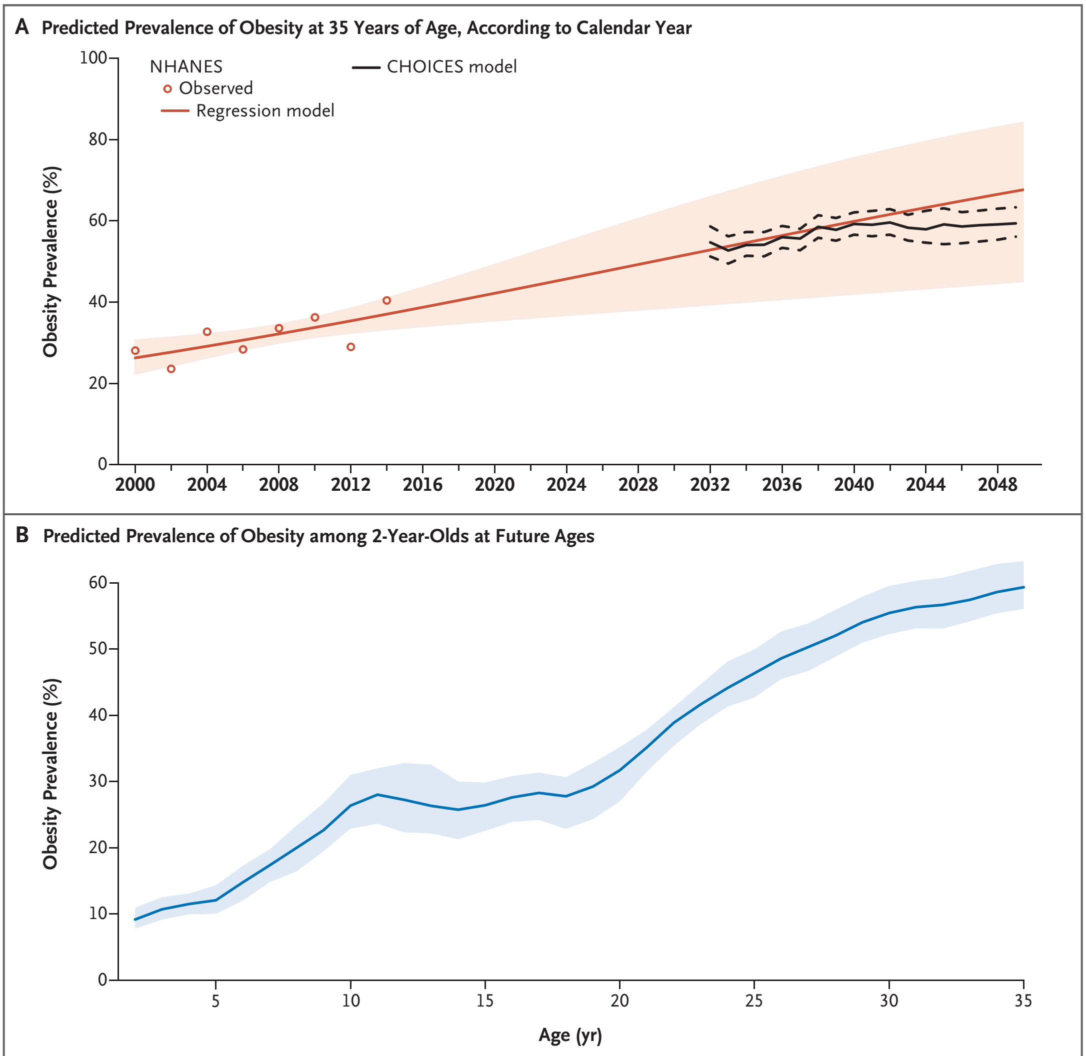

Figure 2. Predicted Prevalence of Obesity at the Age of 35 Years.

Panel A shows the predicted prevalence of obesity at the age of 35 years among today's children from the CHOICES simulation model as compared with logistic-regression predictions on the basis of NHANES data for adults between the ages of 34 and 36 years from 1999 through 2014. The 95% uncertainty intervals are indicated by a shaded area for the NHANES data and by dashed lines for the CHOICES model. Panel B shows the projected prevalence of obesity at future ages among 2-year-olds in 2016. The shaded areas indicate 95% uncertainty intervals.

35 years increased with age, from 74.9% (95% UI, 67.3 to 81.5) at 2 years of age to 88.2% (95% UI, 84.6 to 92.3) at 19 years (Fig. 4A). Among children who were not obese, the probability of obesity at the age of 35 years decreased with age, from 57.8% (95% UI, 54.5 to 62.1) at 2 years of age to 44.4% (95% UI, 40.4 to 49.7) at 19 years. The relative risks of adult obesity in obese children, as compared with children who were not obese, increased with age, from 1.30 (95% UI, 1.17 to 1.45) at 2 years of age to 1.99 (95% UI, 1.80 to 2.17) at 19 years. We found a consistent risk gradient according to BMI category at all ages (Fig. 4B); the relative risk ranged from 1.17 (95% UI, 1.09 to 1.29) for overweight 2-year-olds to 3.10 (95% UI, 2.43 to 3.65) for severely obese 19-year-olds (Section 5.3 in the Supplementary Appendix).

Although these projections indicated that obese children are likely to be obese as adults, we also found that the majority of obese 35-year-olds were not obese as children (Section 5.4 in

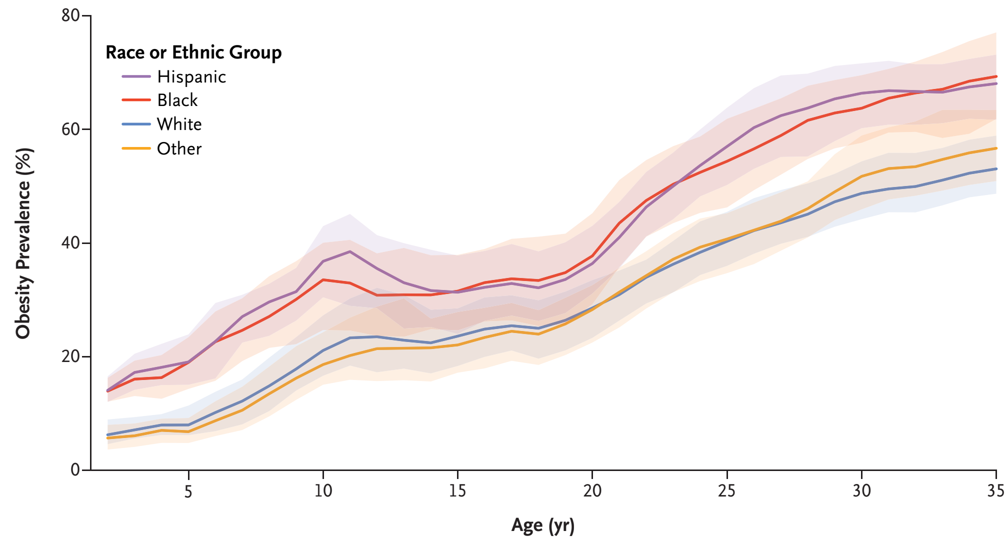

Figure 3. Predicted Prevalence of Obesity, According to Race or Ethnic Group.
Shown is the projected prevalence of obesity at future ages among 2-year-olds in 2016 from the CHOICES simulation model, according to race or ethnic group. The model shows that significant disparities are already established at very young ages. The shaded areas indicate 95% uncertainty intervals.

the Supplementary Appendix). As an indicator of adult obesity, childhood obesity had a high specificity (93.1%) but a low sensitivity (29.3%) on average (Section 5.5 in the Supplementary Appendix). However, the high prevalence of obesity in the population resulted in a higher positive predictive value (85.1%) and a lower negative predictive value (49.5%).

Severely obese children are at especially high risk for adult obesity, with the chance of not being obese at the age of 35 years ranging from 21.0% (95% UI, 7.3 to 47.3) at 2 years of age to 6.1% (95% UI, 2.1 to 9.9) at 19 years (Section 5.6 in the Supplementary Appendix); at the age of 19 years, the chance drops to 3.5% (95% UI, 0.9 to 8.5) among boys and to 8.2% (95% UI, 2.4 to 14.5) among girls. Obesity risk tables at 5-year intervals are provided for each age, sex, and BMI group in Section 6 in the Supplementary Appendix.

SENSITIVITY ANALYSES

In sensitivity analyses in which we assumed that there were no secular trends in weight gain, the predicted prevalence of obesity at the age of 35 years for today's children was 48.9% (95% UI, 48.8 to 49.1), a prevalence that was slightly lower than that in our main results (57.3%), with similar age-related trends and BMI risk gradients. Details regarding the sensitivity analyses are provided in Section 7 in the Supplementary Appendix.

DISCUSSION

Although a broad range of public health and clinical efforts appear to have stabilized early childhood obesity rates,[1] in this study we estimated that among children between the ages of 2 and 19 years in 2016, more than half (57.3%) will be obese by the age of 35 years. However, the majority of these children were not currently obese; about half of the total prevalence of obesity began in childhood, and adult-onset obesity by 35 years of age accounted for the rest.

Given the increased risk of adult obesity, it seems clear that children who are obese are prime candidates for early intervention. Children with severe obesity, a condition that now affects 4.5 million children (6%) in the United States,[1] are at particularly high risk. At 2 years of age, severely obese children have only a 1-in-5 chance of not being obese by the age of 35 years; by 5 years, that chance is halved, to 1 in 10. The persistence of elevated risk is striking: a 2-year-

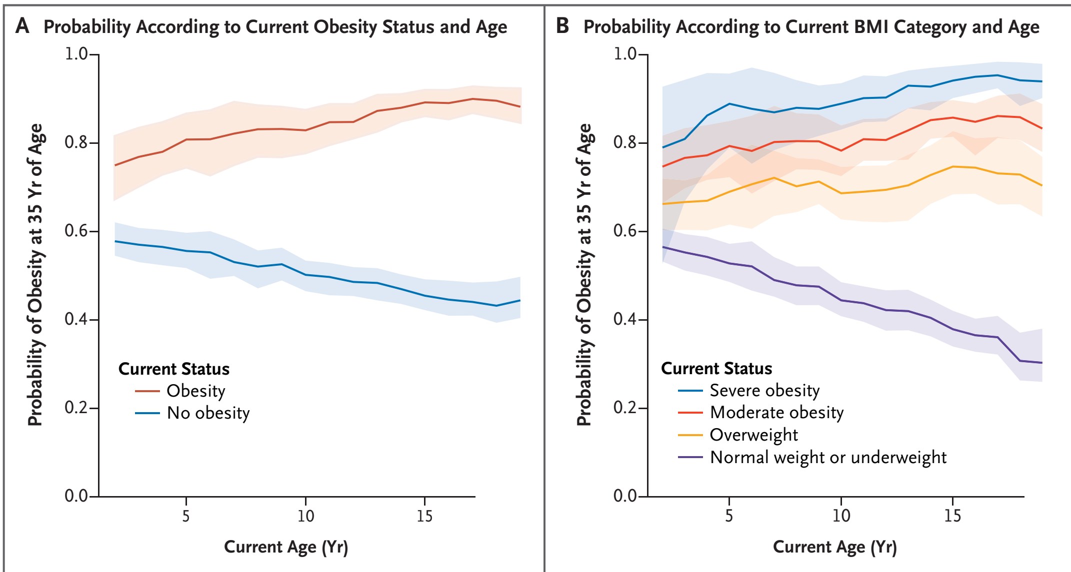

Figure 4. Predicted Probability of Obesity at the Age of 35 Years, According to Current Age, Obesity Status, and BMI Category.

Shown is the probability of obesity at the age of 35 years, according to current age and obesity status (Panel A) and BMI category (Panel B). The shaded areas indicate 95% uncertainty intervals.

old who is obese is more likely to be obese at 35 years of age than an overweight 19-year-old. Thus, our findings highlight the importance of promoting a healthy weight throughout childhood and adulthood. A narrow focus solely on preventing childhood obesity will not avert potential future health damage that may be induced by the ongoing obesity epidemic.[27] In our sensitivity analyses, even when we assumed no continuing secular trends in weight gain, we predicted that almost half of children will be obese when they are 35 years of age. There is evidence that cost-effective approaches with broad population reach could have substantial effects for the present generation of children.[40,41]

A strength of our study is that we used a rigorous approach to simulate demographic and public health surveillance data together with nationally representative growth trajectories over the life course while simultaneously adjusting for secular trends. Our approach provides estimates that were not possible with simpler methods, since it generated projections of population-level obesity consistent with current trends while maintaining individual-level heterogeneity in growth. Our cross-validation analyses have shown that our algorithm could be used to predict the prevalence of obesity at various ages with a high degree of accuracy.

Although our approach may facilitate more accurate predictions of future obesity risk for a given child than were possible in previous studies, our results generally yielded insights that were consistent with those of previous studies, such as the persistence of childhood obesity over time,[3,5-7,9] especially among severely obese children.[44] Our simulated trajectories also showed age-related correlations with respect to BMI and test characteristics (sensitivity and specificity) that were similar to those in previous studies.[3,11,14-16,26] However, our calculated relative risks of obesity were smaller than those in past studies, since we accounted for secular trends of an increasing risk of obesity in the reference group of children who were underweight or of normal weight. We also found significant disparities in the prevalence of obesity according to race or ethnic group that were already present by 2 years of age, an insight that was consistent with previous findings.[45]

Our study has certain limitations. The main assumption and potential limitation underlying our method of predicting growth patterns is that on average, persons with similar trajectories in height and weight for a given period of their lives will also grow similarly in future periods. The assumption that secular trends will continue, and the assumptions underlying our estimation of these trends, may also have influenced our results. However, in our analyses, the age-related trends in relative risk were robust to sensitivity analyses in which no secular trends were applied.

Our reference group also included children who were underweight, which is known to be problematic in the estimation of the risk of death or complications because of confounding associated with low weight.[24] However, it is unlikely that the inclusion of underweight children in our study presents similar issues for comparisons of future obesity risks, although it may underestimate the risks in our combined group of children who are underweight or of normal weight. Finally, because overweight and obesity are defined by the CDC starting at 2 years of age, we could not examine the effect of excess weight in infancy on adult obesity.

In conclusion, using simulated growth trajectories across the life course and adjusting for secular trends, we found that only those children with a current healthy weight have less than a 50% chance of becoming obese by the age of 35 years. For children with severe obesity, the risk of adult obesity is particularly high.

The views expressed in this article are those of authors and do not represent the official views of the Centers for Disease Control and Prevention or any of the other funders.

No potential conflict of interest relevant to this article was reported.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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