RESEARCH ARTICLE

Health Warnings on Sugar-Sweetened Beverages: Simulation of Impacts on Diet and Obesity Among U.S. Adults

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Introduction: Overconsumption of sugar-sweetened beverage (SSB) is a significant contributor to obesity. Policymakers have proposed requiring health warnings on SSBs to reduce SSB consumption. Randomized trials indicate that SSB warnings reduce SSB purchases, but uncertainty remains about how warnings affect population-level dietary and health outcomes.

Methods: This study developed a stochastic microsimulation model of dietary behaviors and body weight using the 2005–2014 National Health and Nutrition Examination Surveys, research on SSB health warnings, and a validated model of weight change. In 2019, the model simulated a national SSB health warning policy's impact on SSB intake, total energy intake, BMI, and obesity among U.S. adults over 5 years. Sensitivity analyses varied assumptions about: (1) how warning efficacy changes over time, (2) the magnitude of warnings' impact on SSB intake, and (3) caloric compensation.

Results: A national SSB health warning policy would reduce average SSB intake by 25.3 calories/day (95% uncertainty interval [UI]= −27.0, −23.6) and total energy intake by 31.2 calories/day (95% UI= −32.2, −30.1). These dietary changes would reduce average BMI by 0.64 kg/m^2 (95% UI= −0.67, −0.62) and obesity prevalence by 3.1 percentage points (95% UI= −3.3%, −2.8%). Obesity reductions persisted when assuming warning efficacy wanes over time and when using conservative estimates of warning impact and caloric compensation. Benefits were larger for black and Hispanic adults than for white adults, and for adults with lower SES than for those with higher SES.

Conclusions: A national SSB health warning policy could reduce adults' SSB consumption and obesity prevalence. Warnings could also narrow sociodemographic disparities in these outcomes.
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INTRODUCTION

Nearly 40% of U.S. adults have obesity.[1] A leading cause of death,[2,3] obesity increases the risk of cardiovascular disease, type 2 diabetes, and some cancers.[4,5] Overconsumption of sugar-sweetened beverages (SSBs) is a key driver of the obesity epidemic.[6–9] Average SSB consumption among U.S. adults remains well above recommended levels,[10–12] and is even higher among non-Hispanic black and Hispanic individuals[10] and those with lower educational attainment and income.[13] To reduce obesity, policymakers continue to seek strategies for addressing overconsumption of SSBs.[14]

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Implementing health warnings on harmful products is a critical tool that governments use to reduce unhealthy behaviors. For example, warnings on cigarettes are required in more than 150 countries,[15] including the U.S., and have been found to reduce smoking.[16] Increasingly, governments are also considering health warnings on foods and beverages, including SSBs. As of early 2019, 5 U.S. states have proposed policies that would require health warnings be displayed on SSB containers, vending machines selling SSBs, and at the point of purchase of unsealed SSBs.[14,17−21] Online studies find that health warnings reduce intentions to purchase SSBs[22−24] and recent experimental and quasi-experimental research indicates that warnings reduce SSB purchases by up to 22%.[25,26]

Although experimental studies provide insight into how purchases may change under SSB health warning policies, it remains unknown how these individual-level changes affect the population-level health outcomes of most interest to policymakers. These population-level impacts depend not just on warnings' effects on SSB purchases, but also on pre-policy beverage consumption, the relationship between SSB consumption and other dietary behaviors, and how dietary behaviors affect health outcomes like obesity.[27] Simulation models can integrate this information systematically to estimate a policy's impact on population health.[28] Previous studies have used simulation models to examine SSB taxes,[29−31] changes to federal nutrition assistance programs,[32,33] and city-level SSB warning policies.[27] To date, SSB warning policies have been proposed at the state and local levels, but the U.S. Food and Drug Administration has the regulatory authority to require SSB warnings nationwide.[34,35] Recent experience with other public health policies (e.g., tobacco control efforts,[36] requirements that restaurants post calorie information on menus[37]) suggests that state and local policies can spur national regulations. Thus, to inform ongoing policy debates, this study aimed to project the plausible effects of a national SSB health warning policy on U.S. adults' dietary behaviors and body weight.

METHODS

This study developed and applied a stochastic microsimulation model, representing events at the individual level (Technical Appendix, Section 1, available online).[38] Analyses assessed outcomes for 5 years. Nearly all weight loss occurs in the first 3 years after a reduction in caloric intake,[39,40] making a 5-year time horizon sufficient to capture the weight loss benefits from simulated policy changes. Table 1 describes the crucial significant input parameters (see also Technical Appendix Tables 1 and 10, available online).

Study Population

The model simulated an analytic sample of U.S. adults with varying demographic characteristics predictive of SSB intake[10,13,41−43]

(Figure 1; Technical Appendix Figure 1, available online). Each individual was assigned an age group (18−39 versus 40−65 years), sex (male versus female), race/ethnicity (non-Hispanic white, non-Hispanic black, and Hispanic/Mexican American), education (some college or lower versus college degree or higher), and income (≤185% versus >185% of the federal poverty level, the eligibility cut off for nutrition assistance programs in many states), similar to the approach used in previous studies[32] (Technical Appendix, Section 2A, available online).

The model used Monte Carlo sampling to assign baseline (pre-policy) height, weight, and SSB intake to simulated individuals, drawing from demographic-specific distributions estimated using dietary recall and anthropometric data from the National Health and Nutrition Examination Survey Cycles 2005−2014 (Technical Appendix, Section 2B and Table 2, available online). Based on previous literature[41−45] and existing U.S. policies,[46,47] analyses defined SSBs as nondiet, nonalcoholic beverages with added sugars containing ≥5 calories/100 g, including sodas, sports drinks, energy drinks, fruit drinks, and presweetened coffees and teas, but excluding 100% juice, milk-based drinks, and homemade SSBs (e.g., coffee sweetened with sugar by the consumer) that would not be subject to warnings.[17−21]

Procedures

The model represented 2 scenarios: a policy scenario assuming simulated individuals experienced a national SSB health warning policy and a status quo scenario assuming they experienced no SSB health warning policy (Technical Appendix, Section 3, available online). The policy scenario assumed that simulated individuals could change their SSB intake in response to the warnings, then represented how change in SSB consumption would affect total energy intake, and finally translated change in total energy intake into change in body weight over time using a validated model of weight change dynamics.[39] The status quo scenario assumed no change in SSB intake in response to health warnings. Both scenarios allowed SSB intake to change as individuals aged into the older category[10,43] and incorporated secular trends in total energy intake (Technical Appendix, Section 4A and 4B, available online).

The policy scenario represented how individuals would respond to an SSB health warning policy (Technical Appendix, Section 4A, available online). The primary policy scenario assumed that warnings would yield an average reduction in SSB intake of 12.7%, the most conservative (i.e., smallest) estimate of warning impact from previous experimental[22,26] and quasi-experimental[25] studies measuring the effect of SSB warnings on willingness to pay or beverage purchases among adults (assumption varied in sensitivity analyses described in the Statistical Analysis section). The model allowed for variation in individual responses to the SSB health warning policy by assigning each simulated individual a proportional change in SSB intake drawn from a triangular distribution of potential responses centered on a 12.7% reduction. The primary policy scenario assumed that change in SSB intake would be constant over time; for example, if an individual reduced their SSB intake by 10%, this one-time reduction would persist throughout the 5-year simulation period (assumption varied in sensitivity analyses). The status quo scenario assumed no change in SSB intake except from aging.

Table 1. Input Parameters and Sources

Parameter	Source(s)
Baseline characteristics	
Height and weight distributions for each demographic group	NHANES 2005−2014 cycles[75]
Distribution of usual SSB intake for each demographic group	NHANES 2005−2014 cycles[75]
Model representations of changes in diet and weight over time	
Change in SSB intake because of a health warning policy	
Primary policy scenario	
Smallest reduction (12.7%)	A previous study of effect of health warnings on willingness to pay for SSBs[22]; systematic review of price elasticity of demand for SSBs[76]
Alternative scenarios	
Smallest reduction + decreasing efficacy over time (−10%/year)	A previous study of change in cigarette warnings' efficacy over time[58]
Smallest reduction + increasing efficacy over time (+10%/year)	A previous study of change in cigarette warnings' efficacy over time[61]
Medium reduction (14.7%)	A previous study of graphic health warnings' effect on SSB purchases[25]
Largest reduction (22.4%)	A previous study of effect on SSB health warnings on SSB calories purchased[26]
Change in total energy intake because of a change in SSB intake (i.e., caloric compensation)	
Primary policy scenario	
Sample from a distribution of possible values for caloric compensation suggesting a 1.0-calorie change in SSB intake yields a 0.63- to 1.84-calorie change in total energy intake	Range of estimates from previous studies[25,48−52]
Alternative scenario	
A more conservative estimate of caloric compensation applied to all individuals (1.0-calorie change in SSB intake yields a 0.63-calorie change in total energy intake)	Previous crossover trial examining caloric compensation after supplementation with SSBs or artificially sweetened beverages[48]
Change in body weight because of a change in total energy intake	Validated equations by Hall et al. (2011)[39]
Population structure	
Population demographic distribution	American community survey public use microdata sample[55]

NHANES, National Health and Nutrition Examination Survey; SSB, sugar-sweetened beverage.

Individuals who reduce their SSB intake may replace SSB calories with calories from other sources. Previous studies suggest that a 1.0-calorie reduction in SSB intake yields a reduction in total energy intake of 0.63−1.84 calories[25,48−52]; that is, individuals may partially compensate reductions in SSB intake or may make additional dietary changes that further reduce total energy intake beyond SSB reductions. The primary policy scenario accounted for potential compensatory eating and drinking by having each simulated individual sample from a uniform distribution of values for caloric compensation (range, 0.63−1.84), following the approach used by Long et al.[53] and others[30,54] (Technical Appendix, Section 4B and Table 8, available online; assumption varied in sensitivity analyses). The model multiplied individuals' simulated change in SSB intake by their sampled compensation factor to yield a change in total energy intake in calories/day.

To translate the change in total energy intake into a change in body weight, the model applied NIH's validated model of weight change dynamics,[39] which quantifies how body weight responds to changes in net caloric intake (Technical Appendix Table 9, available online). The weight change model was run in daily time steps during the 5-year simulation period, updating each

individual's body weight daily based on their net energy intake relative to their energy needs (Technical Appendix, Section 4C, available online). Individuals' BMI (kg/m^2) and obesity status (BMI ≥30 kg/m^2) were calculated using baseline height.

Statistical Analysis

The model estimated the effect of implementing a national SSB health warning policy on 4 outcomes: SSB intake, total energy intake, BMI, and obesity prevalence. Analyses used a difference-in-differences (DD) framework, comparing the change from baseline to the end of the 5-year simulation period when the simulated population experienced the SSB health warning policy scenario to change over time when the simulated population experienced the status quo scenario (Technical Appendix, Section 5, available online). Results show policy impacts for U.S. adults aged 18−65 years at model initiation (hereafter "U.S. adults"), who were aged 23−70 years at the end of the 5-year simulation period. All analyses weighted observations based on the American Community Survey Public Use Microdata Sample[55] (Technical Appendix, Section 5, available online) to produce estimates representative of this subset of
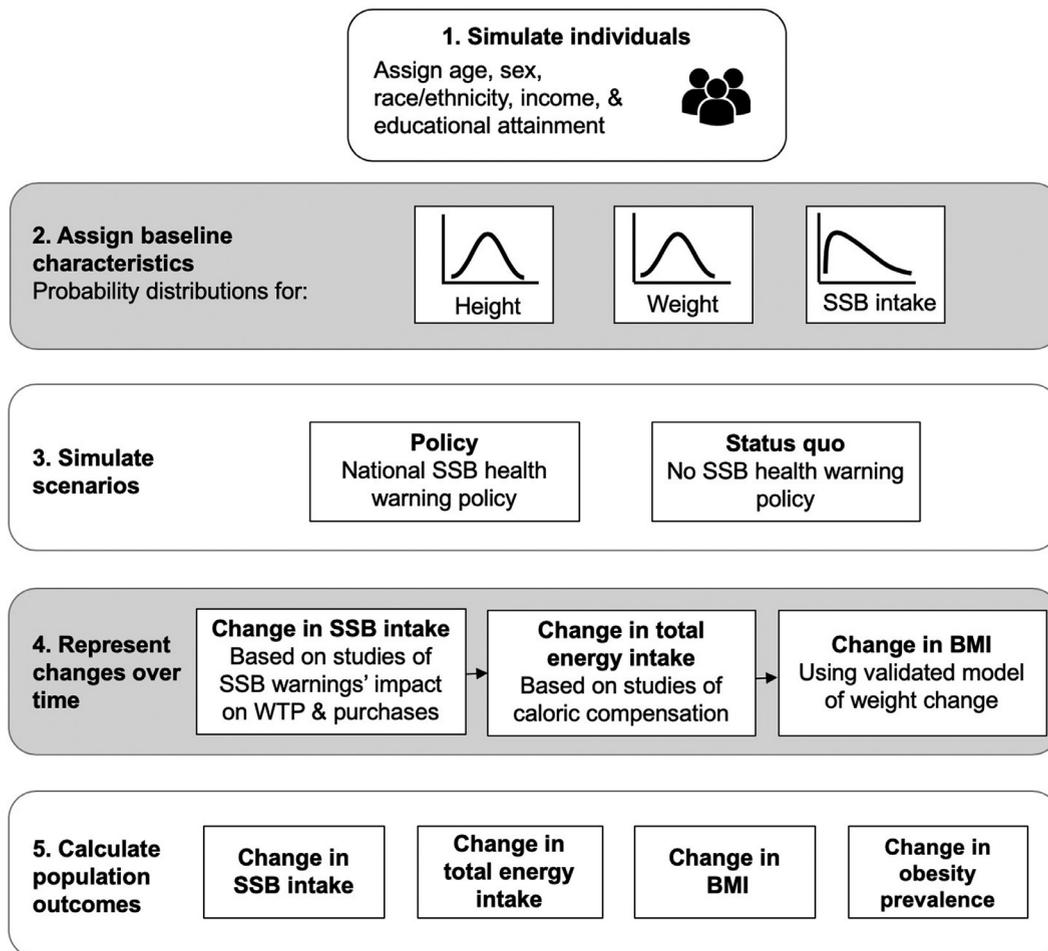
Figure 1. Simulation model overview.
SSB, sugar-sweetened beverage; WTP, willingness to pay.

U.S. adults. Analyses examined outcomes both overall and within demographic subgroups. Analyses computed differences in warning impact between demographic subgroups to explore the potential for warnings to reduce disparities.

The model used Monte Carlo sampling from predetermined distributions of model input parameters (Technical Appendix, Section 6 and Table 10, available online). Analyses calculated average impacts as the mean of the DD estimates from 10,000 repetitions[56,57] of the model and reported 95% uncertainty intervals (UIs) bounded by the 2.5th and 97.5th percentiles of the DD estimates. This study used deidentified secondary data and was exempt from review by the University of North Carolina, Chapel Hill, IRB. Analyses occurred in 2019 using Stata, SE version 15.1 (StataCorp, College Station, TX).

Sensitivity analyses examined other assumptions about 3 key model parameters: (1) the trajectory of warning efficacy over time, (2) the magnitude of warnings' impact on SSB intake, and (3) caloric compensation (Technical Appendix, Section 7, available online). First, analyses varied assumptions about how SSB health warnings' effectiveness may change over time. To date, only 1 study has examined the efficacy of SSB health warnings beyond immediate impacts, finding that graphic SSB health

warnings exerted stable effects on SSB purchases during 2 weeks.[25] The literature on tobacco warnings provides additional estimates of how warning efficacy may change over time. Some studies have reported that cigarette warnings' efficacy "wears out" (decreases) by 1.1%−4.8% per year,[58] whereas others found the opposite, that behavioral responses to cigarette warnings increase over time by as much as 20% per year.[59−61] Sensitivity analyses evaluated 2 scenarios: first, assuming the impact of warnings on SSB consumption decreases by 10% per year (about twice the maximum rate of decline observed in a prior study[58]) and second, assuming impact increases by 10% per year (about half the maximum rate of increase observed in a prior study[61]).

Second, sensitivity analyses evaluated 2 other estimates of the impact of SSB health warnings on SSB consumption. Based on a quasi-experiment of graphic SSB health warnings,[25] analyses evaluated policy impact when assuming SSB health warnings would yield a 14.8% reduction in SSB consumption. Analyses also examined outcomes when assuming that warnings produce a 22.4% reduction in SSB consumption, the impact of text health warnings on SSB purchases observed in a recent RCT.[26] Finally, analyses evaluated an alternate assumption about caloric compensation, assuming that a 1-calorie reduction in SSB intake would yield only a 0.63-calorie
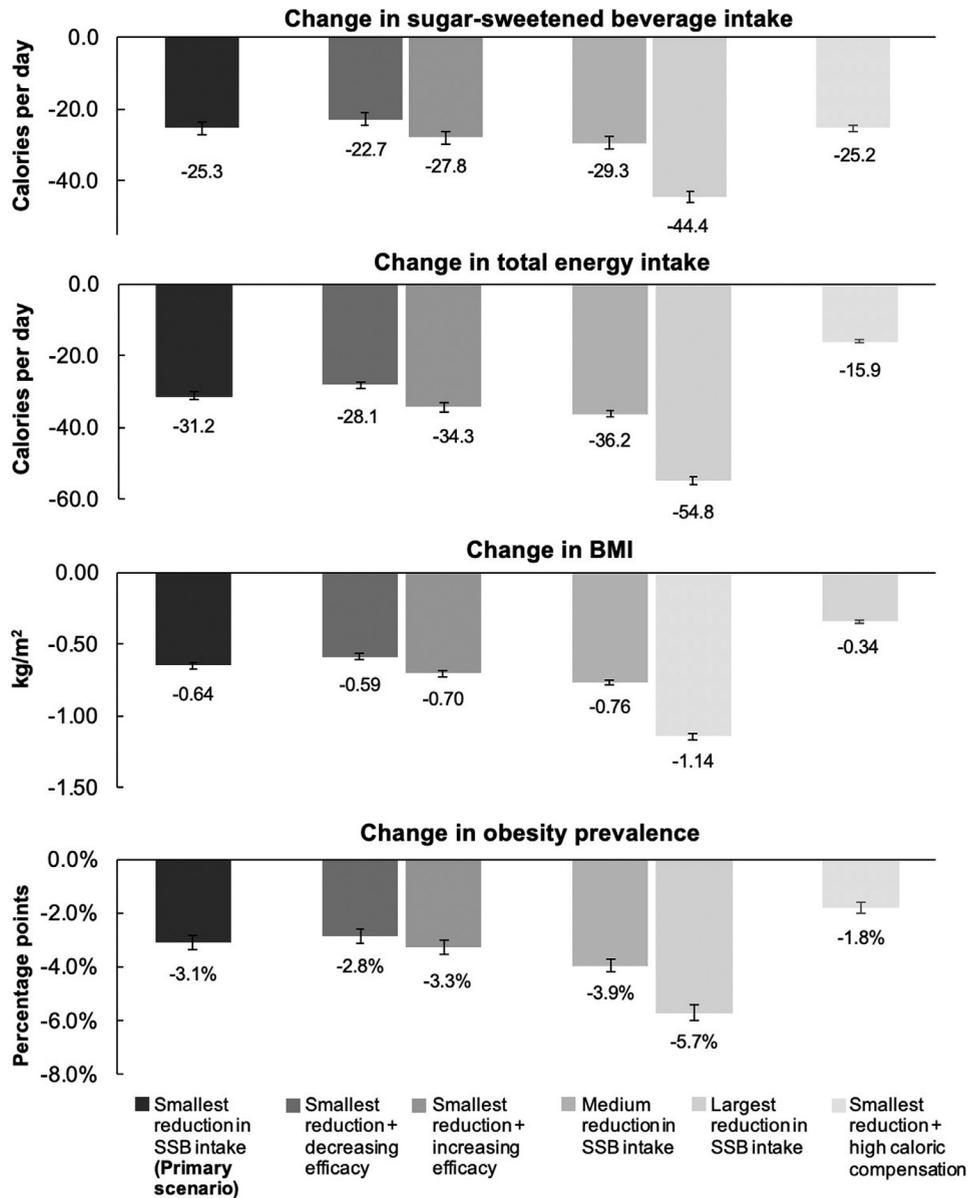
Figure 2. Estimated impacts of a national sugar-sweetened beverage (SSB) health warning policy by model assumptions, mean (95% uncertainty interval).

reduction in total energy intake, the most conservative estimate of caloric compensation (i.e., highest degree of compensation) from previous trials of SSB caloric compensation in adults.[48,50,51]

Simulated baseline average height, weight, and SSB intake accurately reflected actual population averages of these variables (Technical Appendix, Section 8 and Tables 3−5, available online). In addition, the model's simulated average changes in SSB intake and total energy intake closely matched changes in these variables expected based on input parameters (Technical Appendix, Section 8 and Tables 6 and 7, available online). The NIH weight change model has been validated previously against observed weight changes in weight loss trials.[39] Model testing analyses[62] provided additional evidence supporting the validity of the weight change model by showing that it accurately reproduced secular trends

in BMI from 2007−2014 (Technical Appendix, Section 8 and Figure 2, available online).

RESULTS

Relative to the status quo, implementing a national SSB health warning policy would reduce SSB intake over baseline consumption levels by 25.3 calories/day (95% UI= −27.0, −23.6) under primary policy scenario assumptions (Figure 2). The reduction in SSB intake would reduce total energy intake by 31.2 calories/day (95% UI= −32.2, −30.1; Figure 2). These dietary
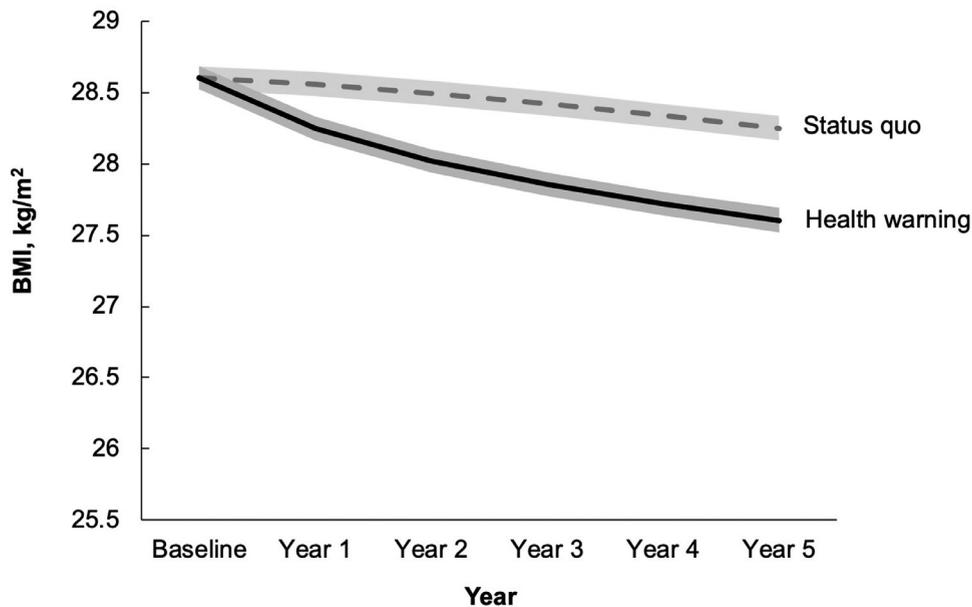
Figure 3. Impact of a national sugar-sweetened beverage health warning policy on average BMI over 5 years, primary policy scenario vs. status quo scenario (95% uncertainty interval).

changes would yield gradual reductions in BMI over time (Figure 3). At the end of the 5-year simulation period, average BMI among individuals experiencing the SSB health warning policy would be 0.64 kg/m² lower than in the status quo model (95% UI= −0.67, −0.62; Figure 2). In turn, obesity prevalence among U.S. adults (aged 23−70 years at the end of the 5-year simulation period) would be reduced by 3.1 percentage points (95% UI= −3.3%, −2.8%; Figure 2).

Reductions in SSB intake, total energy intake, BMI, and obesity were present for all demographic groups, including white, black, and Hispanic adults; younger and older adults; those with lower and higher education and income; and male and female adults (Appendix Figure 3, available online). Some groups experienced larger reductions than others (Appendix Table 11, available online). For example, black adults experienced larger reductions in obesity prevalence (−3.7 percentage points) than white adults (−2.7 percentage points; difference in reductions: 0.9 percentage points, 95% UI=0.4%, 1.5%), as did Hispanic adults compared with white adults (difference in reductions: 1.1 percentage points, 95% UI=0.6%, 1.7%). Adults with lower education showed larger reductions in obesity prevalence than adults with higher education (difference in reductions: 1.7 percentage points, 95% UI=1.2%, 2.2%). Likewise, a similar pattern was found for adults with lower versus higher income (difference in reductions: 0.9 percentage points, 95% UI=0.4%, 1.4%).

The dietary and health benefits of the SSB warning policy were robust to different assumptions about the trajectory of warnings' efficacy over time. Results were similar to the primary policy scenario when assuming warning efficacy would decrease by 10% per year, and when assuming that warning efficacy would increase by 10% per year (Figure 2).

When SSB health warnings were assumed to reduce SSB intake by 14.8%, reductions in obesity prevalence increased in magnitude (DD= −3.9 percentage points, 95% UI= −4.2%, −3.7%; Figure 2). Benefits were even greater when assuming SSB health warnings would reduce SSB consumption by 22.4% (Figure 2).

Using a more conservative assumption about caloric compensation yielded smaller reductions in total energy intake compared with the primary policy scenario (DD= −15.9 calories/day, 95% UI= −16.4, −15.4), but still yielded reductions in obesity prevalence (DD= −1.8 percentage points, 95% UI= −2.0, −1.6).

DISCUSSION

Average SSB consumption in the U.S. remains well above recommended levels.[10−12] Recent research indicates SSB health warnings would reduce SSB purchases,[22,25,26] suggesting warnings could be a promising strategy for improving population health. The current study found that implementing a national SSB health warning policy could reduce adults' SSB consumption by about 25 calories/day. This reduction in SSB intake yielded a 3.1−percentage point reduction in obesity prevalence, consistent with previous simulations showing that modest dietary changes can affect obesity.[27,29−32,53] Although this

reduction in obesity prevalence may appear modest, on a national scale, it equates to more than 5 million fewer adults with obesity.

Warnings reduced obesity prevalence in all demographic groups. Further, obesity reductions were larger for black and Hispanic adults compared with white adults, and for adults with lower educational attainment and lower-income compared to adults with higher educational attainment and higher income. These larger obesity reductions reflect the persistently higher levels of SSB intake and obesity among racial/ethnic minorities and those with lower SES.[13,63] These results suggest that SSB health warnings could help narrow these disparities.

Results were robust to a range of assumptions tested in sensitivity analyses. Assuming that SSB health warnings will become 10% less effective per year had minimal effect on results compared with assuming constant efficacy over time. This finding reflects the dynamics of weight change and the limited time horizon of the model: because much of expected weight loss occurs in the first year after reducing caloric intake,[39] substantial weight loss is achieved before warning efficacy begins to wane.

Of the parameters varied in sensitivity analyses, changing assumptions about SSB health warnings' impact on SSB consumption had the largest effect on projected dietary and health outcomes. Compared with the primary policy scenario, which assumed the most conservative reduction, using the largest estimate of warnings' impact on SSB consumption nearly doubled the obesity reduction benefits of implementing a national SSB health warning policy. These findings highlight the importance of designing SSB warnings to maximize behavioral impact. Previous research suggests this goal may be accomplished by using pictorial warnings,[16,24,25,64] making warnings larger and more prominent,[65,66] or presenting warnings on black[67] or red[68] labels.

Two key strengths of this study are that it used detailed, nationally representative dietary and anthropometric data to establish characteristics of the simulated population and that it applied a validated model of weight change. This study also evaluated a range of sensitivity analyses to account for uncertainty about key parameters.

Limitations

This study also had several limitations. First, like all models, this microsimulation was a simplification of reality and did not reflect all possible factors affecting diet and obesity. Second, this study conducted one-way sensitivity analyses, and future studies should explore interactions between different assumptions about critical parameters. Third, because no studies to date have estimated SSB health warnings' impact on SSB consumption, the model used estimates of impact on willingness to pay or purchases as proxies for impact on consumption. In addition, the model assumed that SSB health warnings would exert the same proportional effect on SSB consumption for all demographic groups. Previous studies of SSB[22,23,26,68] and cigarette warnings[16] have generally not found differences in warning efficacy by key demographic characteristics, but sociodemographics may moderate SSB warnings' impact on behavior in ways not reflected in the model, causing overestimation or underestimation of warnings' benefits.

The model's scope was constrained by lack of data on warnings' impacts on social norms, reformulation, and interactions with other policies. SSB warnings could strengthen norms about limiting SSB consumption, which might amplify warnings' impacts,[69−71] but the model did not examine this possibility. The model also did not incorporate the possibility that manufacturers will reformulate products in response to warning policies, for example, by lowering SSBs' calorie content to avoid triggering a warning, thereby providing healthier options for consumers.[72−74] These assumptions could cause analyses to underestimate warnings' benefits. In addition, the model assumed no other policy changes, though SSB warnings could be implemented in tandem with other policies, such as SSB taxes. As more data on norms, reformulation, and other policies become available, future studies can incorporate this information.

CONCLUSIONS

Average SSB consumption in the U.S. remains high,[10−12] increasing the risks for obesity and weight-related chronic diseases. This microsimulation study provides timely evidence that implementing a national SSB health warning policy could yield meaningful reductions in obesity prevalence.

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This study used deidentified secondary data and was exempt from review by the IRB.

Author contributions: AHG conceptualized and designed the study, developed and validated the microsimulation model, applied the model to compute results, drafted the initial manuscript, and oversaw all aspects of the study. NSR provided essential input on model development and validation. SDG, LF, and LST provided critical input on developing and validating the model and interpreting results. NTB provided expert guidance on study conceptualization, interpreting results, and writing and data visualization. All authors provided critical feedback on manuscript drafts and approved the final manuscript.

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SUPPLEMENTAL MATERIAL

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