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Complete List of Authors:	Yoon, Seok-Jun; Korea University, Department of Preventive Medicine, Korea University College of Medicine Jung, Yoon-Sun; Korea University, Department of Public Health, Graduate School, Korea University Kim, Young-Eun ; Korea University, Department of Preventive Medicine, Korea University College of Medicine Go, Dun-Sol; Korea University, Department of Preventive Medicine, Korea University College of Medicine
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Title: Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

Authors: Yoon-Sun Jung [a*], Young-Eun Kim[b], Dun-Sol Go[b], Seok-Jun Yoon[b]

Affiliations:

[a]Department of Public Health, Korea University, Seoul, Korea

[b]Department of Preventive Medicine, Korea University College of Medicine, Seoul, Korea

Address for Correspondence:

Seok-Jun Yoon, M.D., Ph.D.

Department of Preventive Medicine, Korea University College of Medicine,

73 Goryeodae-ro, Seongbuk-gu, Seoul, 02841, Korea

E-mail: yoonsj02@korea.ac.kr

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E-mail addresses:

sunnyaurora@nate.com (Yoon-Sun Jung)

kimyes4454@gmail.com (Young-Eun Kim)

kds237@gmail.com (Dun-Sol Go)

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ABSTRACT

Objective To project the future prevalence of obesity among populations 19 years and older by 2040 in South Korea

Design, setting, and participants Using the 'Population Health Model-Body Mass Index' (BMI) microsimulation model, the prevalence of obesity in Korean adults 19 years and over was projected until the year 2040. The model integrates individual survey data from the Korea Health Panel Survey of 2011 and 2012, population statistics based on resident registration, population projections, and complete life tables categorized by sex and age. Birth rate, life expectancy, and international migration were based on a medium growth scenario. The base population of Korean adults in 2012, devised through data aggregation, was 39,842,730. Prediction equations were formulated using BMI as the dependent variable; the individual's sex, age, smoking status, physical activity, and the preceding year's BMI were used as predictive factors.

Outcome measure BMI categorized by sex.

Results The average BMI for Korean adults in 2040 was forecast to be 23.47 kg/m^2 (23.91 and 23.04 kg/m^2 for men and women, respectively). According the Korean BMI classification, 70.05% of all adults were forecast to be 'pre-obese' (i.e., have BMIs 23 to 24.9) by 2040 (81.23% of men and 59.07% of women), followed by 25.45% who would be 'underweight or normal'.

Conclusions Public health interventions need to be established so that the current average BMI, smoking rate, and physical activity rate among Korean adults can be improved.

Strengths and limitations of this study

- This study is the first in South Korea to analyze individual and national data using microsimulation to predict the prevalence of obesity among adults.
- We estimated the proportions of adults who will fall into various BMI categories by the year 2040 assuming that the average BMI, smoking rate, and physical activity rates measured in 2012 retain the same trend.
- Our predictive model did not take into account nation-specific factors as applicable to Korea.

BACKGROUND

The prevalence of overweight and obesity has increased markedly over the past 3 decades, and concerns about health risks associated with obesity have become almost universal.[1] The increasing rate of obesity is a growing public health concern not only in Western countries but also in South Korea.[2] From the 1990s through the beginning of the new millennium, the prevalence of adult and child obesity has increased rapidly and continues to rise steadily in parallel with rapid social and economic development.[3]

Obesity is not only a major public health problem in and of itself, but also a factor in the development of many chronic diseases; hence, it constitutes a strain on individuals and health systems worldwide. In the Global Burden of Disease Study,[4] globally in 2017, a high body mass index (BMI) accounted for 4.72 million deaths and 148.0 million disability-adjusted life-years. It is associated with an increased risk of many disorders, including diabetes, hypertension, dyslipidemia, heart disease, stroke, sleep apnea, early death, and cancer.[5-9] Moreover, obesity among older people increases the risk of knee osteoarthritis[10] and reduces functional capacity and quality of life.[11-14] The prevalence of these conditions rises commensurate with increased obesity, [15-18] and are associated with significant morbidity, higher risks of mortality, and increased economic costs for both individuals and the society at large.[19]

A study of data from the National Health Insurance Service in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US dollars; medical expenses accounted for 51.3% of this amount, followed by decreasing productivity (20.5%), productivity loss (13.1%), early mortality (10.0%), care costs (4.3%), and transportation costs (0.8%).[20] Several studies on the long-term trends of obesity prevalence in South Korea found that obesity is increasing in men but not in women.[21-23] Although numerous investigators in other countries have attempted to predict the prevalence of obesity into the future, only one such study by Inkyung Baik was recently performed in South Korea.[2] More recent trends still need to be investigated through predictive studies, and the accurate prediction of obesity prevalence remains an important public health-related goal in the country.

To efficiently establish and execute an effective healthcare policy, which would require a large budget, it is necessary to select future targets for policy interventions (such as high-risk groups) to predict future healthcare needs and prevent budget waste.

Past prediction models incorporated a country's entire population; as such, macroscopic inferences based on average projections for the future society were generalized. However, when establishing a healthcare policy, it is necessary to estimate the future disease burden and medical needs of the entire population based on future projections that reflect individual characteristics, because a real-world understanding of the factors that are influenced by the policies or institutions is required. Individuals are independent entities with different characteristics and needs that govern their future decisions and behaviors. By applying these needs to the healthcare sector, health-related projections can be modeled by reflecting health risk factors such as sex, age, life cycle activities, smoking, etc.; as such, the effects of policy interventions can be quantified.[24] In this study, we aimed to predict the prevalence of obesity in Korea by using microsimulation, which is optimal for considering individual properties.

Microsimulation is a modeling technique that typically uses individual microunits, each with its own set of properties, to simulate downstream events based on the probability of transition between predefined states and their changes over time. When used in medicine, microsimulation can be particularly powerful because it preserves the patterns of previous behaviors and conditions, and allows for a clearer representation and understanding of how various processes affect the total outcome of the population over time. Collecting individual events from within a population that has varying attributes can be used to predict and plan outcomes (such as incidence, prevalence, and cost), and can also be used to assess the clinical and cost effectiveness of alternative health interventions.[25] Microsimulation modeling is particularly useful for studying BMI trends because it can simultaneously explain population dynamics such as aging, migration, and mortality. Additionally, the longitudinal framework of these models allows for interpreting a person's change in BMI as it is affected by factors such as a person's physical activity and behavior and thus act as a contributing factor to other diseases, [26]

Obesity prevalence and trend estimates provide important information for research, policy, and intervention.[27] As mentioned above, it is necessary to estimate the magnitude of obesity because it has been identified as a risk factor for various chronic diseases. Because health forecasting predicts disease episodes and portends future events, it facilitates healthcare strategies by promoting the setting of goals to reduce obesity, establish health promotion interventions, and optimize resource allocation.[28] Obesity trends may also be used to urge governments to implement preventative approaches to reducing obesity.[29] Based on the above, we performed this study to project the future trends in obesity prevalence in South Korea up to the year 2040.

METHODS

Model

We used the Population Health Model (POHEM)-BMI to estimate the prevalence of obesity in adults 19 years and over in South Korea from 2012 through 2040. In brief, POHEM is a time-continuous, population-based, dynamic microsimulation model with individual underlying units of analysis. Through dynamic simulation, POHEM creates a population and ages it, one person at a time, until death.[30] The model dynamically simulates an individual's disease state, risk factors, and health determinants to describe and plan health outcomes.[31] The POHEM models include cardiovascular disease, various cancers, osteoarthritis, physical activity, and neurological events. The model used in this study was the POHEM-BMI; the performance of each prediction step is shown in Figure 1.

[Insert Figure 1 here]

Base population

To create the base population for the POHEM-BMI model, we used the 2011- 2012 Korea Health Panel survey and the resident registration-based population statistics. This constituted the base population for POHEM-BMI (n=39,842,730), reflecting the Korean population. Each Korean respondent 19 years of age and over (n=11,501) in 2012 was replicated using their survey-recorded weights to generate a simulated cohort of approximately 39,842,730 individuals. Korea Health Panel survey data are nationally representative panel surveys that incorporate health status, chronic diseases, health risk behaviors, and socio-demographic characteristics. Among them, we extracted sex, age, current smoking status, physical activity, and the previous and current years' BMI values; these variables were required for the predictive equation. We then used a multiple linear regression model to estimate the BMI value using the independent variables age, sex, smoking status, physical activity, and previous BMI value as predictors. The POHEM-BMI model is auto-regressive and includes previous BMI values as a main explanatory variable.[26] For comparison with other international studies using this model, we used the variables as-is without normalizing them to Korean standards. In terms of predictor definitions, a current smoker was an individual who reported smoking 'every day' or 'sometimes'. Practicing physical activity was defined as performing either intense physical activity for at least 10 continuous minutes a day, 20 minutes total per day, 3 days a week during the preceding week, or moderate physical activity for at least 30 minutes a day, 5 days a week during the preceding week.

Simulation: Annual updates and risk transition

The population makeup was updated by aging each person by 1 year and changing the total population size based on population statistics, population projections, and complete life tables categorized by sex and age from Statistics Korea. For population projections, we assumed a medium growth scenario in terms of birth rate, life expectancy, and international migration. Each person's BMI was updated annually by applying a predictive equation that incorporates his/her own characteristics. The transition probability for each stochastic characteristic was calculated based on a generalized linear model.

Similar to the original POHEM-BMI, we assumed that the current individual behavioral patterns persisted, and no new factors arose to prevent obesity. We also assumed that the attributes of 19-year-old individuals, which were entered annually, remained similar year-to-year.

Model validation and calibration

We established the model's validity by comparing the projected BMI average obtained from the prediction model to estimates obtained from the Korea Health Panel survey. We set the calibration cutoff point to 5% and adjusted the model by comparing the difference between the mean BMI estimates observed from the Korea Health Panel survey and the values derived from the prediction model categorized by sex and age. We analyzed the BMIs of each group by comparing the 2016 data available from the Korea Health Panel with the most recent data. We accepted a difference of less than 5% overall as well as in the sex- and age-categorized groups. Finally, we adjusted the demographics of the 2040 population so that the predictions were similar within a 5% margin of error.

Projection

The model projected the BMI of each person from 2017 to 2040. Based on demographic characteristics, the projections were then aggregated by year for each of the predefined subgroups. The various trends observed in the Korean population data were used to generate algorithms that were applied to future projections.

Model outputs

The final results of the BMI distributions were calculated overall and by sex. Individuals with a BMI ≥25 kg/m^2 were obese according to the Guidelines for the Management of Obesity in Korean, which is not the internationally accepted standard (see Table 1). According to this guideline, BMI is categorized into standard groupings for underweight (<18.5 kg/m^2), normal weight (18.5–22.9 kg/m^2), pre-obese (23–24.9 kg/m^2), obese class Ⅰ (25–29.9 kg/m^2), obese class Ⅱ (30–34.9 kg/m^2), and obese class Ⅲ (≥35 kg/m^2). All analyses in this study were performed using STATA version 13 (StataCorp LLC, College Station, TX, USA).

Table 1 BMI classification of South Korea

Classification	**Body mass index (kg/m^2)**
Underweight	< 18.5
Normal	18.5 – 22.9
Pre-obese	23 – 24.9
Obese class Ⅰ	25 – 29.9
Obese class Ⅱ	30 – 34.9
Obese class Ⅲ	≥ 35

RESULTS

We compared the total numbers of the individuals and characteristics in the initial 2012 population to those in the projected 2040 population (see Table 2) There were 39,842,730 adults who were 19 or over in 2012 and 43,818,808 in 2040. The male:female ratio was nearly 1:1 in both 2012 and 2040. The rapid aging of the Korean population was clearly observed when comparing the 2 eras. The average age of adults was expected to increase by 10.9 years from 45.69 years in 2012 to 56.59 years in 2040 (from 44.57 to 55.54 years among men and from 46.77 to 57.63 years among women). In 2012, the proportion of young people (those in the 19–24, 25–29, 30–34, 35–39, 40–44, 45–49, and 50–54 year age groups combined) accounted for approximately 71% of the adult population (with approximately 10% in each aforementioned age group), while the proportion of individuals aged 65 years and older was relatively low at approximately 14% and that of individuals 80 years of age and older at 2.6%. However, the age group structure in South Korea 28 years later (2040) is predicted to be quite different, as the proportion of the elderly population (≥80 years) was estimated to be almost 12% of the total adult population, while the proportion of individuals 19–64 years (i.e., the working age population) was only 60.95% of the adult population.

There was no significant difference between the average BMIs in 2012 and 2040; however, according to the BMI classification in South Korea, approximately 50% of the adult population was ‘underweight or normal’ in 2012, whereas only 25.45% of the population was predicted to be the same in 2040. On the other hand, the ‘pre-obese’ group was expected to account for approximately 70% of the total adult population.

Table 2 Comparison of number of people, by sex and BMI classification, South Korea, 2012 and 2040

	Men		**Women**		**Total**	
Population at baseline (2012)						
Number of people	19,709,628		20,133,102		39,842,730	
Age (mean)	44.57		46.77		45.69	
19-24	2,094,471	(10.63)	1,873,563	(9.31)	3,968,034	(9.96)
25-29	1,748,148	(8.87)	1,642,257	(8.16)	3,390,405	(8.51)
30-34	2,047,849	(10.39)	1,962,314	(9.75)	4,010,163	(10.06)

35-39	2,095,269	(10.63)	2,027,690	(10.07)	4,122,959	(10.35)
40-44	2,316,943	(11.76)	2,248,910	(11.17)	4,565,853	(11.46)
45-49	2,120,987	(10.76)	2,026,584	(10.07)	4,147,571	(10.41)
50-54	2,160,552	(10.96)	2,128,759	(10.57)	4,289,311	(10.77)
55-59	1,616,103	(8.20)	1,631,900	(8.11)	3,248,003	(8.15)
60-64	1,145,904	(5.81)	1,194,718	(5.93)	2,340,622	(5.87)
65-69	879,627	(4.46)	997,490	(4.95)	1,877,117	(4.71)
70-74	737,954	(3.74)	954,289	(4.74)	1,692,243	(4.25)
75-79	445,317	(2.26)	707,930	(3.52)	1,153,247	(2.89)
80-	300,504	(1.52)	736,698	(3.66)	1,037,202	(2.60)
BMI (mean)	23.60		22.48		23.03	
Number of people by BMI classification						
Underweight / Normal	8,254,562	(41.88)	11,482,066	(57.03)	19,736,628	(49.54)
Pre-obese	5,264,866	(26.71)	4,207,673	(20.90)	9,472,539	(23.77)
Obese class Ⅰ	5,867,369	(29.77)	4,046,607	(20.10)	9,913,976	(24.88)
Obese class Ⅱ	318,297	(1.61)	324,205	(1.61)	642,502	(1.61)
Obese class Ⅲ	4,534	(0.02)	72,551	(0.36)	77,085	(0.19)
Smoking status						
Smoker	8,879,037	(45.05)	450,946	(2.24)	9,329,983	(23.42)
Non-smoker	10,830,591	(54.95)	19,682,156	(97.76)	30,512,747	(76.58)
Physical activity						
Physical activity	5,199,273	(26.38)	3,103,036	(15.41)	8,302,309	(20.84)
Physical inactivity	14,510,355	(73.62)	17,030,066	(84.59)	31,540,421	(79.16)
Projected population (2040)						
Number of people	21,717,128		22,101,680		43,818,808	
Age (mean)	55.54		57.63		56.59	
19-24	1,249,921	(5.76)	1,189,386	(5.38)	2,439,307	(5.57)
25-29	1,165,520	(5.37)	1,106,562	(5.01)	2,272,082	(5.19)
30-34	1,160,786	(5.35)	1,091,788	(4.94)	2,252,574	(5.14)
35-39	1,297,513	(5.97)	1,201,131	(5.43)	2,498,644	(5.70)
40-44	1,696,199	(7.81)	1,552,548	(7.02)	3,248,747	(7.41)
45-49	1,838,461	(8.47)	1,632,766	(7.39)	3,471,227	(7.92)
50-54	1,599,077	(7.36)	1,475,843	(6.68)	3,074,920	(7.02)
55-59	1,882,322	(8.67)	1,821,485	(8.24)	3,703,807	(8.45)
60-64	1,880,827	(8.66)	1,866,992	(8.45)	3,747,819	(8.55)
65-69	2,078,232	(9.57)	2,101,456	(9.51)	4,179,688	(9.54)
70-74	1,956,454	(9.01)	2,055,954	(9.30)	4,012,408	(9.16)
75-79	1,739,807	(8.01)	1,919,444	(8.68)	3,659,251	(8.35)
80-	2,172,009	(10.00)	3,086,325	(13.96)	5,258,334	(12.00)
BMI (mean)	23.91		23.04		23.47	
Number of people by BMI classification						
Underweight / Normal	2,327,521	(10.72)	8,823,981	(39.92)	11,151,502	(25.45)

Pre-obese	17,641,668	(81.23)	13,055,482	(59.07)	30,697,150	(70.05)
Obese class Ⅰ	1,712,332	(7.88)	221,829	(1.00)	1,934,161	(4.41)
Obese class Ⅱ	33,455	(0.15)	388	(0.00)	33,843	(0.08)
Obese class Ⅲ	2,152	(0.01)	0	(0.00)	2,152	(0.00)

The model was well calibrated in both the initial population and from 2017 to 2040. Differences in each of the variables estimated between 2013 to 2016, which were derived from the Korea Health Panel data, were within the 5% range only when using the predictive model. Additionally, when compared to the population structure for 2040 (the final year) as predicted by Statistics Korea, the total population and gender and age-specific ratio were similar.

Figure 2 shows the average predicted BMIs between 2017 and 2040. Each average BMI value from 2013 to 2016 was estimated from the Korea Health Panel survey. The average BMI for the entire adult population is predicted to increase very slightly from 23.19 kg/m^2 in 2017 to 23.46 kg/m^2 in 2036 and is expected to remain steady thereafter. The predicted mean BMI trends are similar for men and women; the mean BMI in adult men was projected to increase only slightly, from 23.72 kg/m^2 in 2017 to 23.91 kg/m^2 in 2036 (from 22.67 kg/m^2 in 2017 to 23.01 in 2036 kg/m^2 for adult women) and then almost plateau thereafter.

[Insert Figure 2 here]

The BMI distributions for men and women from 2012 to 2040 are shown in Figure 3. The proportions of 'pre-obese' individuals in both sexes are predicted to increase dramatically over time, while the proportions of individuals who are classified as 'underweight or normal' and 'obese' will gradually decrease. As of 2025, 52.35% of all male adults were expected to be pre-obese, with that proportion expected to be close to 81.23% by 2040. Moreover, 53.24% of all adult women are expected to be 'pre-obese' by 2035, with the proportion rising to almost 59.078% by 2040.

[Insert Figure 3A and 3B here]

DISCUSSION

The purpose of this study was to predict the prevalence of obesity in South Korea in the year 2040 using a microsimulation model. In the field of healthcare, microsimulation can predict the burden of disease by modeling various health risk factors that occur during an individual's lifetime. Given macro-effects such as changes in population structures in the forecasting model, microsimulation is very useful in that it can estimate both disease burdens and medical needs across the country.[24] While microsimulation models have been steadily evolving across health- and economy-related fields in many European countries,[32] they have yet to be actively utilized in South Korea (especially for healthcare). In this study, we strove to predict future adult obesity rates in South Korea using the POHEM-BMI, which is developed by Statistics Canada. POHEM is one of several population-based health dynamic microsimulation models used worldwide. Dynamic microsimulation, in the context of social science and population health, is a simulation of individuals (i.e., micro-level) and their behaviors, statuses, and actions (dynamics) over time.[33] These are modeled as desired using multiple sources of empirical data, including cross-sectional surveys, administrative databases, vital statistics, and census data.[31]

Summarizing the predicted results, the average BMI of South Korea's adult population aged 19 years and older was expected to be 23.47 in 2040, while the percentage of 'pre-obese' individuals was expected to increase over time. While it is encouraging that the proportion of 'obese' people (i.e., those with BMIs ≥25 kg/m^2) in 2040 is predicted to be much lower than that in 2012, it is discouraging that the proportion of 'underweight or normal' individuals is also markedly lower. Most notably, the pre-obesity rate is predicted to rise dramatically. In addition to the sex and age of each individual, our model includes only smoking and physical activity as health-related behaviors. The distributions of these factors were assumed to remain equal across the years; hence, our data show that maintaining smoking and physical activity rates at 2012 levels among adults will lead to a sharp increase in the 'pre-obese' population by 2040.

To our knowledge, the only other study that predicted future obesity rates among South Korean adults was the aforementioned investigation by Baik.[2] That study explored factors affecting adult obesity as well as abdominal obesity, and constructed forecasting models to predict obesity prevalence rates in 2020 and 2030 using the Korea National Health and Nutritional Examination Survey (KNHANES). The prevalence rates of obesity among men and women in that study were predicted to be 47% and 32%, respectively, in 2020 and 62% and 37%, respectively, in 2030; these data were inconsistent with our own. The differences appeared to be caused by the different secondary sources used in the 2 studies, as well as the different independent variables and prediction methodologies. In particular, the obesity rate in the initial population according to the KNHANES tended to be higher; as such, a higher initial prevalence rate would lead to a higher projection.[34] Most importantly, Baik's study did not consider the preceding year's BMI, which was a major independent variable in our study; this may be a major explanation for the differences in findings between the 2 studies. We also compared our results to those predicted in Canada using the same model we used; based on self-reported BMIs, approximately 59% of the adult Canadian population was predicted to be 'overweight or obese' (i.e., BMIs >25 kg/m^2) by 2030, which is a much higher percentage than that predicted in South Korea (10.12%).

With respect to worldwide comparisons, whether cutoff points for overweight and obesity should be lower for Asians than for another ethnic group remains debated.[35] Because of racial differences, the World Health Organization has proposed regarding BMIs of 18.5–22.9 kg/m^2 as optimal, 23–24.9 kg/m^2 as overweight, 25–29.9 kg/m^2 as moderate obesity, and ≥30 kg/m^2 as severe obesity for Asians.[36] If the international BMI standard were to be applied in our study, the results would be much more favorable given that a large proportion of subjects would be classified as normal. However, more research is needed to determine particular BMI values that increase the likelihood of developing particular chronic disease, depending on the sex and age of the individual. The Korean Society of Obesity, which was established to improve obesity management through research and education, revised its clinical practical guidelines for the prevention and treatment of obesity in 2018. The new guidelines renamed the "overweight" category to "pre-obese", and divided obesity into 3 categories, thereby aiming to highlight the risk of obesity instead of promoting the term "overweight." The most recent guidance is based in part on data from of 84,690,131 Korean adults extracted from

306 the Korean National Health Insurance Service Health Checkup Database between 2006 and 2015. By
307 including the entire population registered in the National Health Insurance Services Database, they
308 calculated the first and second cutoff points corresponding to the increased risk of any of 3
309 accompanying diseases (type 2 diabetes, hypertension, and dyslipidemia). The first and second BMI
310 cutoff levels were 23 kg/m^2 and 25 kg/m^2, respectively.[37,38] Rather than emphasizing the BMI
311 classification criteria, however, future studies ought to analyze the BMI reference points that can
312 significantly predict the occurrence of chronic diseases by sex and age group. Based on such evidence,
313 the developing governmental 'National Health Promotion Comprehensive Plan' needs to incorporate
314 additional, wider-ranging goals that take into account the characteristics of each sex and age group,
315 rather than presenting goals for obesity prevalence among adult men and women. Moreover,
316 systematic public health interventions that are tailored to individual characteristics need to be
317 established.

318 A limitation of this study was that the forecast model was not specific to Korea, as no
319 microsimulation model for predicting obesity prevalence has been developed in this country.
320 Therefore, we borrowed a model from Statistics Canada and performed an international comparison.
321 For that reason, the variables used as predictors included only sex, age, smoking, physical activity,
322 and the preceding year's BMI value. Nevertheless, our study's importance is that it is the first to
323 examine the possibility of using microsimulation to predict future BMI averages in South Korea.
324 Additionally, it is important to note that the BMI of the future adult population was predicted after
325 considering the change in population structure at the macro level as well as individual health behavior
326 components at the micro level.

327

328 **CONCLUSION**

329 The key finding of this study is that by 2040, 70.05% of Korean adults are predicted to be
330 pre-obese. Utilizing data sources available in Korea, the possibility of applying and expanding on the
331 concept of microsimulation was explored. In future studies, a model suitable for South Korea needs to
332 be developed, and the effectiveness of specific health policies ought to be assessed by applying

various relevant scenarios to the basic forecasting model.

Abbreviations

BMI: body mass index; KNHANES: Korea National Health and Nutritional Examination Survey, POHEM: Population Health Model

Contributions

YS (the first author) designed the study, analyzed and interpreted the data, and wrote the paper. YE participated in the statistical analysis. DS provided assistance in the interpretation of the data and preparation of the manuscript. SJ (the corresponding author) directed this study. All authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics approval

This study used publicly available data of Korea Health Panel Survey 2011-2012 from The Korea Institute for Health and Social Affairs and the National Health Insurance, population statistics based on resident registration, population projections, complete life tables and future mortality rates from Statistics Korea. The dataset does not contain any identifiable personal information. Ethical approval was given by the Institutional Review Board of Korea University, Seoul, Korea (IRB No. KUIRB-2020-0018-01).

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement

The Korea Health Panel Survey data used in this article is available in https://www.khp.re.kr:444/eng/data/data.do. Detailed information on the survey design and data characteristics are provided at https://www.khp.re.kr:444/eng/survey/sampling.do. Population statistics, population projections, and complete life tables are available from http://kosis.kr/eng/.

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Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012-2040

Figure 2 Population Health Model (POHEM) projections of average BMI in South Korea, 2012-2040

Figure 3A Projection of distribution of BMI, Men aged 19 years and older, South Korea, 2012-2040

Figure 3B Projection of distribution of BMI, Women aged 19 years and older, South Korea, 2012-2040

Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012-2040

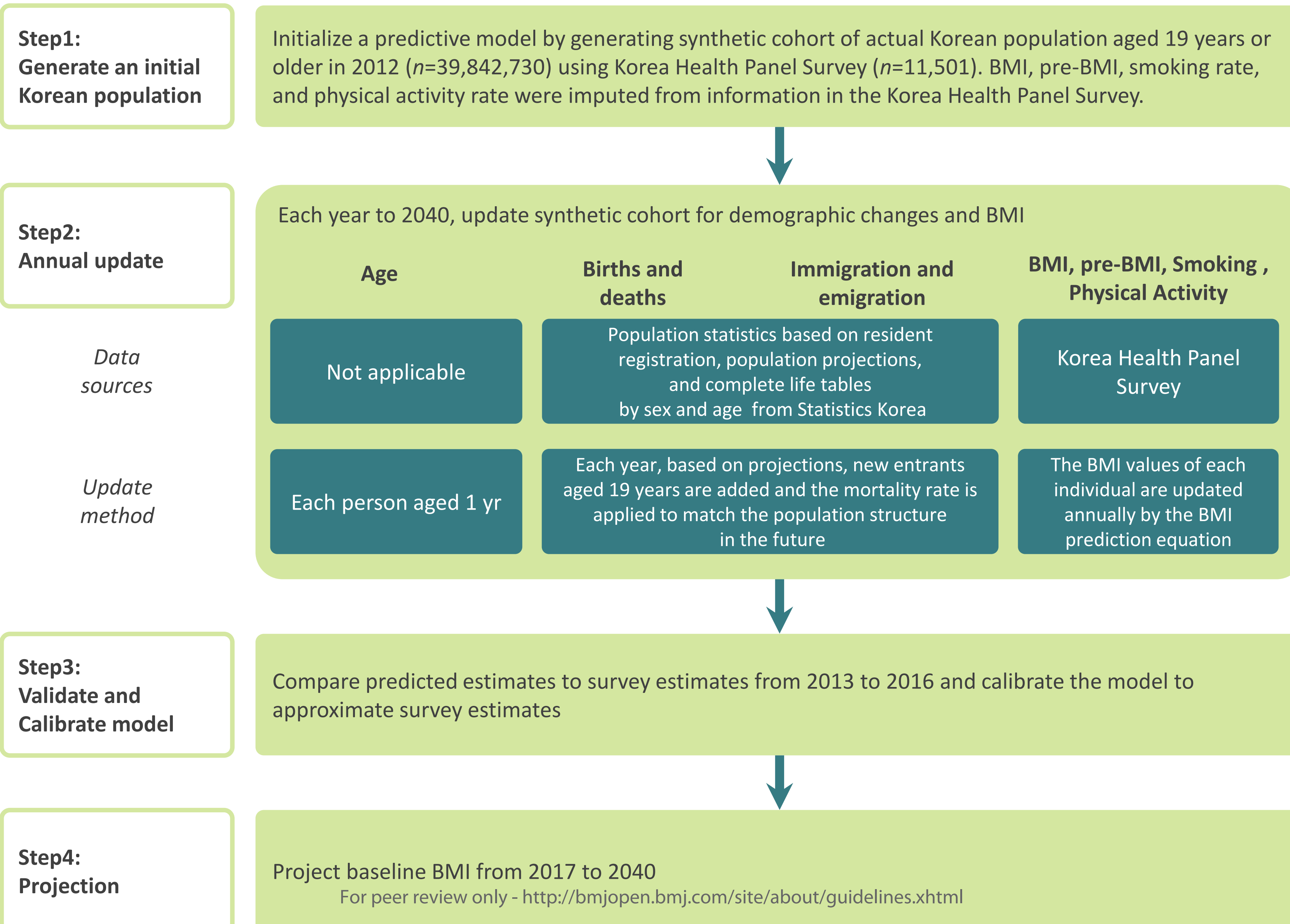


Figure 2 Population Health Model (POHEM) projections of average BMI in South Korea, 2012-2040

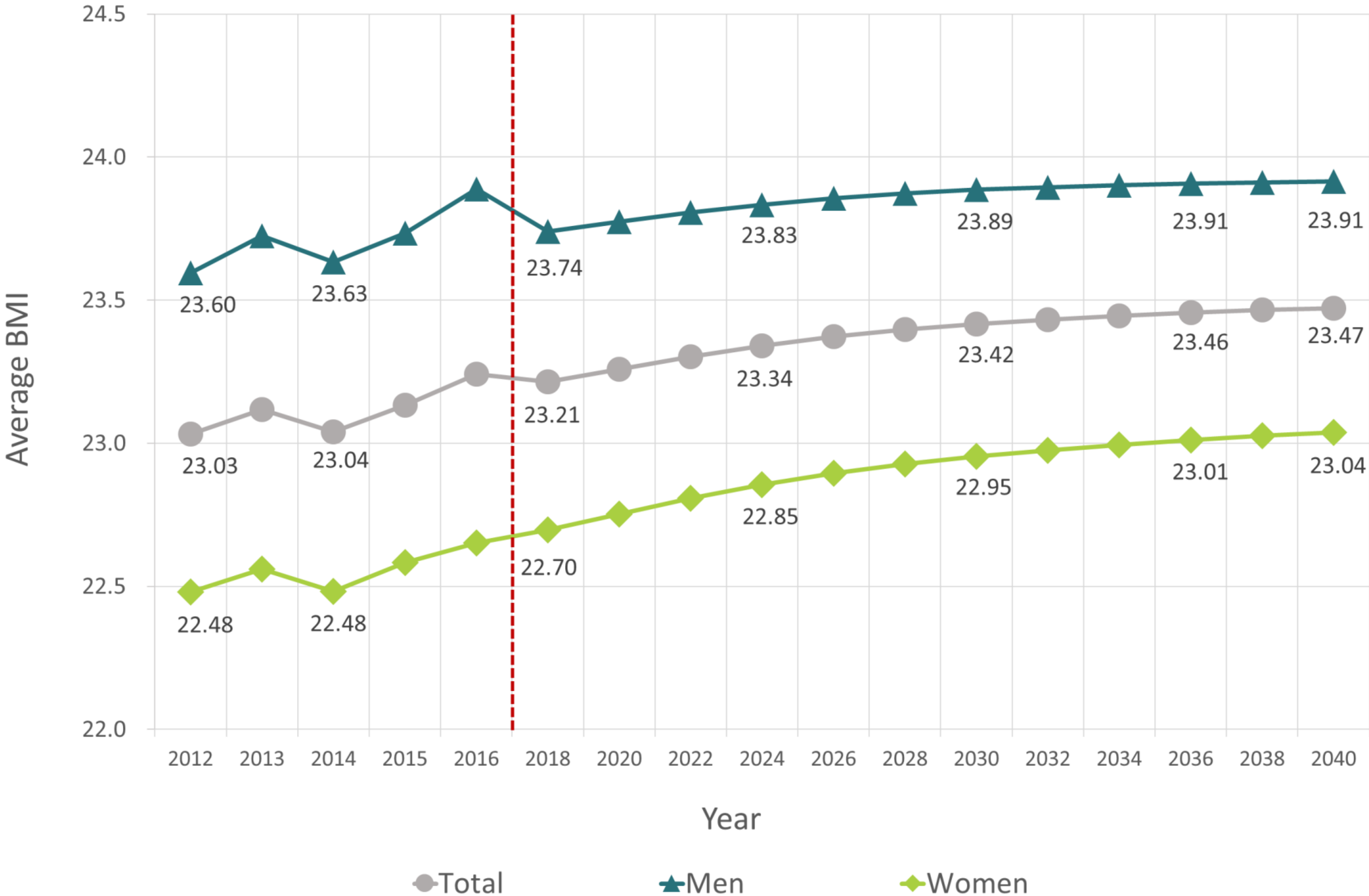


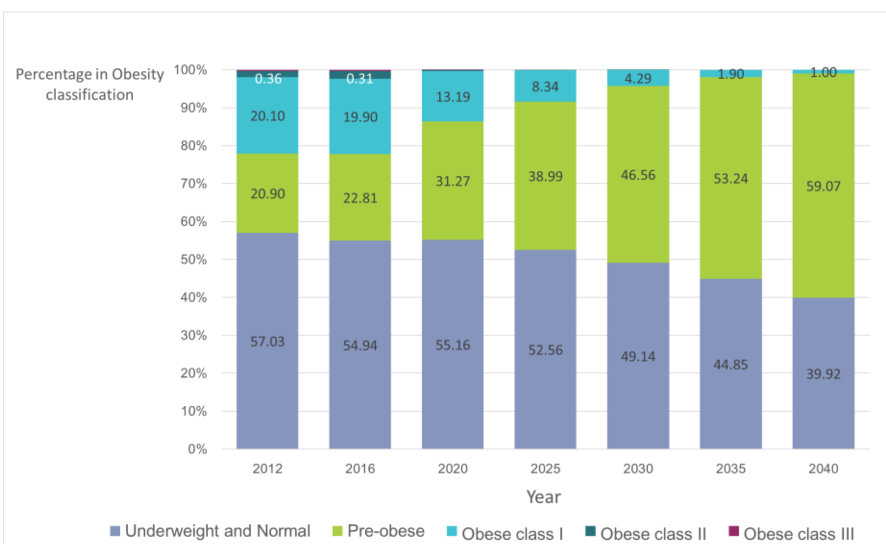
Figure 3 Projection of distribution of BMI, (A) Men and (B) Women, aged 19 years and older, South Korea, 2012-2040

A

1

Figure 3 Projection of distribution of BMI, (A) Men and (B) Women, aged 19 years and older, South Korea, 2012-2040

B



2

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4
Objectives	3	State specific objectives, including any prespecified hypotheses	5
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6-8
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	6-7
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	-
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-8
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6-7
Bias	9	Describe any efforts to address potential sources of bias	7-8
Study size	10	Explain how the study size was arrived at	6
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	6-8
		(*b*) Describe any methods used to examine subgroups and interactions	7
		(*c*) Explain how missing data were addressed	7-8
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	7-8
		(*e*) Describe any sensitivity analyses	-

Continued on next page

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	9-11
		(b) Give reasons for non-participation at each stage	-
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	9-11
		(b) Indicate number of participants with missing data for each variable of interest	9-11
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	9-11
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	11
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	-
		Cross-sectional study—Report numbers of outcome events or summary measures	-
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	9-11
		(*b*) Report category boundaries when continuous variables were categorized	8
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	-
Discussion			
Key results	18	Summarise key results with reference to study objectives	12
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	14
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	12-14
Generalisability	21	Discuss the generalisability (external validity) of the study results	14
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	15

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

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Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

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Title: Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

Authors: Yoon-Sun Jung [a*], Young-Eun Kim[b], Dun-Sol Go[c], Seok-Jun Yoon[d]

Affiliations:

[a]Department of Public Health, Graduate School, Korea University, Seoul, Korea

[b]Big Data Department, National Health Insurance Service, Wonju, Korea

[c]Department of Health Care Policy Research, Korea Institute for Health and Social Affairs

[d]Department of Preventive Medicine, Korea University College of Medicine, Seoul, Korea

Corresponding author:

Seok-Jun Yoon, M.D., Ph.D.

Department of Preventive Medicine, Korea University College of Medicine,

73, Goryeodae-ro, Seongbuk-gu, Seoul, 02841, Korea

E-mail: yoonsj02@korea.ac.kr

E-mail addresses:

sunnyaurora@nate.com (Yoon-Sun Jung)

kimyes4454@gmail.com (Young-Eun Kim)

kds237@gmail.com (Dun-Sol Go)

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ABSTRACT

Objective To project the future prevalence of obesity among populations 19 years and older by 2040 in South Korea

Design, setting, and participants Using the 'Population Health Model-Body Mass Index' (BMI) microsimulation model, the prevalence of obesity in Korean adults 19 years and over was projected until the year 2040. The model integrates individual survey data from the Korea Health Panel Survey of 2011 and 2012, population statistics based on resident registration, population projections, and complete life tables categorized by sex and age. Birth rate, life expectancy, and international migration were based on a medium growth scenario. The base population of Korean adults in 2012, devised through data aggregation, was 39,842,730. Prediction equations were formulated using BMI as the dependent variable; the individual's sex, age, smoking status, physical activity, and the preceding year's BMI were used as predictive factors.

Outcome measure BMI categorized by sex.

Results The median BMI for Korean adults in 2040 was forecast to be 23.55 kg/m^2 (23.97 and 23.17 kg/m^2 for men and women, respectively). According to the Korean BMI classification, 70.05% of all adults were forecast to be 'pre-obese' (i.e., have BMIs 23 to 24.9) by 2040 (81.23% of men and 59.07% of women), followed by 24.88% who would be 'normal'.

Conclusions We explored the possibility of applying and expanding on the concept of microsimulation in the field of healthcare by combining data sources available in Korea using the POHEM model. In future studies, it is necessary to develop a microsimulation model suitable for Korea's domestic situation, and it is necessary to evaluate the effectiveness of special health policies by applying various prediction scenarios to the basic model.

Strengths and limitations of this study

- To the best of our knowledge, this study is the first to use a microsimulation model to predict future obesity prevalence in Korea considering the change in population structure (macro level) as well as individual health behavior components (micro level).
- This study has the greatest significance in exploring the possibility of applying and expanding the concept of microsimulation in the field of healthcare by combining data sources available in Korea.
- Although a representative data source was used in this study, the prevalence of obesity may be underestimated because it is based on a self-reported BMI value.
- The estimated BMI value differs from the Korea Health Statistics, which is based on the data measured by actual measurement.
- There is a limitation that it does not accurately reflect the domestic situation because it borrows a micro-simulation model developed abroad.

BACKGROUND

The prevalence of overweight and obesity has increased markedly over the past 3 decades, and concerns about health risks associated with obesity have become almost universal.[1] The increasing rate of obesity is a growing public health concern not only in Western countries but also in South Korea.[2] From the 1990s through the beginning of the new millennium, the prevalence of adult and child obesity has increased rapidly and continues to rise steadily in parallel with rapid social and economic development.[3]

Obesity is not only a major public health problem in and of itself, but also a factor in the development of many chronic diseases; hence, it constitutes a strain on individuals and health systems worldwide. In the Global Burden of Disease Study,[4] globally in 2017, a high body mass index (BMI) accounted for 4.72 million deaths and 148.0 million disability-adjusted life-years. It is associated with an increased risk of many disorders, including diabetes, hypertension, dyslipidemia, heart disease, stroke, sleep apnea, early death, and cancer.[5-9] Moreover, obesity among older people increases the risk of knee osteoarthritis[10] and reduces functional capacity and quality of life.[11-14] The prevalence of these conditions rises commensurate with increased obesity, [15-18] and are associated with significant morbidity, higher risks of mortality, and increased economic costs for both individuals and the society at large.[19]

Meanwhile, with respect to worldwide comparisons, whether cutoff points for overweight and obesity should be lower for Asians than for another ethnic group remains debated.[20] Because of racial differences, the World Health Organization has proposed regarding BMIs of 18.5–22.9 kg/m^2 as optimal, 23–24.9 kg/m^2 as overweight, 25–29.9 kg/m^2 as moderate obesity, and ≥30 kg/m^2 as severe obesity for Asians.[21] However, it is more important to determine particular BMI values that increase the likelihood of developing particular chronic disease, depending on the sex and age of the individual. The Korean Society of Obesity, which was established to improve obesity management through research and education, revised its clinical practical guidelines for the prevention and treatment of obesity in 2018. The new guidelines renamed the “overweight” category to "pre-obese", and divided obesity into 3 categories, thereby aiming to highlight the risk of obesity instead of promoting the term "overweight." The most recent guidance is based in part on data from of

84,690,131 Korean adults extracted from the Korean National Health Insurance Service Health Checkup Database between 2006 and 2015. By including the entire population registered in the National Health Insurance Service Database, they calculated the first and second cutoff points corresponding to the increased risk of any of 3 accompanying diseases (type 2 diabetes, hypertension, and dyslipidemia). The first and second BMI cutoff levels were reported to be 23 kg/m^2 and 25 kg/m^2, respectively, [22,23] suggesting that obesity criteria reflecting the actual risk of chronic disease in Koreans is necessary.

A study of data from the National Health Insurance Service in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US dollars; medical expenses accounted for 51.3% of this amount, followed by decreasing productivity (20.5%), productivity loss (13.1%), early mortality (10.0%), care costs (4.3%), and transportation costs (0.8%).[24] Several studies on the long-term trends of obesity prevalence in South Korea found that obesity is increasing in men but not in women.[25-27] Although numerous investigators in other countries have attempted to predict the prevalence of obesity into the future, only one such study by Inkyung Baik was recently performed in South Korea.[2] More recent trends still need to be investigated through predictive studies, and the accurate prediction of obesity prevalence remains an important public health-related goal in the country. To efficiently establish and execute an effective healthcare policy, which would require a large budget, it is necessary to select future targets for policy interventions (such as high-risk groups) to predict future healthcare needs and prevent budget waste.

Past prediction models incorporated a country's entire population; as such, macroscopic inferences based on average projections for the future society were generalized. However, when establishing a healthcare policy, it is necessary to estimate the future disease burden and medical needs of the entire population based on future projections that reflect individual characteristics, because a real-world understanding of the factors that are influenced by the policies or institutions is required. Individuals are independent entities with different characteristics and needs that govern their future decisions and behaviors. By applying these needs to the healthcare sector, health-related projections can be modeled by reflecting health risk factors such as sex, age, life cycle activities, smoking, etc.; as such, the effects of policy interventions can be quantified.[28] In this study, we aimed to predict the prevalence of obesity in Korea by using microsimulation, which is optimal for considering individual properties.

Microsimulation is a modeling technique that typically uses individual microunits, each with its own set of properties, to simulate downstream events based on the probability of transition between predefined states and their changes over time. When used in medicine, microsimulation can be particularly powerful because it preserves the patterns of previous behaviors and conditions, and allows for a clearer representation and understanding of how various processes affect the total outcome of the population over time. In other words, microsimulation can predict the burden of disease by modeling various health risk factors that occur during an individual's lifetime. Given macro-effects such as changes in population structures in the forecasting model, microsimulation is very useful in that it can estimate both disease burdens and medical needs across the country.[28] Collecting individual events from within a population that has varying attributes can be used to predict and plan outcomes (such as incidence, prevalence, and cost), and can also be used to assess the clinical and cost effectiveness of alternative health interventions.[29] Microsimulation modeling is particularly useful for studying BMI trends because it can simultaneously explain population dynamics such as aging, migration, and mortality. Additionally, the longitudinal framework of these models allows for interpreting a person's change in BMI as it is affected by factors such as a person's physical activity and behavior and thus act as a contributing factor to other diseases. [30] However, while microsimulation models have been steadily evolving across health- and economy-related fields in many European countries,[31] they have yet to be actively utilized in South Korea (especially for healthcare).

Obesity prevalence and trend estimates provide important information for research, policy, and intervention.[32] As mentioned above, it is necessary to estimate the magnitude of obesity because it has been identified as a risk factor for various chronic diseases. Because health forecasting predicts disease episodes and portends future events, it facilitates healthcare strategies by promoting the setting of goals to reduce obesity, establish health promotion interventions, and optimize resource allocation.[33] Obesity trends may also be used to urge governments to implement preventative approaches to reducing obesity.[34] Based on the above, we performed this study to project the future trends in obesity prevalence in South Korea up to the year 2040.

METHODS

Model

We used the Population Health Model (POHEM)-BMI to estimate the prevalence of obesity in adults 19 years and over in South Korea from 2012 through 2040. In brief, POHEM is a time-continuous, population-based, dynamic microsimulation model with individual underlying units of analysis used worldwide. Dynamic microsimulation, in the context of social science and population health, is a simulation of individuals (i.e., micro-level) and their behaviors, statuses, and actions (dynamics) over time.[35] These are modeled as desired using multiple sources of empirical data, including cross-sectional surveys, administrative databases, vital statistics, and census data.[36] Through dynamic simulation, POHEM creates a population and ages it, one person at a time, until death.[37] The model dynamically simulates an individual's disease state, risk factors, and health determinants to describe and plan health outcomes.[36] POHEM is accessible because it wants the general process to be constant across the country's population, with the exception of variables unique to each country, such as marriage and mortality. The POHEM models include cardiovascular disease, various cancers, osteoarthritis, physical activity, and neurological events. The model used in this study was the POHEM-BMI; the performance of each prediction step is shown in Figure 1.

[Insert Figure 1 here]

Base population

To create the base population for the POHEM-BMI model, we used the 2011- 2012 Korea Health Panel survey and the resident registration-based population statistics. This constituted the base population for POHEM-BMI (n=39,842,730), reflecting the Korean population. Each Korean respondent 19 years of age and over (n=11,501) in 2012 was replicated using their survey-recorded weights to generate a simulated cohort of approximately 39,842,730 individuals. Korea Health Panel survey data are nationally representative panel surveys that incorporate health status, chronic diseases, health risk behaviors, and socio-demographic characteristics. Among them, we extracted sex, age, current smoking status, physical activity, and the previous and current years' BMI values; these variables were required for the predictive equation. We then used a multiple linear regression model to estimate the BMI value using the independent variables age, sex, smoking status, physical activity, and previous BMI value as predictors. The POHEM-BMI model is auto-regressive and includes previous BMI values as a main explanatory variable.[30] For comparison with other international studies using this model, the variable composition was the same, but the variable definition was not. The definition of variables was consistent with the definition of indicators in the Korea Health Statistics. In terms of predictor definitions, a current smoker was an individual who reported smoking 'every day' or 'sometimes'. Practicing physical activity was defined as performing either intense physical activity for at least 10 continuous minutes a day, 20 minutes total per day, 3 days a week during the preceding week, or moderate physical activity for at least 30 minutes a day, 5 days a week during the preceding week.

Simulation: Annual updates and risk transition

The population makeup was updated by aging each person by 1 year and changing the total population size based on population statistics, population projections, and complete life tables categorized by sex and age from Statistics Korea. For population projections, we assumed a medium growth scenario in terms of birth rate, life expectancy, and international migration. Each person's BMI was updated annually by applying a predictive equation that incorporates his/her own characteristics. The transition probability for each stochastic characteristic was calculated based on a generalized linear model.

Similar to the original POHEM-BMI, we assumed that the current individual behavioral patterns persisted, and no new factors arose to prevent obesity. We also assumed that the attributes of 19-year-old individuals, which were entered annually, remained similar year-to-year.

Model validation and calibration

We established the model's validity by comparing the projected BMI median obtained from the prediction model to estimates obtained from the Korea Health Panel survey. We set the calibration cutoff point to 5% and adjusted the model by comparing the difference between the median BMI estimates observed from the Korea Health Panel survey and the values derived from the prediction model categorized by sex and age. We analyzed the BMIs of each group by comparing the 2016 data available from the Korea Health Panel with the most recent data. We accepted a difference of less than 5% overall as well as in the sex- and age-categorized groups. Finally, we adjusted the demographics of the 2040 population so that the predictions were similar within a 5% margin of error. In this study, all necessary data for model building and projection were obtained from publicly available data and does not include any identifiable personal information, so no additional ethical approval was required. In addition, ethical and governance approvals were granted by the Korea Institute for Health and Social Affairs which conducts Korea Health Panel Survey. All participants gave written informed consent to take part before they were allowed to complete the survey.

Projection

The model projected the BMI of each person from 2017 to 2040. Based on demographic characteristics, the projections were then aggregated by year for each of the predefined subgroups. The various trends observed in the Korean population data were used to generate algorithms that were applied to future projections.

Model outputs

The final results of the BMI distributions were calculated overall and by sex. Individuals with a BMI ≥25 kg/m^2 were obese according to the Guidelines for the Management of Obesity in Korean, which is not the internationally accepted standard (see Table 1). According to this guideline, BMI is categorized into standard groupings for underweight (<18.5 kg/m^2), normal weight (18.5–22.9 kg/m^2), pre-obese (23–24.9 kg/m^2), obese class Ⅰ (25–29.9 kg/m^2), obese class Ⅱ (30–34.9 kg/m^2), and obese class Ⅲ (≥35 kg/m^2). All analyses in this study were performed using STATA version 13 (StataCorp LLC, College Station, TX, USA).

Table 1 BMI classification of South Korea

Classification	Body mass index (kg/m^2)
Underweight	< 18.5

Normal	18.5 – 22.9
Pre-obese	23 – 24.9
Obese class Ⅰ	25 – 29.9
Obese class Ⅱ	30 – 34.9
Obese class Ⅲ	≥ 35

Patient and public involvement

No patient involved

RESULTS

We compared the total numbers of the individuals and characteristics in the initial 2012 population to those in the projected 2040 population (see Table 2) There were 39,842,730 adults who were 19 or over in 2012 and 43,818,808 in 2040. The male:female ratio was nearly 1:1 in both 2012 and 2040. The rapid aging of the Korean population was clearly observed when comparing the 2 eras. The average age of adults was expected to increase by 10.9 years from 45.69 years in 2012 to 56.59 years in 2040 (from 44.57 to 55.54 years among men and from 46.77 to 57.63 years among women). In 2012, the proportion of young people (those in the 19–39 and 40–64 year age groups combined) accounted for approximately 85.54% of the adult population, while the proportion of individuals aged 65 years and older was relatively low at approximately 14%. However, the age group structure in South Korea 28 years later (2040) is predicted to be quite different, as the proportion of individuals 19–64 years (i.e., the working age population) was only 60.95% of the adult population, while the proportion of the elderly population (≥65 years) was estimated to be almost 40% of the total adult population.

Table 2 Comparison of number of people, South Korea, 2012 and 2040

	Population at baseline (2012)						***Projected population (2040)***					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**
Number of people	19,709,628		20,133,102		39,842,730		21,717,128		22,101,680		43,818,808	
Age (mean±s.d.)	44.57±15.60		46.77±16.92		45.69±16.31		55.54±18.60		57.63±19.33		56.59±19.00	
19-39	7,985,737	(40.52)	7,505,824	(37.29)	15,491,561	(38.88)	4,873,740	(22.45)	4,588,867	(20.76)	9,462,607	(21.60)
40-64	9,360,489	(47.49)	9,230,871	(45.85)	18,591,360	(46.66)	8,896,886	(40.97)	8,349,634	(37.78)	17,246,520	(39.35)
65-	2,363,402	(11.98)	3,396,407	(16.87)	5,759,809	(14.45)	7,946,502	(36.59)	9,163,179	(41.45)	17,109,681	(39.05)
Smoking status												
Smoker	8,879,037	(45.05)	450,946	(2.24)	9,329,983	(23.42)						
Non-smoker	10,830,591	(54.95)	19,682,156	(97.76)	30,512,747	(76.58)						
Physical activity												
Physical activity	5,199,273	(26.38)	3,103,036	(15.41)	8,302,309	(20.84)						
Physical inactivity	14,510,355	(73.62)	17,030,066	(84.59)	31,540,421	(79.16)						

There was no significant difference between the median BMIs in 2012 and 2040; however, according to the BMI classification in South Korea, approximately 41.48% of the adult population was 'normal' in 2012, whereas only 24.88% of the population was predicted to be the same in 2040. (see Table 3) On the other hand, the 'pre-obese' group was expected to account for approximately 70% of the total adult population.

Table 3 Comparison of number of people, by BMI classification, South Korea, 2012 and 2040

	Population at baseline (2012)						***Projected population (2040)***					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**
BMI (median)	23.59		22.41		23.04		23.97		23.17		23.55	
Number of people by BMI classification												
Underweight	840,251	(4.26)	2,368,051	(11.76)	3,208,302	(8.05)	98,954	(0.46)	152,500	(0.69)	251,454	(0.57)
Normal	7,414,311	(37.62)	9,114,015	(45.27)	16,528,326	(41.48)	2,228,567	(10.26)	8,671,481	(39.23)	10,900,048	(24.88)
Pre-obese	5,264,866	(26.71)	4,207,673	(20.90)	9,472,539	(23.77)	17,641,668	(81.23)	13,055,482	(59.07)	30,697,150	(70.05)
Obese class Ⅰ	5,867,369	(29.77)	4,046,607	(20.10)	9,913,976	(24.88)	1,712,332	(7.88)	221,829	(1.00)	1,934,161	(4.41)
Obese class Ⅱ	318,297	(1.61)	324,205	(1.61)	642,502	(1.61)	33,455	(0.15)	388	(0.00)	33,843	(0.08)
Obese class Ⅲ	4,534	(0.02)	72,551	(0.36)	77,085	(0.19)	2,152	(0.01)	0	(0.00)	2,152	(0.00)

The model was well calibrated in both the initial population and from 2017 to 2040. Differences in each of the variables estimated between 2013 to 2016, which were derived from the Korea Health Panel data, were within the 5% range only when using the predictive model. Additionally, when compared to the population structure for 2040 (the final year) as predicted by Statistics Korea, the total population and gender and age-specific ratio were similar.

Figure 2 shows the median predicted BMIs between 2017 and 2040. Each median BMI value from 2013 to 2016 was estimated from the Korea Health Panel survey. The median BMI for the entire adult population is predicted to increase very slightly from 23.23 kg/m^2 in 2018 to 23.53 kg/m^2 in 2036 and is expected to remain steady thereafter. The predicted median BMI trends are similar for men; the median BMI in adult men was projected to increase only slightly, from 23.74 kg/m^2 in 2018 to 23.95 kg/m^2 in 2036 and then almost plateau thereafter. On the other hand, women were expected to experience a relatively steep rise compared to men; the median BMI in adult women was projected to increase from 22.66 kg/m^2 in 2018 to 23.17 kg/m^2 in 2040.

[Insert Figure 2 here]

The BMI distributions for men and women from 2012 to 2040 are shown in Figure 3. The proportions of 'pre-obese' individuals in both sexes are predicted to increase dramatically over time, while the proportions of individuals who are classified as 'normal' and 'obese' will gradually decrease. As of 2025, 52.35% of all male adults were expected to be pre-obese, with that proportion expected to be close to 81.23% by 2040. Moreover, 53.24% of all adult women are expected to be 'pre-obese' by 2035, with the proportion rising to almost 59.078% by 2040.

[Insert Figure 3A and 3B here]

DISCUSSION

The purpose of this study was to predict the prevalence of obesity in South Korea in the year 2040 using a microsimulation model. In this study, we strove to predict future adult obesity rates in South Korea using the POHEM-BMI, which is developed by Statistics Canada. Summarizing the predicted results, the median BMI of South Korea's adult population aged 19 years and older was expected to be 23.55 in 2040, while the percentage of 'pre-obese' individuals was expected to increase over time. While it is encouraging that the proportion of 'obese' people (i.e., those with BMIs ≥25 kg/m^2) in 2040 is predicted to be much lower than that in 2012, it is discouraging that the proportion of 'normal' individuals is also markedly lower. Most notably, the pre-obesity rate is predicted to rise dramatically. In addition to the sex and age of each individual, our model includes only smoking and physical activity as health-related behaviors. The distributions of these factors were assumed to remain equal across the years; hence, our data show that maintaining smoking and physical activity rates at 2012 levels among adults will lead to a sharp increase in the 'pre-obese' population by 2040.

To our knowledge, the only other study that predicted future obesity rates among South Korean adults was the aforementioned investigation by Baik.[2] That study explored factors affecting adult obesity as well as abdominal obesity, and constructed forecasting models to predict obesity prevalence rates in 2020 and 2030 using the Korea National Health and Nutritional Examination Survey (KNHANES). The prevalence rates of obesity among men and women in that study were predicted to be 47% and 32%, respectively, in 2020 and 62% and 37%, respectively, in 2030; these data were inconsistent with our own. The differences appeared to be caused by the different secondary sources used in the 2 studies, as well as the different independent variables and prediction methodologies. In particular, the obesity rate in the initial population according to the KNHANES tended to be higher; as such, a higher initial prevalence rate would lead to a higher projection.[38] Most importantly, Baik's study did not consider the preceding year's BMI, which was a major independent variable in our study; this may be a major explanation for the differences in findings between the 2 studies. We also compared our results to those predicted in Canada using the same model we used; based on self-reported BMIs, approximately 59% of the adult Canadian population was predicted to be 'overweight or obese' (i.e., BMIs >25 kg/m^2) by 2030, which is a much higher percentage than that predicted in South Korea (10.12%).

With reference to international comparisons, if the international BMI standard were to be applied in our study, the results would be much more favorable given that a large proportion of subjects would be classified as normal. However, this study defined obesity by applying the BMI classification system according to 2018 Korean Society for the Study of Obesity guideline for the management of obesity in Korea. Of course, it would be appropriate to use international standards in international comparison, but it is necessary to reflect the situation of individual countries in the management of obesity for the purpose of preventing and managing chronic diseases. Therefore, rather than emphasizing the BMI classification criteria, more research is needed to analyze the BMI values that can significantly predict the occurrence of chronic diseases. In other words, it is necessary to continuously accumulate sufficient epidemiologic evidence for the relationship between the BMI and the actual risk of disease and death for Koreans, and based on such evidence, efforts to establish appropriate diagnostic and medical standards for Koreans are needed. In particular, the relationship is likely to vary by age as well as sex, so it should be considered as well. In the meantime, the obesity standard has been applied collectively regardless of sex and age. However, in order to deviate from a uniform approach to obesity, gender- and age-based approaches are needed, considering the changes in hormones and body composition.

Because health management policies including obesity management requires a large budget, it is most important to establish cost-effective policies, and this requires selecting targets for policy intervention. The results from this study made it possible to grasp the obese high-risk group by sex and age group, and furthermore, it is expected to enable estimation of medical needs. As it is necessary to apply obesity standards differently according to sex and age group, it is a similar problem in setting goals of the 'National Health Promotion Comprehensive Plan'. The developing governmental 'National Health Promotion Comprehensive Plan' needs to suggest additional, wider-ranging goals considering the characteristics of each sex and age group, rather than presenting goals for obesity prevalence among adult men and women. In this case, the goal should be presented at an achievable level in consideration of future prediction patterns. Finally, systematic public health interventions that are tailored to individual characteristics need to be established.

Findings from this study should be interpreted with consideration of several limitations. First, since a microsimulation model for predicting obesity prevalence has not been developed in this country, we borrowed the model developed by the Statistics Canada, and accordingly it is not built to fit the domestic situation. Therefore, not only is the definition of obesity different, but the predictors of BMI include only sex, age, smoking, physical activity, and preceding year's BMI values. In the future, research to develop a new model of microsimulation in the field of healthcare for domestic conditions will be very valuable. In this process, it is necessary to consider practical suitability and efficiency in selecting basic data, module-specific behavioral equations, and variables for use in the model. Second, it is a limitation of data sources. There is a difference between the current prevalence of obesity calculated from the Korea Health Panel data used in this study and the Korea Health Statistics using the KNHANES. As of 2011, the prevalence of adult obesity in Korea Health Statistics was 31.9%, and the prevalence of adult obesity calculated by the Korea Health Panel data was 23.7%, a difference of 8.2%.[39] Unlike the Korea Health Statistics, which contains body-measured height and weight information, the Korea Health Panel (although this is a representative data source) generates data based on self-reported by respondents, which may underestimate obesity. However, in the POHEM-BMI model used in this study, the BMI of the previous year was regarded as the main explanatory variable, and therefore, the Korea Health panel data that followed the same subject once a year was inevitably used. In addition, the original POHEM-BMI model includes the process of converting self-reported BMI into a measured BMI, but we omitted this due to limitations of the data source.

Nevertheless, our study's importance is that it is the first to examine the possibility of using microsimulation to predict future BMI medians in South Korea. Additionally, it is important to note that the BMI of the future adult population was predicted after considering the change in population structure at the macro level as well as individual health behavior components at the micro level.

CONCLUSION

The key finding of this study is that by 2040, 70.05% of Korean adults are predicted to be pre-obese. Utilizing data sources available in Korea, the possibility of applying and expanding on the concept of microsimulation was explored. In future studies, a model suitable for South Korea needs to be developed, and the effectiveness of specific health policies ought to be assessed by applying various relevant scenarios to the basic forecasting model.

Abbreviations

BMI: body mass index; KNHANES: Korea National Health and Nutritional Examination Survey, POHEM: Population Health Model

Authors' Contributions

YS (the first author) designed the study, analyzed and interpreted the data, and wrote the paper. YE participated in the statistical analysis. DS provided assistance in the interpretation of the data and preparation of the manuscript. SJ (the corresponding author) directed this study. All authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics approval

This study used publicly available data of Korea Health Panel Survey 2011-2012 from The Korea Institute for Health and Social Affairs and the National Health Insurance, population statistics based on resident registration, population projections, complete life tables and future mortality rates from Statistics Korea. The dataset does not contain any identifiable personal information. Ethical approval was given by the Institutional Review Board of Korea University, Seoul, Korea (IRB No. KUIRB-2020-0018-01).

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement

The Korea Health Panel Survey data used in this article is available in https://www.khp.re.kr:444/eng/data/data.do. Detailed information on the survey design and data characteristics are provided at https://www.khp.re.kr:444/eng/survey/sampling.do. Population statistics, population projections, and complete life tables are available from http://kosis.kr/eng/.

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Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012-2040

Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012-2040

Figure 3A Projection of distribution of BMI, Men aged 19 years and older, South Korea, 2012-2040

Figure 3B Projection of distribution of BMI, Women aged 19 years and older, South Korea, 2012-2040

Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012-2040

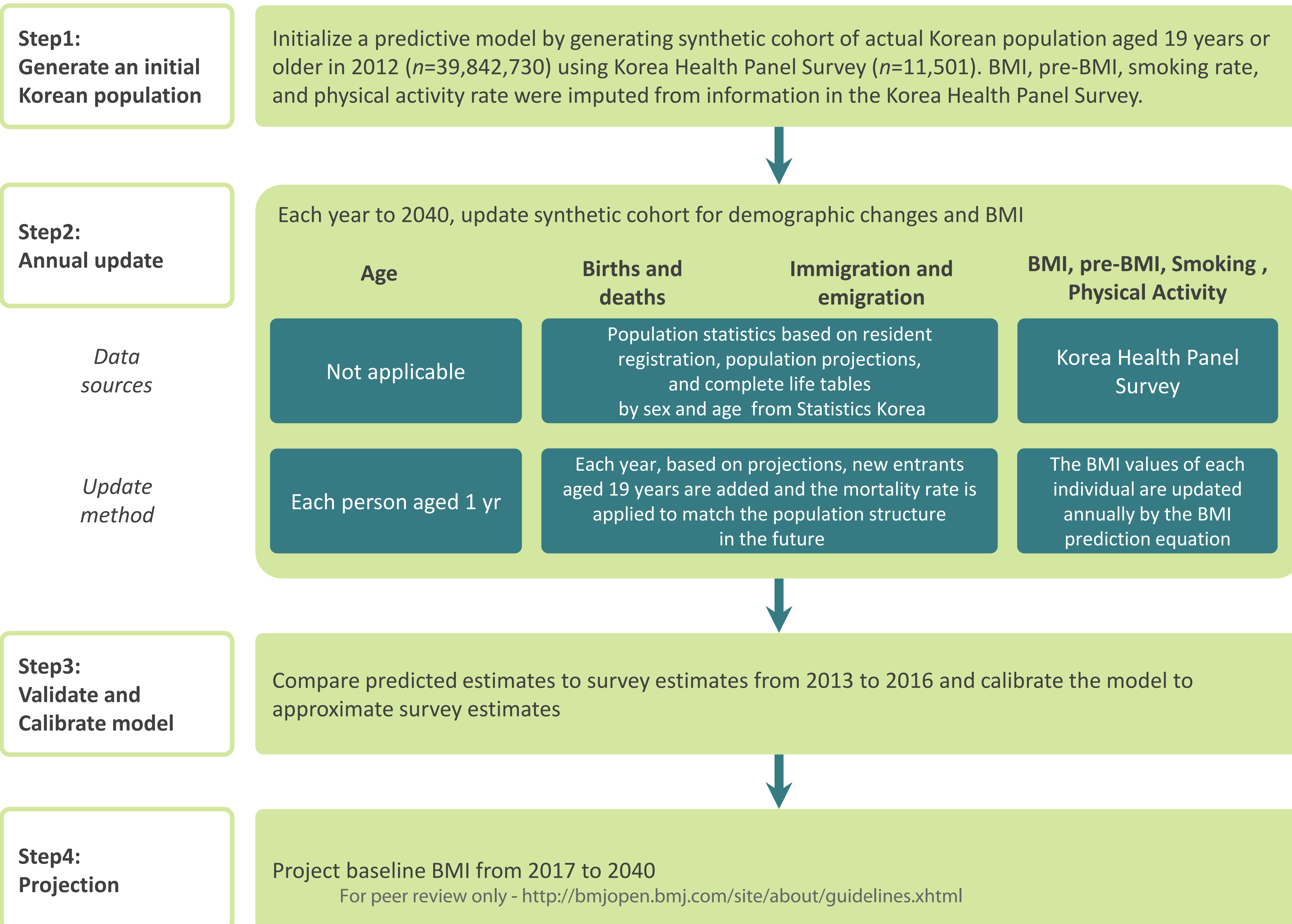


Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012-2040

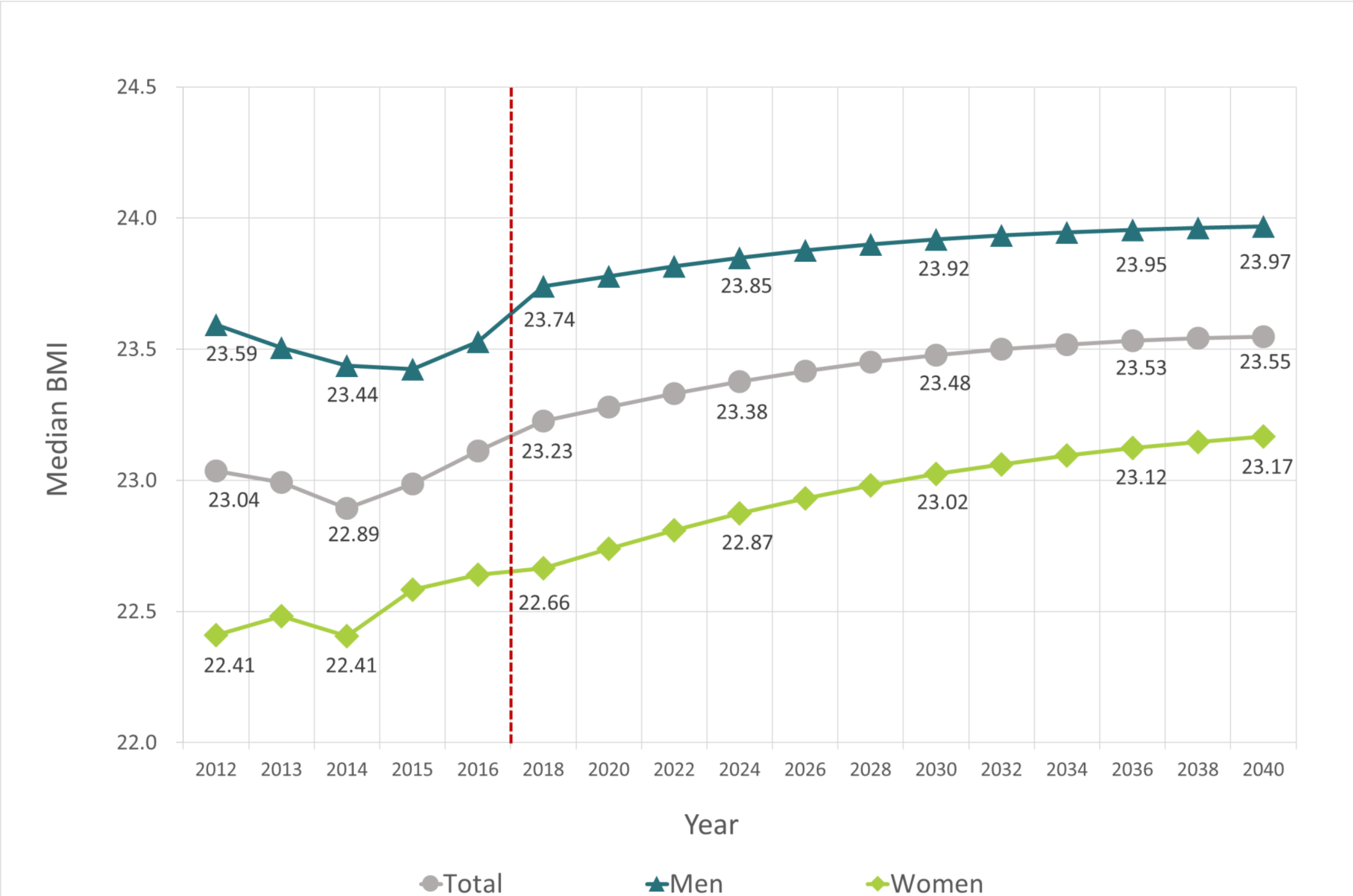


Figure 3 Projection of distribution of BMI, (A) Men and (B) Women, aged 19 years and older, South Korea, 2012-2040

A

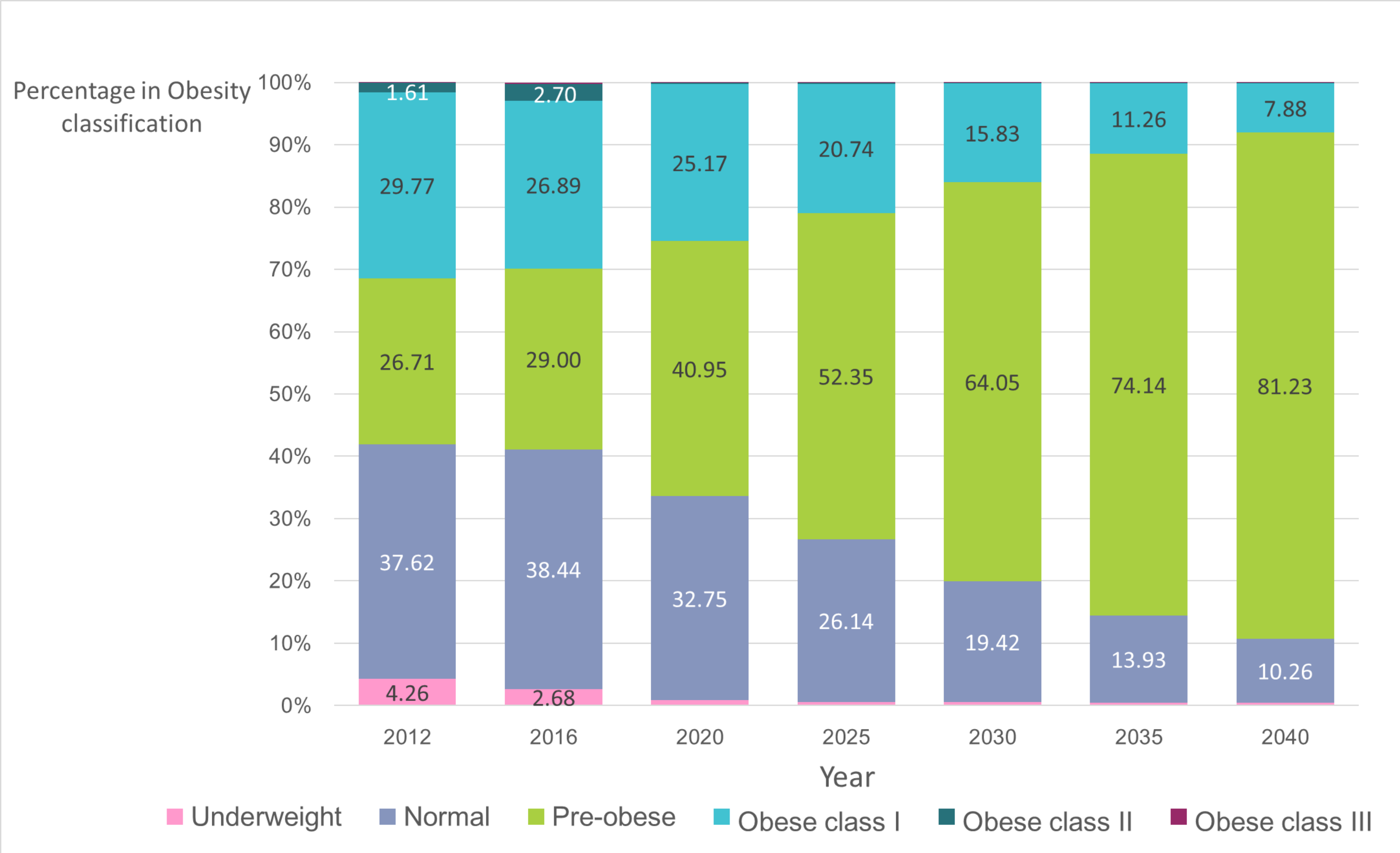
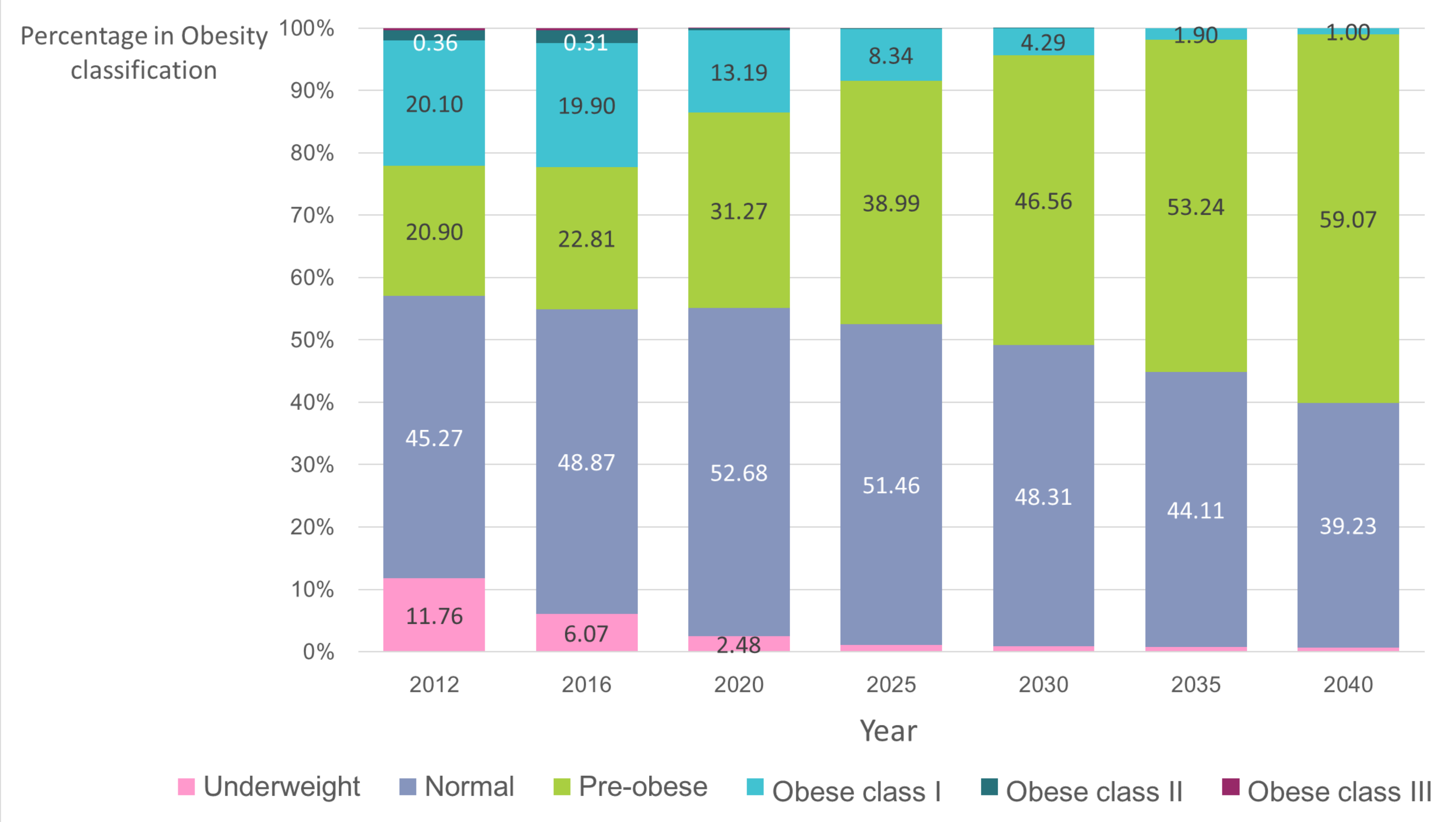


Figure 3 Projection of distribution of BMI, (A) Men and (B) Women, aged 19 years and older, South Korea, 2012-2040

B



STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4-7
Objectives	3	State specific objectives, including any prespecified hypotheses	6-7
Methods			
Study design	4	Present key elements of study design early in the paper	7
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	7-8
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	8-9
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	-
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-9
Bias	9	Describe any efforts to address potential sources of bias	8-9
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	7-9
		(*b*) Describe any methods used to examine subgroups and interactions	8-9
		(*c*) Explain how missing data were addressed	8-9
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	8-9
		(*e*) Describe any sensitivity analyses	-

Continued on next page

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	10-13
		(b) Give reasons for non-participation at each stage	-
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10-12
		(b) Indicate number of participants with missing data for each variable of interest	10-12
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	10-12
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	13
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	-
		Cross-sectional study—Report numbers of outcome events or summary measures	-
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-12
		(*b*) Report category boundaries when continuous variables were categorized	11
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	-
Discussion			
Key results	18	Summarise key results with reference to study objectives	13-14
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	15-16
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	14-16
Generalisability	21	Discuss the generalisability (external validity) of the study results	15
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	17

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

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Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

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Title: Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

Authors: Yoon-Sun Jung [a*], Young-Eun Kim[b], Dun-Sol Go[c], Seok-Jun Yoon[d]

Affiliations:

[a]Department of Public Health, Graduate School, Korea University, Seoul, Korea

[b]Big Data Department, National Health Insurance Service, Wonju, Korea

[c]Department of Health Care Policy Research, Korea Institute for Health and Social Affairs

[d]Department of Preventive Medicine, Korea University College of Medicine, Seoul, Korea

Corresponding author:

Seok-Jun Yoon, M.D., Ph.D.

Department of Preventive Medicine, Korea University College of Medicine,

73, Goryeodae-ro, Seongbuk-gu, Seoul, 02841, Korea

E-mail: yoonsj02@korea.ac.kr

E-mail addresses:

sunnyaurora@nate.com (Yoon-Sun Jung)

kimyes4454@gmail.com (Young-Eun Kim)

kds237@gmail.com (Dun-Sol Go)

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ABSTRACT

Objective To project the prevalence of obesity in 2040 among individuals 19 years and older in South Korea.

Design, setting, and participants Using the 'Population Health Model-Body Mass Index' (POHEM-BMI) microsimulation model, the prevalence of obesity in Korean adults 19 years and older was projected until 2040. The model integrated individual survey data from the Korea Health Panel Survey of 2011 and 2012, population statistics based on resident registration, population projections, and complete life tables categorized by sex and age. Birth rate, life expectancy, and international migration were based on a medium growth scenario. The base population of Korean adults in 2012, devised through data aggregation, was 39,842,730. The prediction equations were formulated using BMI as the dependent variable; the individual's sex, age, smoking status, physical activity, and preceding year's BMI were used as predictive factors.

Outcome measure BMI categorized by sex.

Results The median BMI for Korean adults in 2040 was forecast to be 23.55 kg/m^2 (23.97 and 23.17 kg/m^2 for men and women, respectively). According to the Korean BMI classification, 70.05% of all adults were forecast to be 'pre-obese' (i.e., have BMIs 23 to 24.9) by 2040 (81.23% of men and 59.07% of women) and 24.88% to be 'normal'.

Conclusions We explored the possibility of applying and expanding on the concept of microsimulation in the field of healthcare by combining data sources available in Korea and found that more than half of the adults in this study population will be pre-obese, and the proportions of "obesity" and "normal" will decrease compared with those in 2012. The results of our study will aid in devising healthy strategies and spreading public awareness for preventing this condition.

Strengths and limitations of this study

- To the best of our knowledge, this is the first study to use a microsimulation model to predict future obesity prevalence in Korea considering the change in population structure (macro level) as well as individual health behavior components (micro level).
- The results of our study aid in suggesting additional and wider-ranging strategies for obesity prevention by considering sex and age group in the formulation of the 'National Health Promotion Comprehensive Plan'.
- Although a representative data source was used in this study, the prevalence of obesity may be underestimated because it is based on a self-reported BMI value.
- This study uses a micro-simulation model developed abroad, and hence, may not reflect the domestic situations accurately.
- Another limitation is that we assumed the attributes of 19-year-old individuals to remain similar each year.

BACKGROUND

The prevalence of overweight and obesity has increased markedly over the past 3 decades, and concerns about health risks associated with obesity have become almost universal.[1] The increasing rate of obesity is a growing public health concern not only in Western countries but also in South Korea.[2] From the 1990s through the beginning of the new millennium, the prevalence of adult and child obesity has increased rapidly and continues to rise steadily in parallel with rapid social and economic development.[3]

Obesity is not only a major public health problem in itself, but also a factor in the development of many chronic diseases; hence, it constitutes a strain on individuals and health systems worldwide. It is associated with an increased risk of many disorders, including diabetes, hypertension, dyslipidemia, heart disease, stroke, sleep apnea, early death, and cancer.[4-8] Moreover, obesity among older people increases the risk of knee osteoarthritis[9] and reduces functional capacity and quality of life.[10-13] The prevalence of these conditions rises in proportion to the increase in obesity[14-17] and is associated with increased economic costs for both individuals and the society at large.[18] A study of data from the National Health Insurance Service in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US dollars.[19]

Meanwhile, with respect to worldwide comparisons, whether cutoff points for overweight and obesity should be lower for Asians than for another ethnic groups remains debatable.[20] The World Health Organization has proposed BMIs of 18.5–22.9 kg/m^2 as optimal, 23–24.9 kg/m^2 as overweight, 25–29.9 kg/m^2 as moderate obesity, and $\geq$30 kg/m^2 as severe obesity for Asians.[21] The Korean Society of Obesity, which was established to improve obesity management through research and education, revised its clinical practical guidelines for the prevention and treatment of obesity in 2018. The new guidelines renamed the “overweight” category to "pre-obese", and divided obesity into 3 categories, thereby aiming to highlight the risk of obesity instead of promoting the term "overweight." The most recent guidance is based in part on data of 84,690,131 Korean adults extracted from the Korean National Health Insurance Service Health Checkup Database between 2006 and 2015. By including the entire population registered in the National Health Insurance Service Database, they calculated the first and second cutoff points corresponding to the increased risk of any of the 3 accompanying diseases (type 2 diabetes, hypertension, and dyslipidemia) The first cutoff BMI level was 23 kg/m^2, and the second cutoff BMI level was 25 kg/m^2, suggesting the necessity of obesity criteria that accurately reflect the risk of chronic disease among Koreans.[22,23]

Although numerous investigators in other countries have attempted to predict the future prevalence of obesity, only one such study by Inkyung Baik was recently performed in South Korea.[2] More recent trends still need to be investigated through predictive studies, and the accurate prediction of obesity prevalence remains an important public health-related goal in the country. To efficiently establish and execute an effective healthcare policy, which would require a large budget, it is necessary to select future targets for policy interventions (such as high-risk groups) to predict healthcare needs and prevent budget waste.

Past prediction models incorporated a country's entire population; as such, macroscopic inferences based on average projections for the future society were generalized. However, when establishing a healthcare policy, it is necessary to estimate the future disease burden and medical needs of the entire population based on future projections that reflect individual characteristics because a real-world understanding of factors that are influenced by policies or institutions is required. Individuals are independent entities with different characteristics and needs that govern their future decisions and behaviors. By applying these needs, health-related projections can be modeled to reflect health risk factors such as sex, age, life cycle activities, smoking, etc., and the effects of policy interventions can be quantified.[24] In this regard, we aimed to predict the prevalence of obesity in Korea by using microsimulation, which is optimal for considering individual properties.

Microsimulation is a modeling technique, which typically uses individual microunits, each with its own set of properties, to simulate downstream events based on the probability of transition between predefined states and their changes over time. When used in medicine, microsimulation can be particularly powerful because it preserves the patterns of previous behaviors and conditions, and allows for a clearer representation and understanding of how various processes affect the total outcome of the population over time.[25] Given macro-effects such as changes in population structures in the forecasting model, microsimulation is very useful as it can estimate both disease burdens and medical needs across the country.[24] Microsimulation modeling is particularly useful for studying BMI trends because it can simultaneously explain population dynamics such as aging and mortality. Additionally, the longitudinal framework of these models allows for interpreting a person's change in BMI as it is affected by factors such as a person's physical activity and behavior, and thus, acts as a contributing factor for other diseases.[26] However, while microsimulation models have been steadily evolving across health- and economy-related fields in many European countries,[27] they are yet to be actively utilized in South Korea (especially for healthcare).

Obesity prevalence and trend estimates provide important information for research, policy, and intervention.[28] Because health forecasting predicts disease episodes and portends future events, it facilitates healthcare strategies by promoting the setting of goals to reduce obesity, establish health promotion interventions, and optimize resource allocation.[29] Obesity trends may also be used to urge governments to implement preventative approaches for reducing obesity.[30] Based on the above findings, we performed this study to project the future trends in obesity prevalence in South Korea up to the year 2040.

METHODS

Model

We used the Population Health Model (POHEM)-BMI to estimate the prevalence of obesity among adults 19 years and older in South Korea from 2012 through 2040. In brief, POHEM is a time-continuous, population-based, dynamic microsimulation model with individual underlying units of analysis used worldwide. Dynamic microsimulation, in the context of social science and population health, is a simulation of individuals (i.e., micro-level) and their behaviors, statuses, and actions (dynamics) over time.[31] These are modeled as desired using multiple sources of empirical data, including cross-sectional surveys, administrative databases, vital statistics, and census data.[32]

Through dynamic simulation, POHEM creates a population and ages it, one person at a time, until death.[33] The model dynamically simulates an individual's disease state, risk factors, and health determinants to describe and plan health outcomes.[32] POHEM is accessible because it wants the general process to be constant across the country's population, with the exception of variables unique to each country, such as marriage and mortality. The POHEM models include cardiovascular disease, various cancers, osteoarthritis, physical activity, and neurological events. The model used in this study was the POHEM-BMI; the performance of each prediction step is shown in Figure 1.

Base population

To create the base population for the POHEM-BMI model, we used the 2011–2012 Korea Health Panel survey and the resident registration-based population statistics. The base population for POHEM-BMI (n=39,842,730), reflected the Korean population. Each Korean respondent 19 years of age and older (n=11,501) in 2012 was replicated using their survey-recorded weights to generate a simulated cohort of approximately 39,842,730 individuals.

167 Korea Health Panel survey data are nationally representative, and incorporate health status, chronic diseases, health risk behaviors, and socio-demographic characteristics. Among them, we extracted sex, age, current smoking status, physical activity, and the previous and current years' BMI values; these variables were required for the predictive equation. We then used a multiple linear regression model to estimate the BMI value using the extracted independent variables as predictors. The POHEM-BMI model is auto-regressive and includes previous BMI values as a main explanatory variable.[26] For comparison with other international studies using this model, the variable composition was the same, but the variable definition was not. The definition of variables was consistent with the definition of indicators in the Korea Health Statistics. A current smoker was an individual who reported smoking 'every day' or 'sometimes'. Practicing physical activity was defined as performing either intense physical activity for at least 10 continuous minutes a day, 20 minutes total per day, 3 days a week during the preceding week, or moderate physical activity for at least 30 minutes a day, 5 days a week during the preceding week. Height and weight, which are components of BMI, were based on self-reported data.

Simulation: Annual updates and risk transition

The study population was updated by aging each person by 1 year and changing the total population size based on population statistics, population projections, and complete life tables categorized by sex and age from Korean Statistics. For population projections, we assumed a medium growth scenario in terms of birth rate, life expectancy, and international migration. Each person's BMI was updated annually by applying a predictive equation that incorporates his/her own characteristics. The transition probability for each stochastic characteristic was calculated based on a generalized linear model.

We assumed that the current individual behavioral patterns persisted, and no new factors arose to prevent obesity, like the original POHEM-BMI. We also assumed that the attributes of 19-year-old individuals, which were entered annually, remained similar each year.

Model validation and calibration

We established the model's validity by comparing the projected BMI median obtained from the prediction model to estimates obtained from the Korea Health Panel survey. We set the calibration cutoff point to 5% and adjusted the model by comparing the difference between the median BMI estimates observed from the Korea Health Panel survey and the values derived from the prediction model categorized by sex and age. We analyzed the BMIs of each group by comparing the 2016 data available from the Korea Health Panel with the most recent data. We accepted a difference of less than 5% overall in the sex- and age-categorized groups. Finally, we adjusted the demographics of the 2040 population so that the predictions were within a 5% margin of error. In this study, all necessary data for model building and projection were obtained from publicly available data and does not include any identifiable personal information. Hence, no ethical approval was required, in addition to the ethical and governance approvals granted by the Korea Institute for Health and Social Affairs (KIHASA), which conducts the Korea Health Panel Survey. All participants gave written informed consent before they completed the survey.

Projection

The model projected the BMI of each person from 2017 to 2040. Based on demographic characteristics, the projections were then aggregated by year for each of the predefined subgroups. The various trends observed in the Korean population data were used to generate algorithms that were applied to future projections.

Model outputs

The BMI distributions were calculated overall and by sex. Individuals with a BMI $\geq$25 kg/m^2 were obese according to the Guidelines for the Management of Obesity in Korea, which is not the internationally accepted standard (Table 1). All analyses in this study were performed using STATA version 13 (StataCorp LLC, College Station, TX, USA).

Table 1 BMI classification of South Korea

Classification	**Body mass index (kg/m²)**
Underweight	< 18.5
Normal	18.5 – 22.9
Pre-obese	23 – 24.9
Obese class Ⅰ	25 – 29.9
Obese class Ⅱ	30 – 34.9
Obese class Ⅲ	≥ 35

Patient and public involvement

No patient involved

RESULTS

We compared the total number of the individuals and their characteristics in the initial 2012 population to those in the projected 2040 population (Table 2). There were 39,842,730 adults who were 19 years of age or older in 2012 and 43,818,808 in 2040. The male: female ratio was nearly 1:1 in both 2012 and 2040. Rapid aging of the Korean population was clearly observed when comparing the 2 populations. The average age of adults was expected to increase by 10.9 years (from 45.69 years in 2012 to 56.59 years in

2040 [from 44.57 to 55.54 years among men and 46.77 to 57.63 years among women]). In 2012, the proportion of young people (those in the 19–39 and 40–64-year age groups combined) accounted for approximately 85.54% of the adult population, while the proportion of individuals aged 65 years and older was relatively low at approximately 14%. However, the age group structure in South Korea 28 years later (2040) is predicted to be quite different, as the proportion of individuals 19–64 years (i.e., the working age population) was only 60.95% of the adult population, while the proportion of the elderly population (≥65 years) was estimated to be almost 40% of the total adult population.

Table 2 Comparison of number of people, South Korea, 2012 and 2040

	Population at baseline (2012)						***Projected population (2040)***					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**
Number of people	19,709,628		20,133,102		39,842,730		21,717,128		22,101,680		43,818,808	
Age (mean±s.d.)	44.57±15.60		46.77±16.92		45.69±16.31		55.54±18.60		57.63±19.33		56.59±19.00	
19-39	7,985,737	40.52%	7,505,824	37.29%	15,491,561	38.88%	4,873,740	22.45%	4,588,867	20.76%	9,462,607	21.60%
40-64	9,360,489	47.49%	9,230,871	45.85%	18,591,360	46.66%	8,896,886	40.97%	8,349,634	37.78%	17,246,520	39.35%
65 and above	2,363,402	11.98%	3,396,407	16.87%	5,759,809	14.45%	7,946,502	36.59%	9,163,179	41.45%	17,109,681	39.05%

Smoker	8,879,037	45.05%	450,946	2.24%	9,329,983	23.42%						
Physical activity	5,199,273	26.38%	3,103,036	15.41%	8,302,309	20.84%						

244 The model was well calibrated in both the initial population and from 2017 to 2040.
245 Differences in each of the variables estimated between 2013 and 2016, which were derived
246 from the Korea Health Panel data, were within the 5% range only when using the predictive
247 model. Additionally, when compared to the population structure for 2040 (the final year) as
248 predicted by Statistics Korea, the total population, gender, and age-specific ratio were similar.

249 Figure 2 shows the median predicted BMIs between 2017 and 2040. Each median
250 BMI value from 2013 to 2016 was estimated from the Korea Health Panel survey. The
251 median BMI for the entire adult population is predicted to increase very slightly from 23.23
252 kg/m^2 in 2018 to 23.53 kg/m^2 in 2036 and is expected to remain steady thereafter. The
253 predicted median BMI trends are similar for men; the median BMI in adult men was
254 projected to increase only slightly, from 23.74 kg/m^2 in 2018 to 23.95 kg/m^2 in 2036 and then
255 almost plateau thereafter. However, women were expected to experience a relatively steep
256 rise compared to that of men; the median BMI in adult women was projected to increase from
257 22.66 kg/m^2 in 2018 to 23.17 kg/m^2 in 2040.

258

259 The BMI distributions for men and women from 2012 to 2040 are shown in Figure 3.
260 There was no significant difference between the median BMIs in 2012 and 2040, but the
261 results according to the BMI classifications showed large changes. The proportions of 'pre-
262 obese' individuals in both sexes are predicted to increase dramatically over time, while the
263 proportions of individuals who are classified as 'normal' and 'obese' will gradually decrease.
264 As of 2025, 52.35% of all male adults were expected to be pre-obese, with that proportion
265 expected to be close to 81.23% by 2040. Moreover, 53.24% of all women were expected to
266 be 'pre-obese' by 2035, with the proportion rising to almost 59.07% by 2040.

267

268 According to the BMI classification by age group, in South Korea, in 2012, about

20.36% of the population aged 19-39 were ‘pre-obese’, but in 2040, it increased to 39.59%, almost double. The proportion of the 'normal' population was almost the same in 2012 and 2040, and the ‘obese class Ⅰ’ decreased by nearly half. However, in the population aged 40 to 64 and over 65, the proportion of ‘pre-obese’ increased almost three times in 2040 compared to that in 2012, and the proportion of ‘normal’ decreased to less than 20% (Table 3).

Table 3 Comparison of number of people, by BMI classification, South Korea, 2012 and 2040

	Population at baseline (2012)			***Projected population (2040)***		
	19-39	**40-64**	**65-**	**19-39**	**40-64**	**65-**
Number of people	15,491,561	18,591,360	5,759,809	9,462,607	17,246,520	17,109,681
BMI (median)%	22.37	23.52	23.02	23.07	23.64	23.58
Distribution of people by BMI classification						
Underweight %	11.76	5.10	7.60	2.66	0.00	0.00
Normal %	45.66	37.81	42.12	45.68	19.89	18.40
Pre-obese %	20.36	26.51	24.10	39.59	76.60	80.31
Obese class Ⅰ %	20.67	28.40	24.85	11.70	3.51	1.29
Obese class Ⅱ %	1.51	1.79	1.30	0.36	0.00	0.00
Obese class Ⅲ %	0.03	0.38	0.02	0.02	0.00	0.00

DISCUSSION

The purpose of this study was to predict the prevalence of obesity in South Korea in the year 2040 using a microsimulation model. In this study, we strove to predict future adult obesity rates in South Korea using the POHEM-BMI, which was developed by Statistics Canada. Summarizing the predicted results, the median BMI of South Korea's adult population aged 19 years and older was expected to be 23.55 in 2040, while the percentage of 'pre-obese' individuals was expected to increase over time. While it is encouraging that the proportion of 'obese' people (i.e., those with BMIs ≥25 kg/m^2) in 2040 is predicted to be much lower than that in 2012, it is discouraging that the proportion of 'normal' individuals is also markedly lower. Most notably, the pre-obesity rate is predicted to rise dramatically. In addition to the sex and age variables, our model includes only smoking and physical activity as health-related behaviors. The distributions of these factors were assumed to remain equal across the years; hence, our data show that maintaining smoking and physical activity rates at 2012 levels among adults will lead to a sharp increase in the 'pre-obese' population by 2040.

To the best of our knowledge, the only other study that predicted future obesity rates among South Korean adults was the investigation by Baik.[2] That study explored factors affecting adult as well as abdominal obesity, and constructed forecasting models to predict obesity prevalence rates in 2020 and 2030 using the Korea National Health and Nutritional Examination Survey (KNHANES). The prevalence rates of obesity among men and women in that study were predicted to be 47% and 32%, respectively, in 2020 and 62% and 37%, respectively, in 2030; these data were inconsistent with our results. The differences in prediction results appeared to be caused by the different secondary sources and prediction models in the two studies. First, in Baik's study, a prediction model was constructed by applying a linear regression model and an autoregressive integrated moving average model using the KNHANES data. The dependent variable in the prediction model was BMI, and the independent variables included the survey year, age, marital status, job status, income status, smoking, alcohol consumption, sleep duration, psychological factors, dietary intake, and fertility rate. In contrast, in this study, the Korea Health Panel data was used as the data source, and BMI was predicted by performing microsimulation with sex, age, smoking, physical activity, and previous years' BMIs as independent variables. Therefore, the method of measurement of the dependent variable, BMI differs between the studies; unlike the KNHANES, which contains body-measured height and weight information, the Korea Health Panel (although this is a representative data source) generates data based on self-reported by respondents, which may underestimate obesity. Inevitably, the obesity rate in the initial population according to the KNHANES tended to be higher; as such, a higher initial prevalence rate would lead to a higher projection.[34]

We also tried to compare the results from this study with the predicted estimate by country, but few studies have empirically predicted the prevalence of obesity in the future using simulation models. One study compiled nationally-representative data from various sources and predicted the future prevalence of overweight and obesity in Indian adults aged 20-69 years will reach 30.5% and 9.5% among men, 27.4% and 13.9% among women, respectively, by 2040.[35] According to a study that estimated the prevalence of obesity in the future through regression modeling, 42% of Americans were expected to be obese by 2030.[36] Similarly, a study that predicted the prevalence of obesity in Australian adults by 2025 using a multiple linear regression model predicted that 83% of male adults over the age of 20 and 75% of female adults would be overweight or obese.[37] In all three countries, India, the United States, and Australia, overweight and obesity were defined according to the classifications defined by the WHO, and much higher values were found than those in Korea. We also compared our results to those predicted in Canada using the same model, and 59% of the adult Canadian population was predicted to be 'overweight or obese' by 2030.

This study defined obesity by applying the BMI classification system according to 2018 Korean Society for the Study of Obesity guideline for the management of obesity in Korea. It would be appropriate to use international standards for comparison; however, it is necessary to reflect the situation of individual countries in the management of obesity for the purpose of preventing and managing chronic diseases. Therefore, rather than emphasizing the BMI classification criteria, more research is needed to determine the BMI values that can significantly predict the occurrence of chronic diseases. In other words, it is necessary to continuously accumulate sufficient epidemiologic evidence for the relationship between the BMI and the actual risk of disease and death for Koreans, and based on such evidence, efforts to establish appropriate diagnostic and medical standards for Koreans are needed. In particular, the relationship is likely to vary by age and sex; hence, it should be considered too. Here, the obesity standard has been applied collectively regardless of sex and age. However, in order to deviate from a uniform approach to obesity, gender- and age-based approaches are needed, considering the changes in hormones and body composition.

Because health management policies including obesity management require a large budget, it is most important to establish cost-effective policies. The results from this study made it possible to determine the obese high-risk group by sex and age group, and estimate medical needs. As it is necessary to apply obesity standards differently according to sex and age group, it is difficult to set the 'National Health Promotion Comprehensive Plan' goals. This plan needs to suggest additional, wider-ranging goals considering the characteristics of each sex and age group, rather than presenting goals for obesity prevalence among adult men and women. In this case, the goal should be presented at an achievable level in consideration of future prediction patterns. Finally, systematic public health interventions, which are tailored to individual characteristics need to be established.

Findings from this study should be interpreted with consideration of several limitations. First, since a microsimulation model for predicting obesity prevalence has not been developed in this country, we borrowed the model developed by Statistics Canada, and it may not fit the domestic situation; nonetheless, we defined each variable in the predictive equation according to the operational definition in Korea Health Statistics. However, if the model is more suited to the domestic situation, besides sex, age, smoking, physical activity, and previous year's BMI value, various factors related to BMI may be added to the predictors of BMI. However, in this study, as we faithfully followed the existing model and explored the possibility of domestic application, the process of constructing a prediction equation was omitted. In the future, research to develop a new model of microsimulation in the field of healthcare for domestic conditions will be very valuable. In this process, it is necessary to consider practical suitability and efficiency in selecting basic data, module-specific behavioral equations, and variables for use in the model. Second, we had limited data sources. There is a difference between the current prevalence of obesity calculated from the Korea Health Panel data used in this study and the Korea Health Statistics using the KNHANES. As of 2011, the prevalence of adult obesity in Korea Health Statistics was 31.9%, and the prevalence of adult obesity calculated by the Korea Health Panel data was 23.7%, a difference of 8.2%.[38] As mentioned earlier in the difference between the results of Baik's study, this difference originated from the method of measuring BMI in the two data sources. However, in the POHEM-BMI model used in this study, the BMI of the previous year was regarded as the main explanatory variable, and therefore, the Korea Health panel data that followed the same participants once a year was inevitably used. In addition, the original POHEM-BMI model includes the process of converting self-reported BMI into a measured BMI, but we omitted this due to limitations of the data source. Third, we assumed that the attributes of 19-year-old individuals entered each year remain at a similar level each year. This means that the individual attributes of 19-year-old adults are the same for 29 years

377 from 2012 to 2040; thus, it can be considered somewhat less realistic. In future studies, it is
378 expected that more meaningful and realistic results will be derived if the model is constructed
379 by reflecting the trend of changes in the attributes of the 19-year-old population and updating
380 it according to the year.

381 Nevertheless, our study is the first to examine the possibility of using
382 microsimulation to predict future BMI medians in South Korea. Additionally, the BMI of the
383 future adult population was predicted after considering the change in population structure at
384 the macro level as well as individual health behavior components at the micro level.

385

386 **CONCLUSION**

387 The key finding of this study is that by 2040, 70.05% of Korean adults are predicted
388 to be pre-obese. Utilizing data sources available in Korea, the possibility of applying and
389 expanding on the concept of microsimulation was explored. In future studies, a model
390 suitable for South Korea needs to be developed, and the effectiveness of specific health
391 policies ought to be assessed by applying various relevant scenarios to the basic forecasting
392 model.

393

394 **Abbreviations**

395 BMI: body mass index; KNHANES: Korea National Health and Nutritional
396 Examination Survey, POHEM: Population Health Model

397 **Authors' Contributions**

398 YS (the first author) designed the study, analyzed, and interpreted the data, and wrote
399 the paper. YE participated in the statistical analysis. DS aided in the interpretation of the data
400 and preparation of the manuscript. SJ (the corresponding author) directed this study. All
401 authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics approval

This study used publicly available data of Korea Health Panel Survey 2011-2012 from the Korea Institute for Health and Social Affairs and the National Health Insurance, population statistics based on resident registration, population projections, complete life tables and future mortality rates from Statistics Korea. The dataset does not contain any identifiable personal information. Ethical approval was given by the Institutional Review Board of Korea University, Seoul, Korea (IRB No. KUIRB-2020-0018-01).

Data sharing statement

The Korea Health Panel Survey data used in this article is available in https://www.khp.re.kr:444/eng/data/data.do. Detailed information on the survey design and data characteristics are provided at https://www.khp.re.kr:444/eng/survey/sampling.do. Population statistics, population projections, and complete life tables are available from http://kosis.kr/eng/.

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Figure legends

Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012–2040

Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012–2040

Figure 3A Projection of distribution of BMI, adults aged 19 years and older, South Korea, 2012–2040

Figure 3B Projection of distribution of BMI, men aged 19 years and older, South Korea, 2012–2040

Figure 3C Projection of distribution of BMI, women aged 19 years and older, South Korea, 2012–2040

Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012-2040

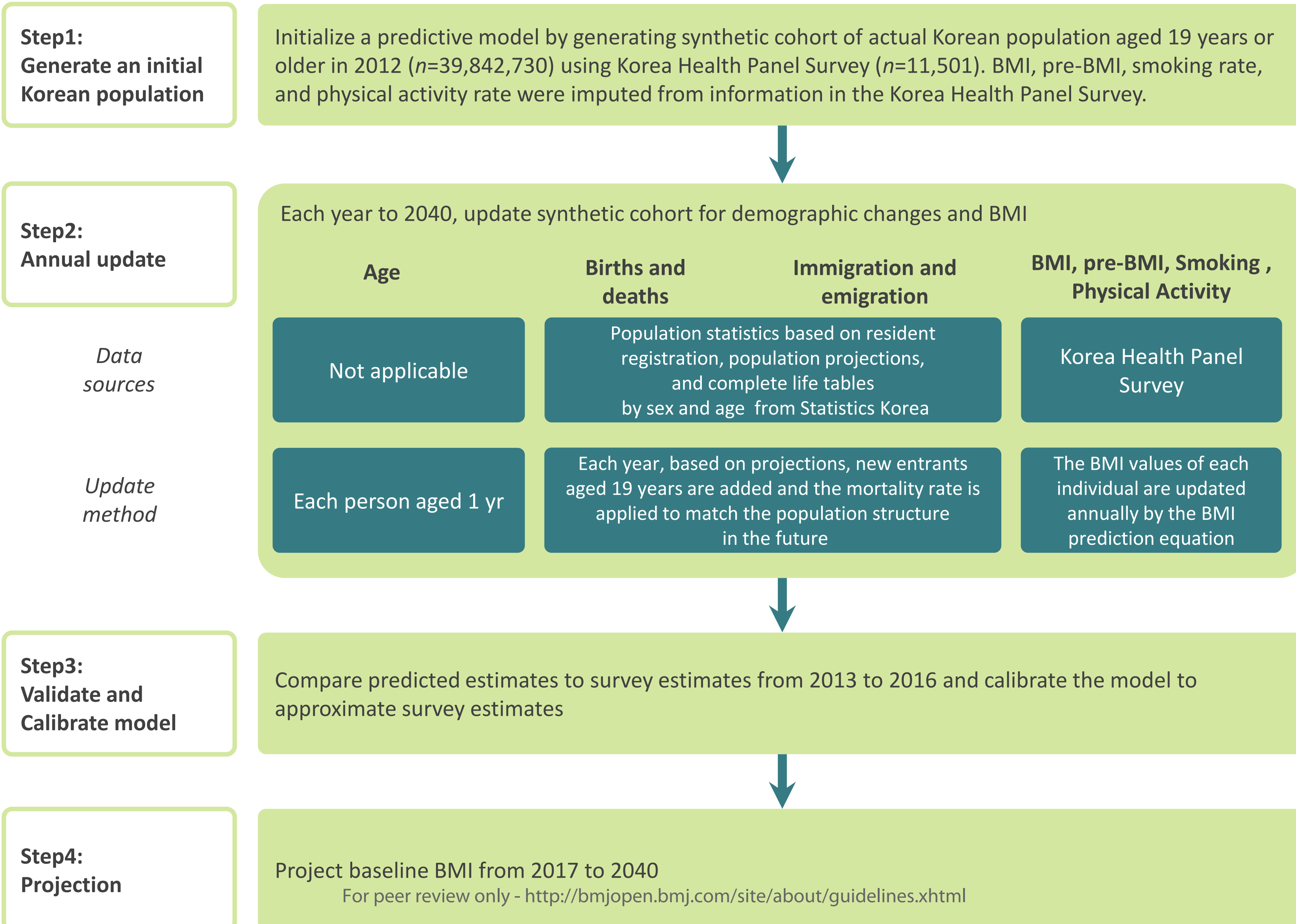


Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012-2040

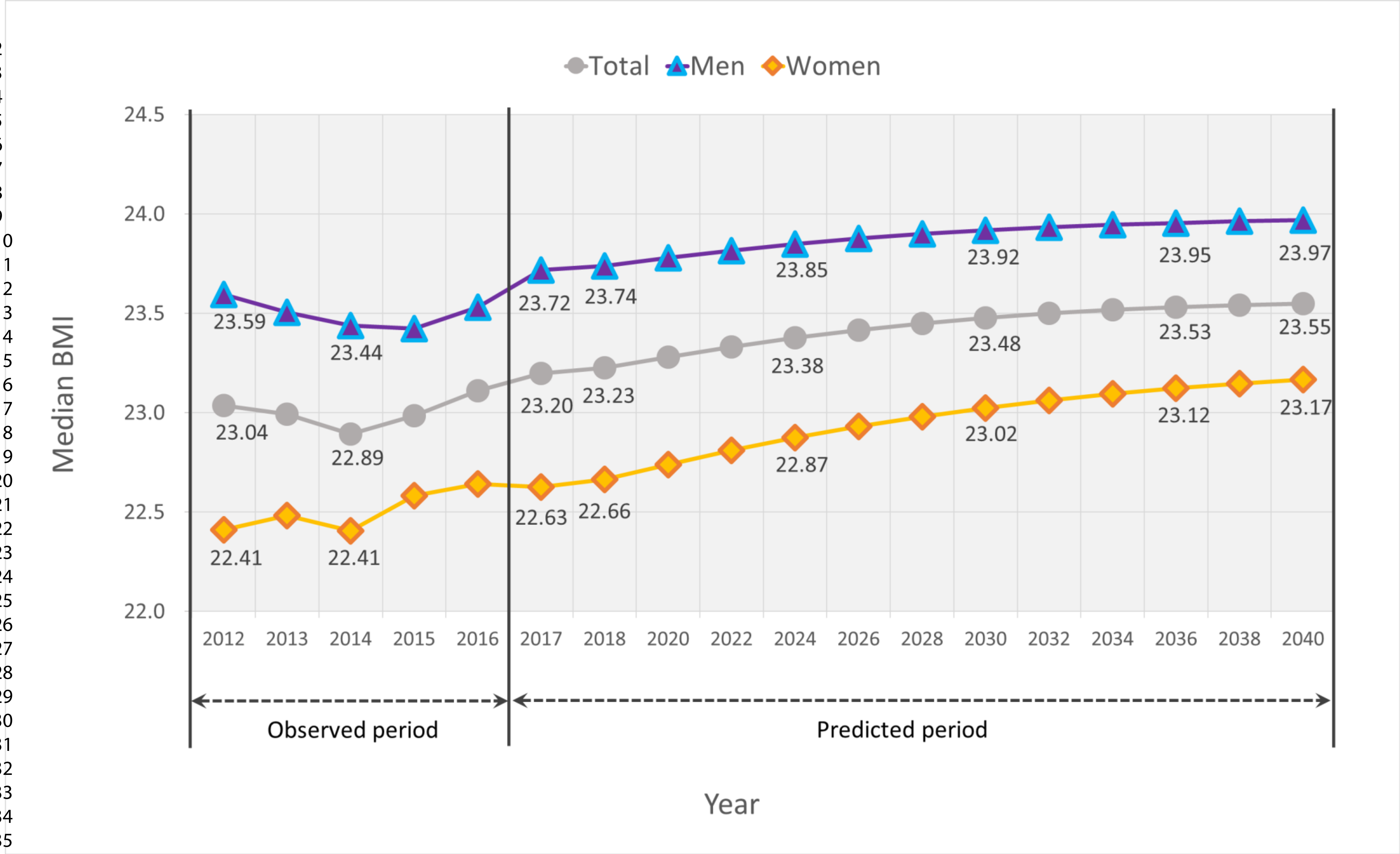


Figure 3 Projection of distribution of BMI, (A) Adults, (B) Men and (C) Women, aged 19 years and older, South Korea, 2012-2040

A

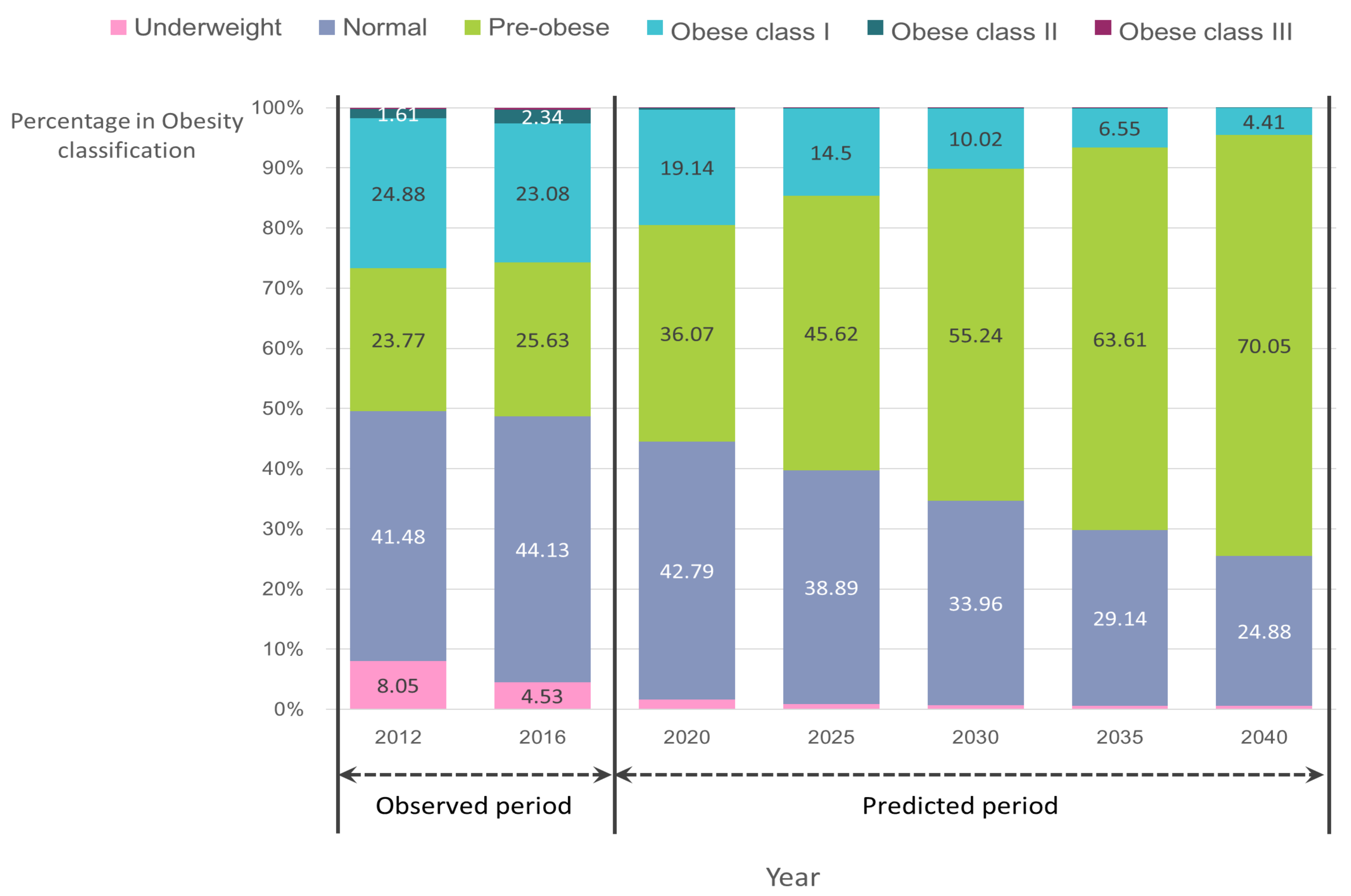


Figure 3 Projection of distribution of BMI, (A) Adults, (B) Men and (C) Women, aged 19 years and older, South Korea, 2012-2040

B

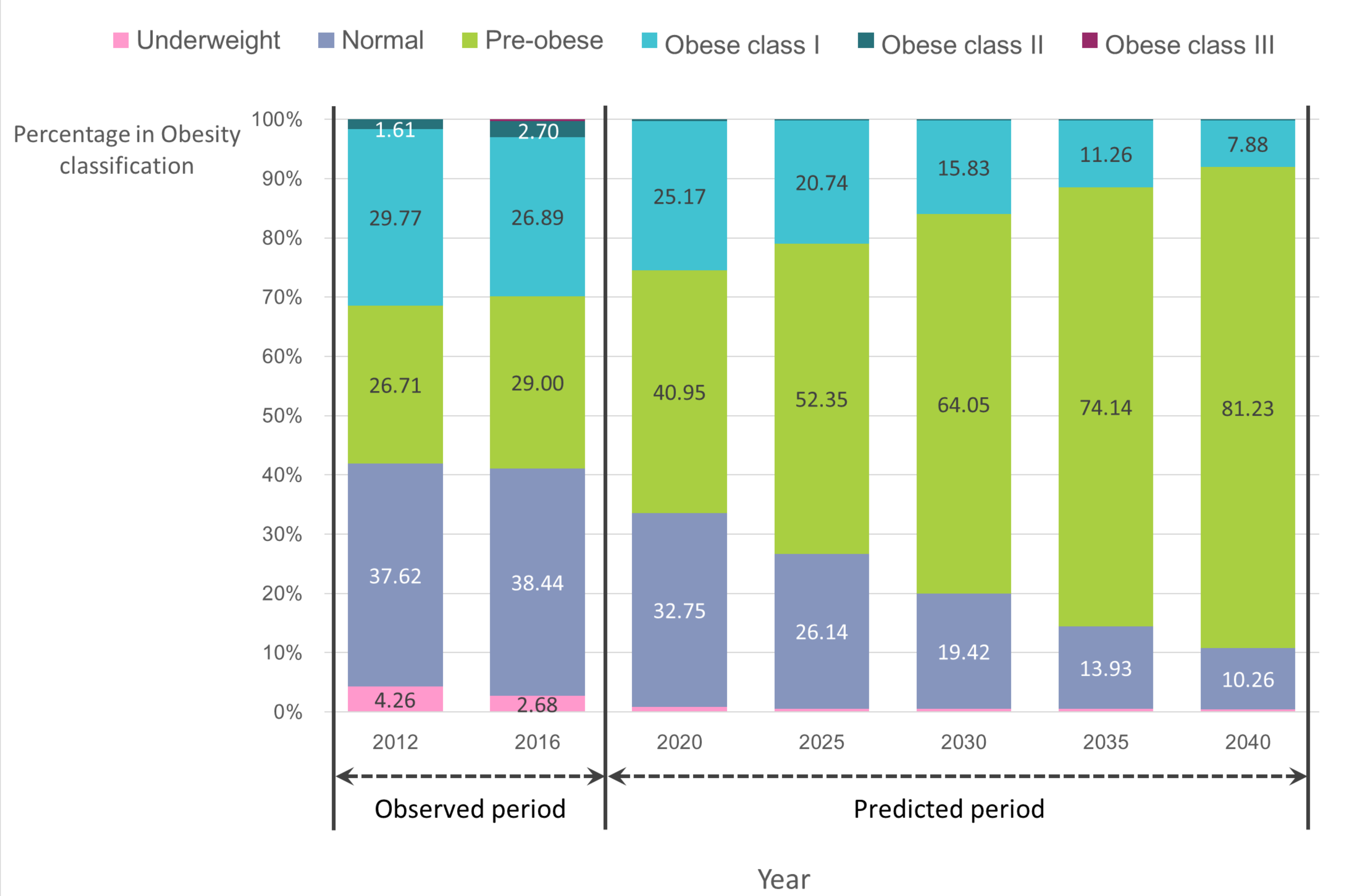
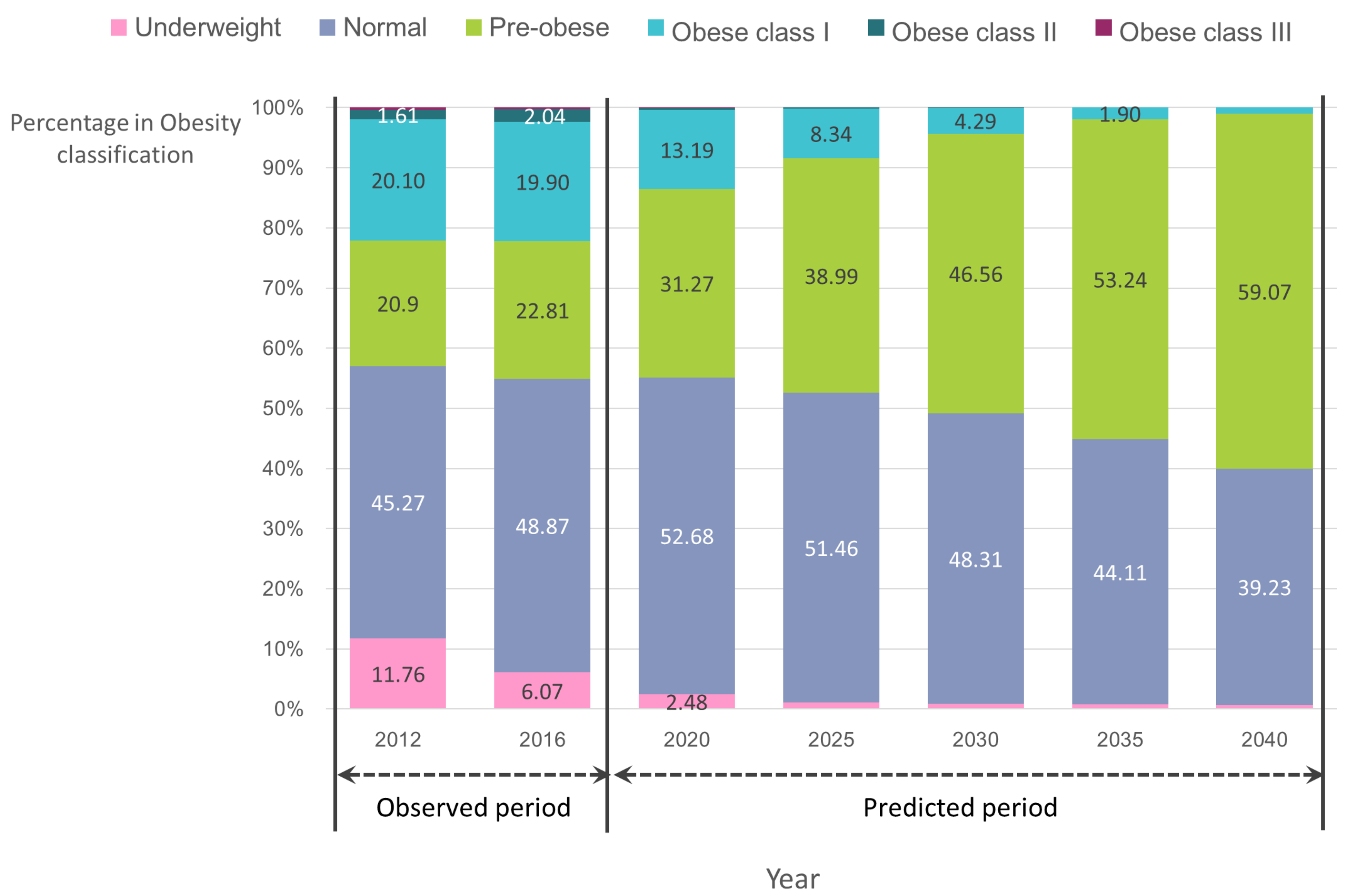


Figure 3 Projection of distribution of BMI, (A) Adults, (B) Men and (C) Women, aged 19 years and older, South Korea, 2012-2040

C



Title: Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

Authors: Yoon-Sun Jung [a*], Young-Eun Kim[b], Dun-Sol Go[c], Seok-Jun Yoon[d]

Affiliations:

[a]Department of Public Health, Graduate School, Korea University, Seoul, Korea

[b]Big Data Department, National Health Insurance Service, Wonju, Korea

[c]Department of Health Care Policy Research, Korea Institute for Health and Social Affairs

[d]Department of Preventive Medicine, Korea University College of Medicine, Seoul, Korea

Corresponding author:

Seok-Jun Yoon, M.D., Ph.D.

Department of Preventive Medicine, Korea University College of Medicine,

73, Goryeodae-ro, Seongbuk-gu, Seoul, 02841, Korea

E-mail: yoonsj02@korea.ac.kr

E-mail addresses:

sunnyaurora@nate.com (Yoon-Sun Jung)

kimyes4454@gmail.com (Young-Eun Kim)

kds237@gmail.com (Dun-Sol Go)

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ABSTRACT

Objective To project the prevalence of obesity in 2040 among individuals 19 years and older in South Korea.

Design, setting, and participants Using the 'Population Health Model-Body Mass Index' (POHEM-BMI) microsimulation model, the prevalence of obesity in Korean adults 19 years and older was projected until 2040. The model integrated individual survey data from the Korea Health Panel Survey of 2011 and 2012, population statistics based on resident registration, population projections, and complete life tables categorized by sex and age. Birth rate, life expectancy, and international migration were based on a medium growth scenario. The base population of Korean adults in 2012, devised through data aggregation, was 39,842,730. The prediction equations were formulated using BMI as the dependent variable; the individual's sex, age, smoking status, physical activity, and preceding year's BMI were used as predictive factors.

Outcome measure BMI categorized by sex.

Results The median BMI for Korean adults in 2040 was forecast to be 23.55 kg/m^2 (23.97 and 23.17 kg/m^2 for men and women, respectively). According to the Korean BMI classification, 70.05% of all adults were forecast to be 'pre-obese' (i.e., have BMIs 23 to 24.9) by 2040 (81.23% of men and 59.07% of women) and 24.88% to be 'normal'.

Conclusions We explored the possibility of applying and expanding on the concept of microsimulation in the field of healthcare by combining data sources available in Korea~~In future studies, it is necessary to develop a microsimulation model suitable for Korea's domestic situation, and it is necessary to evaluate the effectiveness of special health policies by applying various prediction scenarios to the basic model.~~ and found that more than half of the adults in this study population will be pre-obese, and the proportions of "obesity" and

"normal" will decrease compared with those in 2012. The results of our study will aid in devising healthy strategies and spreading public awareness for preventing this condition.

Strengths and limitations of this study

- To the best of our knowledge, this is the first study to use a microsimulation model to predict future obesity prevalence in Korea considering the change in population structure (macro level) as well as individual health behavior components (micro level).
- The results of our study aid ~~has the greatest significance~~ in ~~exploring the possibility of applying and expanding the concept of microsimulation in the field of healthcare by combining data sources available in Korea.~~ suggesting additional and wider-ranging strategies for obesity prevention by considering sex and age group in the formulation of the 'National Health Promotion Comprehensive Plan'.
- Although a representative data source was used in this study, the prevalence of obesity may be underestimated because it is based on a self-reported BMI value.
- ~~The estimated BMI value differs from the Korea Health Statistics, which is based on the data measured by actual measurement.~~
- ~~There is a limitation that it does not accurately reflect the domestic situation because it borrows a micro-simulation model developed abroad.~~ This study uses a micro-simulation model developed abroad, and hence, may not reflect the domestic situations accurately.
- Another limitation is that we assumed the attributes of 19-year-old individuals to remain similar each year.

BACKGROUND

The prevalence of overweight and obesity has increased markedly over the past 3 decades, and concerns about health risks associated with obesity have become almost universal.[1] The increasing rate of obesity is a growing public health concern not only in Western countries but also in South Korea.[2] From the 1990s through the beginning of the new millennium, the prevalence of adult and child obesity has increased rapidly and continues to rise steadily in parallel with rapid social and economic development.[3]

Obesity is not only a major public health problem in itself, but also a factor in the development of many chronic diseases; hence, it constitutes a strain on individuals and health systems worldwide. ~~In the Global Burden of Disease Study,[4] globally in 2017, a high body mass index (BMI) accounted for 4.72 million deaths and 148.0 million disability-adjusted life-years.~~ It is associated with an increased risk of many disorders, including diabetes, hypertension, dyslipidemia, heart disease, stroke, sleep apnea, early death, and cancer.[4-8] Moreover, obesity among older people increases the risk of knee osteoarthritis[9] and reduces functional capacity and quality of life.[10-13] The prevalence of these conditions rises in proportion to the increase in obesity[14-17] ~~commensurate with increased obesity~~ and is associated with ~~significant morbidity, higher risks of mortality, and~~ increased economic costs for both individuals and the society at large.[18] A study of data from the National Health Insurance Service in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US dollars.[19]

Meanwhile, with respect to worldwide comparisons, whether cutoff points for overweight and obesity should be lower for Asians than for another ethnic groups remains debatable.[20] The World Health Organization has proposed BMIs of 18.5–22.9 kg/m^2 as optimal, 23–24.9 kg/m^2 as overweight, 25–29.9 kg/m^2 as moderate obesity, and ≥30 kg/m^2 as severe obesity for Asians.[21] ~~However, it is more important to determine particular BMI~~

~~values that increase the likelihood of developing particular chronic disease, depending on the sex and age of the individual.~~ The Korean Society of Obesity, which was established to improve obesity management through research and education, revised its clinical practical guidelines for the prevention and treatment of obesity in 2018. The new guidelines renamed the "overweight" category to "pre-obese", and divided obesity into 3 categories, thereby aiming to highlight the risk of obesity instead of promoting the term "overweight." The most recent guidance is based in part on data of 84,690,131 Korean adults extracted from the Korean National Health Insurance Service Health Checkup Database between 2006 and 2015. By including the entire population registered in the National Health Insurance Service Database, they calculated the first and second cutoff points corresponding to the increased risk of any of the 3 accompanying diseases (type 2 diabetes, hypertension, and dyslipidemia) The first cutoff BMI level was 23 kg/m^2, and the second cutoff BMI level was ~~The first and second BMI cutoff levels were reported to be 23 kg/m^2 and~~ 25 kg/m^2, ~~respectively,~~ suggesting the necessity of obesity criteria that accurately reflect the risk of chronic disease among Koreans.[22,23]

~~A study of data from the National Health Insurance Service in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US dollars; medical expenses accounted for 51.3% of this amount, followed by decreasing productivity (20.5%), productivity loss (13.1%), early mortality (10.0%), care costs (4.3%), and transportation costs (0.8%).[24] Several studies on the long-term trends of obesity prevalence in South Korea found that obesity is increasing in men but not in women.[25-27]~~ Although numerous investigators in other countries have attempted to predict the future prevalence of obesity, only one such study by Inkyung Baik was recently performed in South Korea.[2] More recent trends still need to be investigated through predictive studies, and the accurate prediction of obesity prevalence remains an important public health-related goal in the country. To efficiently establish and execute an effective healthcare policy, which would require a large budget, it is necessary to select future targets for policy interventions (such as high-risk groups) to predict healthcare needs and prevent budget waste.

Past prediction models incorporated a country's entire population; as such, macroscopic inferences based on average projections for the future society were generalized. However, when establishing a healthcare policy, it is necessary to estimate the future disease burden and medical needs of the entire population based on future projections that reflect individual characteristics because a real-world understanding of factors that are influenced by policies or institutions is required. Individuals are independent entities with different characteristics and needs that govern their future decisions and behaviors. By applying these needs, health-related projections can be modeled to reflect health risk factors such as sex, age, life cycle activities, smoking, etc., and the effects of policy interventions can be quantified.[24] In this regard, we aimed to predict the prevalence of obesity in Korea by using microsimulation, which is optimal for considering individual properties.

Microsimulation is a modeling technique, which typically uses individual microunits, each with its own set of properties, to simulate downstream events based on the probability of transition between predefined states and their changes over time. When used in medicine, microsimulation can be particularly powerful because it preserves the patterns of previous behaviors and conditions, and allows for a clearer representation and understanding of how various processes affect the total outcome of the population over time.[25]~~In other words, microsimulation can predict the burden of disease by modeling various health risk factors that occur during an individual's lifetime.~~ Given macro-effects such as changes in population structures in the forecasting model, microsimulation is very useful as it can estimate both disease burdens and medical needs across the country.[24] ~~Collecting individual events from within a population that has varying attributes can be used to predict and plan outcomes (such~~

~~as incidence, prevalence, and cost), and can also be used to assess the clinical and cost effectiveness of alternative health interventions.[29]~~ Microsimulation modeling is particularly useful for studying BMI trends because it can simultaneously explain population dynamics such as aging~~, migration,~~ and mortality. Additionally, the longitudinal framework of these models allows for interpreting a person's change in BMI as it is affected by factors such as a person's physical activity and behavior, and thus, acts as a contributing factor for other diseases.[26] However, while microsimulation models have been steadily evolving across health- and economy-related fields in many European countries,[27] they are yet to be actively utilized in South Korea (especially for healthcare).

Obesity prevalence and trend estimates provide important information for research, policy, and intervention.[28] ~~As mentioned above, it is necessary to estimate the magnitude of obesity because it has been identified as a risk factor for various chronic diseases.~~ Because health forecasting predicts disease episodes and portends future events, it facilitates healthcare strategies by promoting the setting of goals to reduce obesity, establish health promotion interventions, and optimize resource allocation.[29] Obesity trends may also be used to urge governments to implement preventative approaches for reducing obesity.[30] Based on the above findings, we performed this study to project the future trends in obesity prevalence in South Korea up to the year 2040.

METHODS

Model

We used the Population Health Model (POHEM)-BMI to estimate the prevalence of obesity among adults 19 years and older in South Korea from 2012 through 2040. In brief, POHEM is a time-continuous, population-based, dynamic microsimulation model with individual underlying units of analysis used worldwide. Dynamic microsimulation, in the context of social science and population health, is a simulation of individuals (i.e., micro-level) and their behaviors, statuses, and actions (dynamics) over time.[31] These are modeled as desired using multiple sources of empirical data, including cross-sectional surveys, administrative databases, vital statistics, and census data.[32]

Through dynamic simulation, POHEM creates a population and ages it, one person at a time, until death.[33] The model dynamically simulates an individual's disease state, risk factors, and health determinants to describe and plan health outcomes.[32] POHEM is accessible because it wants the general process to be constant across the country's population, with the exception of variables unique to each country, such as marriage and mortality. The POHEM models include cardiovascular disease, various cancers, osteoarthritis, physical activity, and neurological events. The model used in this study was the POHEM-BMI; the performance of each prediction step is shown in Figure 1.

Base population

To create the base population for the POHEM-BMI model, we used the 2011–2012 Korea Health Panel survey and the resident registration-based population statistics. The base population for POHEM-BMI (n=39,842,730), reflected the Korean population. Each Korean respondent 19 years of age and older (n=11,501) in 2012 was replicated using their survey-recorded weights to generate a simulated cohort of approximately 39,842,730 individuals. Korea Health Panel survey data are nationally representative, and incorporate health status, chronic diseases, health risk behaviors, and socio-demographic characteristics. Among them, we extracted sex, age, current smoking status, physical activity, and the previous and current years' BMI values; these variables were required for the predictive equation. We then used a multiple linear regression model to estimate the BMI value using the extracted independent variables as predictors. The POHEM-BMI model is auto-regressive and includes previous BMI values as a main explanatory variable.[26] For comparison with other international studies using this model, the variable composition was the same, but the variable definition was not. The definition of variables was consistent with the definition of indicators in the Korea Health Statistics. A current smoker was an individual who reported smoking 'every day' or 'sometimes'. Practicing physical activity was defined as performing either intense physical activity for at least 10 continuous minutes a day, 20 minutes total per day, 3 days a week during the preceding week, or moderate physical activity for at least 30 minutes a day, 5 days a week during the preceding week. Height and weight, which are components of BMI, were based on self-reported data.

Simulation: Annual updates and risk transition

The study population was updated by aging each person by 1 year and changing the total population size based on population statistics, population projections, and complete life tables categorized by sex and age from Korean Statistics. For population projections, we assumed a medium growth scenario in terms of birth rate, life expectancy, and international migration. Each person's BMI was updated annually by applying a predictive equation that incorporates his/her own characteristics. The transition probability for each stochastic characteristic was calculated based on a generalized linear model.

We assumed that the current individual behavioral patterns persisted, and no new factors arose to prevent obesity, like the original POHEM-BMI. We also assumed that the attributes of 19-year-old individuals, which were entered annually, remained similar each year.

Model validation and calibration

We established the model's validity by comparing the projected BMI median obtained from the prediction model to estimates obtained from the Korea Health Panel survey. We set the calibration cutoff point to 5% and adjusted the model by comparing the difference between the median BMI estimates observed from the Korea Health Panel survey

224 and the values derived from the prediction model categorized by sex and age. We analyzed
225 the BMIs of each group by comparing the 2016 data available from the Korea Health Panel
226 with the most recent data. We accepted a difference of less than 5% overall in the sex- and
227 age-categorized groups. Finally, we adjusted the demographics of the 2040 population so that
228 the predictions were within a 5% margin of error. In this study, all necessary data for model
229 building and projection were obtained from publicly available data and does not include any
230 identifiable personal information. Hence, no ethical approval was required, in addition to the
231 ethical and governance approvals granted by the Korea Institute for Health and Social Affairs
232 (KIHASA), which conducts the Korea Health Panel Survey. All participants gave written
233 informed consent before they completed the survey.

234 **Projection**

235 The model projected the BMI of each person from 2017 to 2040. Based on demographic
236 characteristics, the projections were then aggregated by year for each of the predefined
237 subgroups. The various trends observed in the Korean population data were used to generate
238 algorithms that were applied to future projections.

239 **Model outputs**

240 The BMI distributions were calculated overall and by sex. Individuals with a BMI $\geq$25
241 kg/m^2 were obese according to the Guidelines for the Management of Obesity in Korea,
242 which is not the internationally accepted standard (Table 1). All analyses in this study were
243 performed using STATA version 13 (StataCorp LLC, College Station, TX, USA).

244

245 **Table 1** BMI classification of South Korea

Classification	**Body mass index (kg/m^2)**

Underweight	< 18.5
Normal	18.5 – 22.9
Pre-obese	23 – 24.9
Obese class Ⅰ	25 – 29.9
Obese class Ⅱ	30 – 34.9
Obese class Ⅲ	≥ 35

Patient and public involvement

No patient involved

RESULTS

We compared the total number of the individuals and their characteristics in the initial 2012 population to those in the projected 2040 population (Table 2). There were 39,842,730 adults who were 19 years of age or older in 2012 and 43,818,808 in 2040. The male: female ratio was nearly 1:1 in both 2012 and 2040. Rapid aging of the Korean population was clearly observed when comparing the 2 populations. The average age of adults was expected to increase by 10.9 years (from 45.69 years in 2012 to 56.59 years in 2040 [from 44.57 to 55.54 years among men and 46.77 to 57.63 years among women]). In 2012, the proportion of young people (those in the 19–39 and 40–64-year age groups combined) accounted for approximately 85.54% of the adult population, while the proportion of individuals aged 65 years and older was relatively low at approximately 14%. However, the age group structure in South Korea 28 years later (2040) is predicted to be quite different, as the proportion of individuals 19–64 years (i.e., the working age population) was only

60.95% of the adult population, while the proportion of the elderly population (≥65 years) was estimated to be almost 40% of the total adult population.

Table 2 Comparison of number of people, South Korea, 2012 and 2040

	Population at baseline (2012)						*Projected population (2040)*					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**
Number of people	19,709,628		20,133,102		39,842,730		21,717,128		22,101,680		43,818,808	
Age (mean±s.d.)	44.57±15.60		46.77±16.92		45.69±16.31		55.54±18.60		57.63±19.33		56.59±19.00	
19-39	7,985,737	40.52%	7,505,824	37.29%	15,491,561	38.88%	4,873,740	22.45%	4,588,867	20.76%	9,462,607	21.60%
40-64	9,360,489	47.49%	9,230,871	45.85%	18,591,360	46.66%	8,896,886	40.97%	8,349,634	37.78%	17,246,520	39.35%
65 and above	2,363,402	11.98%	3,396,407	16.87%	5,759,809	14.45%	7,946,502	36.59%	9,163,179	41.45%	17,109,681	39.05%

Smoker	8,879,037	45.05%	450,946	2.24%	9,329,983	23.42%						
Physical activity	5,199,273	26.38%	3,103,036	15.41%	8,302,309	20.84%						

There was no significant difference between the median BMIs in 2012 and 2040; however, according to the BMI classification in South Korea, approximately 41.48% of the adult population was 'normal' in 2012, whereas only 24.88% of the population was predicted to be the same in 2040. (see Table 3) On the other hand, the 'pre-obese' group was expected to account for approximately 70% of the total adult population.

Table 3 Comparison of number of people, by BMI classification, South Korea, 2012 and 2040

	Population at baseline (2012)						*Projected population (2040)*					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**	**Number**	**(Percentage)**
BMI (median)	23.59		22.41		23.04		23.97		23.17		23.55	
Number of people by BMI classification												
Underweight	840,251	(4.26)	2,368,051	(11.76)	3,208,302	(8.05)	98,954	(0.46)	152,500	(0.69)	251,454	(0.57)
Normal	7,414,311	(37.62)	9,114,015	(45.27)	16,528,326	(41.48)	2,228,567	(10.26)	8,671,481	(39.23)	10,900,048	(24.88)
Pre-obese	5,264,86	(26.71)	4,207,67	(20.90)	-	(23.77	17,641,66	(81.23)	13,055,48	(59.0	30,697,15	(70.05)

	6		3		9,472,539	)	8		2	7)	0	
Obese class I	5,867,369	(29.77)	4,046,607	(20.10)	- 9,913,976	(24.88)	1,712,332	(7.88)	221,829	(1.00)	1,934,161	(4.41)
Obese class II	318,297	(1.61)	— 324,205	(1.61)	— 642,502	(1.61)	33,455	(0.15)	388	(0.00)	33,843	(0.08)
Obese class III	4,534	(0.02)	— 72,551	(0.36)	— 77,085	(0.19)	2,152	(0.01)	0	(0.00)	2,152	(0.00)

The model was well calibrated in both the initial population and from 2017 to 2040. Differences in each of the variables estimated between 2013 and 2016, which were derived from the Korea Health Panel data, were within the 5% range only when using the predictive model. Additionally, when compared to the population structure for 2040 (the final year) as predicted by Statistics Korea, the total population, gender, and age-specific ratio were similar.

Figure 2 shows the median predicted BMIs between 2017 and 2040. Each median BMI value from 2013 to 2016 was estimated from the Korea Health Panel survey. The median BMI for the entire adult population is predicted to increase very slightly from 23.23 kg/m^2 in 2018 to 23.53 kg/m^2 in 2036 and is expected to remain steady thereafter. The predicted median BMI trends are similar for men; the median BMI in adult men was projected to increase only slightly, from 23.74 kg/m^2 in 2018 to 23.95 kg/m^2 in 2036 and then almost plateau thereafter. However, women were expected to experience a relatively steep rise compared to that of men; the median BMI in adult women was projected to increase from 22.66 kg/m^2 in 2018 to 23.17 kg/m^2 in 2040.

The BMI distributions for men and women from 2012 to 2040 are shown in Figure 3. There was no significant difference between the median BMIs in 2012 and 2040, but the results according to the BMI classifications showed large changes. The proportions of 'pre-obese' individuals in both sexes are predicted to increase dramatically over time, while the proportions of individuals who are classified as 'normal' and 'obese' will gradually decrease. As of 2025, 52.35% of all male adults were expected to be pre-obese, with that proportion expected to be close to 81.23% by 2040. Moreover, 53.24% of all women were expected to be 'pre-obese' by 2035, with the proportion rising to almost 59.07% by 2040.

According to the BMI classification by age group, in South Korea, in 2012, about

20.36% of the population aged 19-39 were ‘pre-obese’, but in 2040, it increased to 39.59%, almost double. The proportion of the 'normal' population was almost the same in 2012 and 2040, and the ‘obese class Ⅰ’ decreased by nearly half. However, in the population aged 40 to 64 and over 65, the proportion of ‘pre-obese’ increased almost three times in 2040 compared to that in 2012, and the proportion of ‘normal’ decreased to less than 20% (Table 3).

Table 3 Comparison of number of people, by BMI classification, South Korea, 2012 and 2040

	Population at baseline (2012)			*Projected population (2040)*		
	19-39	**40-64**	**65-**	**19-39**	**40-64**	**65-**
Number of people	15,491,561	18,591,360	5,759,809	9,462,607	17,246,520	17,109,681
BMI (median)%	22.37	23.52	23.02	23.07	23.64	23.58
Distribution of people by BMI classification						
Underweight %	11.76	5.10	7.60	2.66	0.00	0.00
Normal %	45.66	37.81	42.12	45.68	19.89	18.40
Pre-obese %	20.36	26.51	24.10	39.59	76.60	80.31
Obese class Ⅰ %	20.67	28.40	24.85	11.70	3.51	1.29
Obese class Ⅱ %	1.51	1.79	1.30	0.36	0.00	0.00
Obese class Ⅲ %	0.03	0.38	0.02	0.02	0.00	0.00

DISCUSSION

The purpose of this study was to predict the prevalence of obesity in South Korea in the year 2040 using a microsimulation model. In this study, we strove to predict future adult obesity rates in South Korea using the POHEM-BMI, which was developed by Statistics Canada. Summarizing the predicted results, the median BMI of South Korea's adult population aged 19 years and older was expected to be 23.55 in 2040, while the percentage of 'pre-obese' individuals was expected to increase over time. While it is encouraging that the proportion of 'obese' people (i.e., those with BMIs ≥25 kg/m^2) in 2040 is predicted to be much lower than that in 2012, it is discouraging that the proportion of 'normal' individuals is also markedly lower. Most notably, the pre-obesity rate is predicted to rise dramatically. In addition to the sex and age variables, our model includes only smoking and physical activity as health-related behaviors. The distributions of these factors were assumed to remain equal across the years; hence, our data show that maintaining smoking and physical activity rates at 2012 levels among adults will lead to a sharp increase in the 'pre-obese' population by 2040.

To the best of our knowledge, the only other study that predicted future obesity rates among South Korean adults was the investigation by Baik.[2] That study explored factors affecting adult as well as abdominal obesity, and constructed forecasting models to predict obesity prevalence rates in 2020 and 2030 using the Korea National Health and Nutritional Examination Survey (KNHANES). The prevalence rates of obesity among men and women in that study were predicted to be 47% and 32%, respectively, in 2020 and 62% and 37%, respectively, in 2030; these data were inconsistent with our results. The differences in prediction results appeared to be caused by the different secondary sources and prediction models in the two studies. First, in Baik's study, a prediction model was constructed by applying a linear regression model and an autoregressive integrated moving average model using the KNHANES data. The dependent variable in the prediction model was BMI, and the independent variables included the survey year, age, marital status, job status, income status, smoking, alcohol consumption, sleep duration, psychological factors, dietary intake, and fertility rate. In contrast, in this study, the Korea Health Panel data was used as the data source, and BMI was predicted by performing microsimulation with sex, age, smoking, physical activity, and previous years' BMIs as independent variables. Therefore, the method of measurement of the dependent variable, BMI differs between the studies; unlike the KNHANES, which contains body-measured height and weight information, the Korea Health Panel (although this is a representative data source) generates data based on self-reported by respondents, which may underestimate obesity. The differences appeared to be caused by the different secondary sources used in the 2 studies, as well as the different independent variables and prediction methodologies. In particular, Inevitably, the obesity rate in the initial population according to the KNHANES tended to be higher; as such, a higher initial prevalence rate would lead to a higher projection.[34] Most importantly, Baik's study did not consider the preceding year's BMI, which was a major independent variable in our study; this may be a major explanation for the differences in findings between the 2 studies.

We also tried to compare the results from this study with the predicted estimate by country, but few studies have empirically predicted the prevalence of obesity in the future using simulation models. One study compiled nationally-representative data from various sources and predicted the future prevalence of overweight and obesity in Indian adults aged 20-69 years will reach 30.5% and 9.5% among men, 27.4% and 13.9% among women, respectively, by 2040.[35] According to a study that estimated the prevalence of obesity in the future through regression modeling, 42% of Americans were expected to be obese by 2030.[36] Similarly, a study that predicted the prevalence of obesity in Australian adults by 2025 using a multiple linear regression model predicted that 83% of male adults over the age of 20 and 75% of female adults would be overweight or obese.[37] In all three countries, India, the United States, and Australia, overweight and obesity were defined according to the classifications defined by the WHO, and much higher values were found than those in Korea. We also compared our results to those predicted in Canada using the same model, and 59% of the adult Canadian population was predicted to be ‘overweight or obese’ by 2030.

This study defined obesity by applying the BMI classification system according to 2018 Korean Society for the Study of Obesity guideline for the management of obesity in Korea. It would be appropriate to use international standards for comparison; however, it is necessary to reflect the situation of individual countries in the management of obesity for the purpose of preventing and managing chronic diseases. Therefore, rather than emphasizing the BMI classification criteria, more research is needed to determine the BMI values that can significantly predict the occurrence of chronic diseases. In other words, it is necessary to continuously accumulate sufficient epidemiologic evidence for the relationship between the BMI and the actual risk of disease and death for Koreans, and based on such evidence, efforts to establish appropriate diagnostic and medical standards for Koreans are needed. In particular, the relationship is likely to vary by age and sex; hence, it should be considered too. Here, the obesity standard has been applied collectively regardless of sex and age. However, in order to deviate from a uniform approach to obesity, gender- and age-based approaches are needed, considering the changes in hormones and body composition.

Because health management policies including obesity management require a large budget, it is most important to establish cost-effective policies. The results from this study made it possible to determine the obese high-risk group by sex and age group, and estimate medical needs. As it is necessary to apply obesity standards differently according to sex and age group, it is difficult to set the ‘National Health Promotion Comprehensive Plan’ goals. This plan needs to suggest additional, wider-ranging goals considering the characteristics of each sex and age group, rather than presenting goals for obesity prevalence among adult men and women. In this case, the goal should be presented at an achievable level in consideration of future prediction patterns. Finally, systematic public health interventions, which are tailored to individual characteristics need to be established.

Findings from this study should be interpreted with consideration of several limitations. First, since a microsimulation model for predicting obesity prevalence has not been developed in this country, we borrowed the model developed by Statistics Canada, and it may not fit the domestic situation; nonetheless, we defined each variable in the predictive equation according to the operational definition in Korea Health Statistics. However, if the model is more suited to the domestic situation, besides sex, age, smoking, physical activity, and previous year's BMI value, various factors related to BMI may be added to the predictors of BMI. However, in this study, as we faithfully followed the existing model and explored the possibility of domestic application, the process of constructing a prediction equation was omitted. ~~Therefore, not only is the definition of obesity different, but the predictors of BMI include only sex, age, smoking, physical activity, and preceding year's BMI values.~~ In the future, research to develop a new model of microsimulation in the field of healthcare for domestic conditions will be very valuable. In this process, it is necessary to consider practical suitability and efficiency in selecting basic data, module-specific behavioral equations, and variables for use in the model. Second, we had limited data sources. There is a difference between the current prevalence of obesity calculated from the Korea Health Panel data used in this study and the Korea Health Statistics using the KNHANES. As of 2011, the prevalence of adult obesity in Korea Health Statistics was 31.9%, and the prevalence of adult obesity calculated by the Korea Health Panel data was 23.7%, a difference of 8.2%.[38] ~~Unlike the Korea Health Statistics, which contains body-measured height and weight information, the Korea Health Panel (although this is a representative data source) generates data based on self-reported by respondents, which may underestimate obesity.~~ As mentioned earlier in the difference between the results of Baik's study, this difference originated from the method of measuring BMI in the two data sources. However, in the POHEM-BMI model used in this study, the BMI of the previous year was regarded as the main explanatory variable, and therefore, the Korea Health panel data that followed the same participants once a year was inevitably used. In addition, the original POHEM-BMI model includes the process of converting self-reported BMI into a measured BMI, but we omitted this due to limitations of the data source. Third, we assumed that the attributes of 19-year-old individuals entered each year remain at a similar level each year. This means that the individual attributes of 19-year-old adults are the same for 29 years from 2012 to 2040; thus, it can be considered somewhat less realistic. In future studies, it is expected that more meaningful and realistic results will be derived if the model is constructed by reflecting the trend of changes in the attributes of the 19-year-old population and updating it according to the year.

Nevertheless, our study is the first to examine the possibility of using microsimulation to predict future BMI medians in South Korea. Additionally, the BMI of the future adult population was predicted after considering the change in population structure at the macro level as well as individual health behavior components at the micro level.

CONCLUSION

The key finding of this study is that by 2040, 70.05% of Korean adults are predicted to be pre-obese. Utilizing data sources available in Korea, the possibility of applying and expanding on the concept of microsimulation was explored. In future studies, a model suitable for South Korea needs to be developed, and the effectiveness of specific health policies ought to be assessed by applying various relevant scenarios to the basic forecasting model.

Abbreviations

BMI: body mass index; KNHANES: Korea National Health and Nutritional Examination Survey, POHEM: Population Health Model

Authors' Contributions

YS (the first author) designed the study, analyzed, and interpreted the data, and wrote the paper. YE participated in the statistical analysis. DS aided in the interpretation of the data and preparation of the manuscript. SJ (the corresponding author) directed this study. All authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics approval

This study used publicly available data of Korea Health Panel Survey 2011-2012 from the Korea Institute for Health and Social Affairs and the National Health Insurance, population statistics based on resident registration, population projections, complete life tables and future mortality rates from Statistics Korea. The dataset does not contain any identifiable personal information. Ethical approval was given by the Institutional Review Board of Korea University, Seoul, Korea (IRB No. KUIRB-2020-0018-01).

Data sharing statement

The Korea Health Panel Survey data used in this article is available in https://www.khp.re.kr:444/eng/data/data.do. Detailed information on the survey design and data characteristics are provided at https://www.khp.re.kr:444/eng/survey/sampling.do. Population statistics, population projections, and complete life tables are available from http://kosis.kr/eng/.

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Figure legends

Figure 1 Summary of data sources and methods used to generate and validate projections of distribution of BMI categories in South Korea, 2012–2040

Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012–2040

Figure 3A Projection of distribution of BMI, adults aged 19 years and older, South Korea, 2012–2040

Figure 3B Projection of distribution of BMI, men aged 19 years and older, South Korea, 2012–2040

Figure 3C Projection of distribution of BMI, women aged 19 years and older, South Korea, 2012–2040

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	7
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	7-8
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	8-9
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	-
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-9
Bias	9	Describe any efforts to address potential sources of bias	9
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7-8
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	7-9
		(*b*) Describe any methods used to examine subgroups and interactions	-
		(*c*) Explain how missing data were addressed	-
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	9
		(*e*) Describe any sensitivity analyses	-

Continued on next page

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	10
		(b) Give reasons for non-participation at each stage	-
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10-13
		(b) Indicate number of participants with missing data for each variable of interest	14
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	10-11
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	14
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	-
		Cross-sectional study—Report numbers of outcome events or summary measures	-
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	14-15
		(*b*) Report category boundaries when continuous variables were categorized	14-15
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	-
Discussion			
Key results	18	Summarise key results with reference to study objectives	16
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	18-20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	18-20
Generalisability	21	Discuss the generalisability (external validity) of the study results	19
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	21

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

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Title: Projecting the prevalence of obesity in South Korea through 2040: a microsimulation modeling approach

Authors: Yoon-Sun Jung [a*], Young-Eun Kim[b], Dun-Sol Go[c], Seok-Jun Yoon[d]

Affiliations:

[a]Department of Public Health, Graduate School, Korea University, Seoul, Korea

[b]Big Data Department, National Health Insurance Service, Wonju, Korea

[c]Department of Health Care Policy Research, Korea Institute for Health and Social Affairs, Sejong, Korea

[d]Department of Preventive Medicine, Korea University College of Medicine, Seoul, Korea

Corresponding author:

Seok-Jun Yoon, M.D., Ph.D.

Department of Preventive Medicine, Korea University College of Medicine,

73, Goryeodae-ro, Seongbuk-gu, Seoul, 02841, Korea

E-mail: yoonsj02@korea.ac.kr

E-mail addresses:

sunnyaurora@nate.com (Yoon-Sun Jung)

kimyes4454@gmail.com (Young-Eun Kim)

kds237@gmail.com (Dun-Sol Go)

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ABSTRACT

Objective To project the prevalence of obesity in 2040 among individuals 19 years and older in South Korea.

Design, setting, and participants Using the 'Population Health Model-Body Mass Index' (POHEM-BMI) microsimulation model, the prevalence of obesity in Korean adults 19 years and older was projected until 2040. The model integrated individual survey data from the Korea Health Panel Survey of 2011 and 2012, population statistics based on resident registration, population projections, and complete life tables categorized by sex and age. Birth rate, life expectancy, and international migration were based on a medium growth scenario. The base population of Korean adults in 2012, devised through data aggregation, was 39,842,730. The prediction equations were formulated using BMI as the dependent variable; the individual's sex, age, smoking status, physical activity, and preceding year's BMI were used as predictive factors.

Outcome measure BMI categorized by sex.

Results The median BMI for Korean adults in 2040 was expected to be 23.55 kg/m^2 (23.97 and 23.17 kg/m^2 for men and women, respectively). According to the Korean BMI classification, 70.05% of all adults were expected to be 'pre-obese' (i.e., have BMIs 23 to 24.9) by 2040 (81.23% of men and 59.07% of women) and 24.88% to be 'normal'.

Conclusions We explored the possibility of applying and expanding on the concept of microsimulation in the field of healthcare by combining data sources available in Korea and found that more than half of the adults in this study population will be pre-obese, and the proportions of "obesity" and "normal" will decrease compared with those in 2012. The results of our study will aid in devising healthy strategies and spreading public awareness for preventing this condition.

Strengths and limitations of this study

- To the best of our knowledge, this is the first study to use a microsimulation model to predict future obesity prevalence in Korea considering the change in population structure (macro level) as well as individual health behavior components (micro level).
- The results of our study will be beneficial in suggesting additional and wider ranging goals for obesity prevention, by taking into consideration the influence of sex and age in the formulation of the 'National Health Plan'.
- Although a representative data source was used in this study, the prevalence of obesity may be underestimated because it is based on a self-reported BMI value.
- This study uses a micro-simulation model developed abroad, and hence, may not reflect the domestic situations accurately.
- Another limitation is that we assumed the attributes of 19-year-old individuals to remain similar each year.

BACKGROUND

The prevalence of overweight and obesity has increased markedly over the past 3 decades, and concerns about health risks associated with obesity have become almost universal.[1] The increasing rate of obesity is a growing public health concern not only in Western countries but also in South Korea.[2] From the 1990s through the beginning of the new millennium, the prevalence of adult and child obesity has increased rapidly and continues to rise steadily in parallel with rapid social and economic development.[3]

Obesity, a major public health problem and a factor in the development of many chronic diseases, constitutes a strain on individuals and health systems worldwide. The associated disorders of obesity include diabetes, hypertension, dyslipidemia, heart disease, stroke, sleep apnea, early death, and cancer.[4-8] Moreover, obesity among older people increases the risk of knee osteoarthritis[9] and reduces functional capacity and quality of life.[10-13] The prevalence of these conditions rises in proportion to the increase in obesity[14-17] and is associated with increased economic costs for both individuals and the society at large.[18] A study using the National Health Insurance Service data in Korea found that the socioeconomic cost of obesity in 2016 was approximately 9,665.32 million US Dollars.[19]

Meanwhile, with respect to worldwide comparisons, whether cutoff points for overweight and obesity should be lower for Asians than for another ethnic groups remains debatable.[20] The World Health Organization has proposed BMIs of 18.5–22.9, 23–24.9, 25–29.9, and $\geq$30 kg/m^2 as optimal, overweight, moderate, and severe obesity for Asians, respectively.[21] The Korean Society of Obesity, which was established to improve obesity management through research and education, revised its clinical practical guidelines for the prevention and treatment of obesity in 2018. The new guidelines renamed the “overweight” category to "pre-obese", and divided obesity into 3 categories, to highlight the risk of obesity, instead of promoting the term "overweight." The most recent guideline is based in part on data of 84,690,131 Korean adults extracted from the Korean National Health Insurance Service Health Checkup Database between 2006 and 2015. By including the entire population registered in the National Health Insurance Service Database, they calculated the first and second cutoff points corresponding to the increased risk of any of the 3 accompanying diseases (type 2 diabetes, hypertension, and dyslipidemia). The first (23 kg/m^2) and second (25 kg/m^2) cutoff BMI levels suggest the necessity of obesity criteria that accurately reflect the risk of chronic disease among Koreans.[22,23]

Although numerous investigators in other countries have attempted to predict the future prevalence of obesity, only one such study by Inkyung Baik was recently performed in South Korea.[2] More recent trends still need to be investigated through predictive studies, and the accurate prediction of obesity prevalence remains an important public health-related goal in the country. To efficiently establish and execute an effective healthcare policy, which would require a large budget, it is necessary to select future targets for policy interventions (such as high-risk groups) to predict healthcare needs and prevent budget waste.

Past prediction models incorporated a country's entire population; as such, macroscopic inferences based on average projections for the future society were generalized. However, when establishing a healthcare policy, it is necessary to predict the future burden of disease and medical needs of the entire population based on a real-world understanding of individual-level factors that are influenced by policies or institutions. Individuals are independent entities with different characteristics and needs, and health-related projections can be modeled to reflect these individual characteristics, including health risk factors.[24] In this regard, we aimed to predict the prevalence of obesity in Korea by using microsimulation, which is optimal for considering individual properties.

Microsimulation, a modeling technique, typically uses individual microunits, each with its own set of properties, to simulate downstream events based on the probability of transition between predefined states and their changes over time. When used in medicine, microsimulation can be particularly powerful because it preserves the patterns of previous behaviors and conditions, and allows for a clearer representation and understanding of how various processes affect the total outcome of the population over time.[25] Given macro-effects such as changes in population structures in the forecasting model, microsimulation is very useful as it can estimate both disease burdens and medical needs across the country.[24] Microsimulation modeling is particularly useful for studying BMI trends because it can simultaneously explain population dynamics such as aging and mortality.[26] However, while microsimulation models have been steadily evolving across health- and economy-related fields in many European countries,[27] they are yet to be actively utilized in South Korea (especially for healthcare).

Obesity prevalence and trend estimates provide important information for research, policy, and intervention.[28] Because health forecasting predicts disease episodes and portends future events, it facilitates healthcare strategies by promoting the setting of goals to reduce obesity, establish health promotion interventions, and optimize resource allocation.[29] Obesity trends may also be used to urge governments to implement preventative approaches for reducing obesity.[30] Based on the above findings, we performed this study to project the future trends in obesity prevalence in South Korea up to the year 2040.

METHODS

Model

We used the Population Health Model (POHEM)-BMI[26] to estimate the prevalence of obesity among adults 19 years and older in South Korea from 2012 through 2040. In brief, POHEM is a time-continuous, population-based, dynamic microsimulation model with individual underlying units of analysis used worldwide. Dynamic microsimulation, in the context of social science and population health, is a simulation of individuals (i.e., micro-level) and their behaviors, statuses, and actions (dynamics) over time.[31] These are modeled as desired using multiple sources of empirical data, including cross-sectional surveys, administrative databases, vital statistics, and census data.[32]

Through dynamic simulation, POHEM creates a population and ages it, one person at a time, until death.[33] The model dynamically simulates an individual's disease state, risk factors, and health determinants to describe and plan health outcomes.[32] POHEM is accessible because it wants the general process to be constant across the country's population, with the exception of variables unique to each country, such as marriage and mortality. The POHEM models include cardiovascular disease, various cancers, osteoarthritis, physical activity, and neurological events. The model used in this study was the POHEM-BMI; the performance of each prediction step is shown in Figure 1.

Base population

To create the base population for the POHEM-BMI model, we used the 2011–2012 Korea Health Panel survey[34] and the resident registration-based population statistics.[35] The base population for POHEM-BMI (n=39,842,730), reflected the Korean population. Each Korean respondent 19 years of age and older (n=11,501) in 2012 was replicated using their survey-recorded weights to generate a simulated cohort of approximately 39,842,730 individuals. Korea Health Panel survey data are nationally representative, and incorporate health status, chronic diseases, health risk behaviors, and socio-demographic characteristics. Among them, we extracted sex, age, current smoking status, physical activity, and the previous and current years' BMI values; these variables were required for the predictive equation. We then used a multiple linear regression model to estimate the BMI value using the extracted independent variables as predictors. The POHEM-BMI model is auto-regressive and includes previous BMI values as the main explanatory variable.[26] We matched the composition of the variables considered as covariates in the POHEM-BMI model. We did not match the operational definition of the variables because we applied the Korea Health Panel Survey data (not the survey data obtained in Canada where the POHEM model was developed). The definitions of the variables in this study are consistent with the definitions of the indicators in the Korea Health Statistics.[36] A current smoker was an individual who reported smoking 'every day' or 'sometimes'. Practicing physical activity was defined as performing either intense physical activity for at least 10 continuous minutes a day, 20 minutes total per day, 3 days a week during the preceding week, or moderate physical activity for at least 30 minutes a day, 5 days a week during the preceding week. Height and weight, which are components of BMI, were based on self-reported data.

Simulation: Annual updates and risk transition

The study population was updated by aging each person by 1 year and changing the total population size based on population statistics, population projections, and complete life tables categorized by sex and age from the Korean Statistics. For population projections, we assumed a medium growth scenario in terms of birth rate, life expectancy, and international migration. Each person’s BMI was updated annually by applying a predictive equation that incorporates individual’s own characteristics. The transition probability for each stochastic characteristic was calculated based on a generalized linear model.

We assumed that the current individual behavioral patterns persisted, and no new factors arose to prevent obesity, like in the original POHEM-BMI. We also assumed that the attributes of 19-year-old individuals, which were entered annually, remained similar each year. Therefore, in this model, since each individual’s smoking status and physical activity in the initial population remained the same until 2040, the model predicted the BMI when the adult smoking and physical activity rates in the initial year (2012) persisted until 2040.

Model validation and calibration

In order to establish the validity of the prediction model, we adjusted the model by comparing the 2013 to 2016 median BMIs projected from the model with the 2013 to 2016 Korea Health Panel Survey median BMI estimates. We compared the median BMI values for each sex and age group from 2013 to 2016, and accepted a difference between the median BMI values in the prediction model and in the Korea Health Panel Survey to less than 5% by setting the calibration cutoff point to 5%. Finally, we adjusted the demographics of the 2040 population so that the predictions were within the 5% margin of error. In this study, all the necessary data for model building and projection were obtained from publicly available data and do not include any identifiable personal information. Hence, no ethical approval was required in addition to the ethical and governance approvals granted by the Korea Institute for Health and Social Affairs (KIHASA), which conducts the Korea Health Panel Survey. All participants gave written informed consent before they completed the survey.

Projection

The model, validated through calibration, projected the BMI of each person from 2017 to 2040. Based on the demographic characteristics, the projections were then aggregated by year for each of the predefined subgroups. The various trends observed in the Korean population data were used to generate algorithms that were applied to future projections.

Model outputs

The BMI distributions were calculated overall and by sex. Individuals with a BMI $\geq$25 kg/m^2 were regarded as obese according to the Guidelines for the Management of Obesity in Korea, which is not the internationally accepted standard (Table 1). All analyses in this study were performed using STATA version 13 (StataCorp LLC, College Station, TX, USA).

Table 1 BMI classification of South Korea

Classification	Body mass index (kg/m^2)
Underweight	< 18.5
Normal	18.5 – 22.9
Pre-obese	23 – 24.9
Obese class Ⅰ	25 – 29.9
Obese class Ⅱ	30 – 34.9
Obese class Ⅲ	≥ 35

Patient and public involvement

No patient involved

RESULTS

We compared the total number of the individuals and their characteristics in the initial 2012 population to those in the projected 2040 population (Table 2). There were 39,842,730 adults who were 19 years of age or older in 2012 and 43,818,808 in 2040. The male: female ratio was nearly 1:1 in both 2012 and 2040. Rapid aging of the Korean population was clearly observed when comparing the 2 populations. The mean age of adults was expected to increase by 10.9 years (from 45.69 years in 2012 to 56.59 years in 2040 [from 44.57 to 55.54 years among men and 46.77 to 57.63 years among women]). In 2012, the proportion of young people (those in the 19–39 and 40–64-year age groups combined) accounted for approximately 85.54% of the adult population, while the proportion of individuals aged 65 years and older was relatively low at approximately 14%. However, the age group structure in South Korea 28 years later (2040) is predicted to be quite different, as the proportion of individuals 19–64 years (i.e., the working age population) was only 60.95% of the adult population, while the proportion of the elderly population (≥65 years) was estimated to be almost 40% of the total adult population. As of 2012, men and women smoking rates were 45.05% and 2.24%, respectively, and physical activity rates were 15.41% and 20.84%, respectively. In this study, only the BMI was updated annually by the predictive equation, so the adult smoking rate and physical activity rate in 2040 are the same as in the initial 2012 population.

Table 2 Comparison of the number of people, South Korea, 2012 and 2040

	Population at baseline (2012)						*Projected population (2040)*					
	Men		**Women**		**Total**		**Men**		**Women**		**Total**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
Number of people	19,709,628		20,133,102		39,842,730		21,717,128		22,101,680		43,818,808	
Age (mean±s.d.)	44.57±15.60		46.77±16.92		45.69±16.31		55.54±18.60		57.63±19.33		56.59±19.00	
19-39 years	7,985,737	40.52%	7,505,824	37.29%	15,491,561	38.88%	4,873,740	22.45%	4,588,867	20.76%	9,462,607	21.60%
40-64 years	9,360,489	47.49%	9,230,871	45.85%	18,591,360	46.66%	8,896,886	40.97%	8,349,634	37.78%	17,246,520	39.35%
65 years and above	2,363,402	11.98%	3,396,407	16.87%	5,759,809	14.45%	7,946,502	36.59%	9,163,179	41.45%	17,109,681	39.05%
Smoker	8,879,037	45.05%	450,946	2.24%	9,329,983	23.42%						
Physical activity	5,199,273	26.38%	3,103,036	15.41%	8,302,309	20.84%						

s.d. standard deviation

The model was well calibrated to establish the validity. The difference in median BMI between that estimated from the 2013 and 2016 Korea Health Panel survey and that predicted by the 2013 and 2016 model was within the 5% range. Additionally, when compared to the population structure for 2040 (the final year) as predicted by Statistics Korea, the total population, gender, and age-specific ratio in the prediction model were similar.

Figure 2 shows the median BMI of the adult population from 2012 when the initial population was generated to 2040, the final projected year. Each median BMI value from 2013 to 2016 was estimated from the Korea Health Panel survey, and the median BMI from 2017 to 2040 is the predicted value determined by the model. The median BMI for the entire adult population is predicted to increase very slightly from 23.23 kg/m^2 in 2018 to 23.53 kg/m^2 in 2036 and is expected to remain steady thereafter. The predicted median BMI trends are similar for men; the median BMI in adult men was projected to increase only slightly, from 23.74 kg/m^2 in 2018 to 23.95 kg/m^2 in 2036 and then almost plateau thereafter. However, women were expected to experience a relatively steep rise compared to that of men; the median BMI in adult women was projected to increase from 22.66 kg/m^2 in 2018 to 23.17 kg/m^2 in 2040. The model in this study, used to predict the BMI of the population, did not include any uncertainty parameters for the estimates.

The BMI distributions for men and women from 2012 to 2040 are shown in Figure 3. There was no significant difference between the median BMIs in 2012 and 2040, but the results according to the BMI classifications showed large changes. The proportions of 'pre-obese' individuals in both sexes are predicted to increase dramatically over time, while the proportions of individuals who are classified as 'normal' and 'obese' will gradually decrease. As of 2025, 52.35% of all male adults were expected to be pre-obese, with that proportion

270 expected to be close to 81.23% by 2040. Moreover, 53.24% of all women were expected to be 'pre-obese' by 2035, with the proportion rising to almost 59.07% by 2040.

According to the BMI classification by age group, in South Korea, in 2012, about 20.36% of the population aged 19-39 were 'pre-obese', but in 2040, it increased to 39.59%, almost double. The proportion of the 'normal' population was almost the same in 2012 and 2040, and the 'obese class Ⅰ' decreased by nearly half. However, in the population aged 40 to 64 and over 65, the proportion of 'pre-obese' increased almost three times in 2040 compared to that in 2012, and the proportion of 'normal' decreased to less than 20% (Table 3).

Table 3 Comparison of the number of people according to the BMI classification by age group, South Korea, 2012 and 2040

	Population at baseline (2012)			*Projected population (2040)*		
	19-39 years	**40-64 years**	**65- years**	**19-39 years**	**40-64 years**	**65- years**
Number of people	15,491,561	18,591,360	5,759,809	9,462,607	17,246,520	17,109,681
BMI (median)	22.37	23.52	23.02	23.07	23.64	23.58
Distribution of people by BMI classification						
Underweight %	11.76	5.10	7.60	2.66	0.00	0.00
Normal %	45.66	37.81	42.12	45.68	19.89	18.40
Pre-obese %	20.36	26.51	24.10	39.59	76.60	80.31
Obese class Ⅰ %	20.67	28.40	24.85	11.70	3.51	1.29
Obese class Ⅱ %	1.51	1.79	1.30	0.36	0.00	0.00
Obese class Ⅲ %	0.03	0.38	0.02	0.02	0.00	0.00

DISCUSSION

The purpose of this study was to predict the prevalence of obesity in South Korea in the year 2040 using a microsimulation model. In this study, we strove to predict future adult obesity rates in South Korea using the POHEM-BMI, which was developed by Statistics Canada. Summarizing the predicted results, the median BMI of South Korea's adult population aged 19 years and older was expected to be 23.55 in 2040, while the percentage of 'pre-obese' individuals was expected to increase over time. While it is encouraging that the proportion of 'obese' people (i.e., those with BMIs ≥25 kg/m^2) in 2040 is predicted to be much lower than that in 2012, it is discouraging that the proportion of 'normal' individuals is also markedly lower. Most notably, the pre-obesity rate is predicted to rise dramatically. In addition to the sex and age variables, our model includes only smoking and physical activity as health-related behaviors. It was assumed that the status of these health risk factors remain consistent from the initial population period to the final projected year of 2040; hence, our results showed that maintaining smoking and physical activity rates in 2012 among adults will lead to a sharp increase in the 'pre-obese' population by 2040.

To the best of our knowledge, the only other study that predicted future obesity rates among South Korean adults was the investigation by Baik.[2] That study explored factors affecting adult as well as abdominal obesity, and constructed forecasting models to predict obesity prevalence rates in 2020 and 2030 using the Korea National Health and Nutritional Examination Survey (KNHANES). The prevalence rates of obesity among men and women in that study were predicted to be 47% and 32%, respectively, in 2020 and 62% and 37%, respectively, in 2030; these data were inconsistent with our results. The differences in prediction results appeared to be caused by the different secondary sources and prediction models in the two studies. First, in Baik's study, a prediction model was constructed by applying a linear regression model and an autoregressive integrated moving average model using the KNHANES data. The dependent variable in the prediction model was BMI, and the independent variables included the survey year, age, marital status, job status, income status, smoking, alcohol consumption, sleep duration, psychological factors, dietary intake, and fertility rate. In contrast, in this study, the Korea Health Panel data was used as the data source, and BMI was predicted by performing microsimulation with sex, age, smoking, physical activity, and previous years' BMIs as independent variables. Therefore, the method of measurement of the dependent variable, BMI differs between the studies; unlike the KNHANES, which contains body-measured height and weight information, the Korea Health Panel (although this is a representative data source) generates data based on self-reported by respondents, which may underestimate obesity. Inevitably, the obesity rate in the initial population according to the KNHANES tended to be higher; as such, a higher initial prevalence rate would lead to a higher projection.[37]

We also tried to compare the results from this study with the predicted estimate by country, but few studies have empirically predicted the prevalence of obesity in the future using simulation models. One study compiled nationally-representative data from various sources and predicted the future prevalence of overweight and obesity in Indian adults aged 20-69 years will reach 30.5% and 9.5% among men, 27.4% and 13.9% among women, respectively, by 2040.[38] According to a study that estimated the prevalence of obesity in the future through regression modeling, 42% of Americans were expected to be obese by 2030.[39] Similarly, a study that predicted the prevalence of obesity in Australian adults by 2025 using a multiple linear regression model predicted that 83% of male adults over the age of 20 and 75% of female adults would be overweight or obese.[40] In all three countries, India, the United States, and Australia, overweight and obesity were defined according to the classifications defined by the WHO, and much higher values were found than those in Korea. We also compared our results to those predicted in Canada using the same model, and 59% of the adult Canadian population was predicted to be ‘overweight or obese’ by 2030.

This study defined obesity by applying the BMI classification system according to 2018 Korean Society for the Study of Obesity guideline for the management of obesity in Korea. It would be appropriate to use international standards for comparison; however, it is necessary to reflect the situation of individual countries in the management of obesity for the purpose of preventing and managing chronic diseases. Therefore, rather than emphasizing the BMI classification criteria, more research is needed to determine the BMI values that can significantly predict the occurrence of chronic diseases. In other words, it is necessary to continuously accumulate sufficient epidemiologic evidence for the relationship between the BMI and the actual risk of disease and death for Koreans, and based on such evidence, efforts to establish appropriate diagnostic and medical standards for Koreans are needed. In particular, the relationship is likely to vary by age and sex; hence, it should be considered too. Here, the obesity standard has been applied collectively regardless of sex and age. However, in order to deviate from a uniform approach to obesity, gender- and age-based approaches are needed, considering the changes in hormones and body composition.

Because health management policies including obesity management require a large budget, it is most important to establish cost-effective policies. The results from this study made it possible to determine the obese high-risk group by sex and age group, and to estimate medical needs. As it is necessary to apply obesity standards differently according to sex and age group, it is difficult to set the ‘National Health Plan’ [41] goals. This plan needs to suggest additional, wider ranging goals considering the characteristics of each sex and age group, rather than presenting goals for obesity prevalence among adult men and women. In this case, the goal should be presented at an achievable level in consideration of future prediction patterns. Finally, systematic public health interventions, which are tailored to individual characteristics need to be established.

Findings from this study should be interpreted with consideration to several limitations. First, since a microsimulation model for predicting obesity prevalence has not been developed in South Korea, we adapted the model developed by Statistics Canada, and this may not fit our domestic situation. If the BMI predictors are suitable for our domestic situation, that is, if variables that are important for predicting BMI of Koreans are constructed through empirical analysis or literature review, the composition of the covariates may be different from that of the existing POHEM-BMI model. However, in this study, since we explored the possibility of a domestic application of the model and carefully adapted the existing model, the process of constructing a prediction equation was omitted. In the future, research to develop a new model of microsimulation in the field of healthcare for domestic conditions will be very valuable. In this process, it is necessary to consider practical suitability and efficiency in selecting basic data, module-specific behavioral equations, and variables for use in the model. Second, we had limited data sources. The prevalence of obesity calculated in this study is different from that of the Korea Health Statistics using the KNHANES, and as of 2011, the prevalence of adult obesity in the Korea Health Statistics was 8.2% higher than that of the Korea Health Panel Survey.[42] Although the method of measuring BMI in KNHANES is more accurate, in the POHEM-BMI model used in this study, the BMI of the previous year was regarded as the main explanatory variable, and therefore, the Korea Health panel data that followed-up the same participants once a year was inevitably used. In addition, the original POHEM-BMI model includes the process of converting self-reported BMI into a measured BMI, but we omitted this due to limitations of the data source. Third, we assumed that the attributes of 19-year-old individuals entered each year remain at a similar level each year. This means that the individual attributes of 19-year-old adults are the same for 29 years from 2012 to 2040; thus, it can be considered somewhat less realistic. In future studies, it is expected that more meaningful and realistic results will be derived if the model is constructed by reflecting the trend of changes in the attributes of the 19-year-old population and updating it according to the year.

Nevertheless, our study is the first to examine the possibility of using microsimulation to predict future BMI medians in South Korea. Additionally, the BMI of the future adult population was predicted after considering the change in population structure at the macro level as well as individual health behavior components at the micro level.

CONCLUSION

The key finding of this study is that by 2040, 70.05% of Korean adults are predicted to be pre-obese. Utilizing data sources available in Korea, the possibility of applying and expanding on the concept of microsimulation was explored. In future studies, a model suitable for South Korea needs to be developed, and the effectiveness of specific health policies ought to be assessed by applying various relevant scenarios to the basic forecasting model.

Abbreviations

BMI: body mass index; KNHANES: Korea National Health and Nutritional Examination Survey, POHEM: Population Health Model; s.d. standard deviation

Authors' contributions

YS (the first author) designed the study, analyzed, and interpreted the data, and wrote the paper. YE participated in the statistical analysis. DS aided in the interpretation of the data and preparation of the manuscript. SJ (the corresponding author) directed this study. All authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics approval

This study used publicly available data of Korea Health Panel Survey 2011-2012 from the Korea Institute for Health and Social Affairs and the National Health Insurance, population statistics based on resident registration, population projections, complete life tables and future mortality rates from Statistics Korea. The dataset does not contain any identifiable personal information. Ethical approval was given by the Institutional Review Board of Korea University, Seoul, Korea (IRB No. KUIRB-2020-0018-01).

Data sharing statement

The Korea Health Panel Survey data used in this article is available in https://www.khp.re.kr:444/eng/data/data.do. Detailed information on the survey design and data characteristics are provided at https://www.khp.re.kr:444/eng/survey/sampling.do. Population statistics, population projections, and complete life tables are available from http://kosis.kr/eng/.

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Figure legends

Figure 1 Summary of the data sources and methods used to generate and validate the projections of the distribution of BMI categories in South Korea, 2012–2040

Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012–2040

Figure 3A Projection of the distribution of BMI, adults aged 19 years and older, South Korea, 2012–2040

Figure 3B Projection of the distribution of BMI, men aged 19 years and older, South Korea, 2012–2040

Figure 3C Projection of the distribution of BMI, women aged 19 years and older, South Korea, 2012–2040

Figure 1 Summary of the data sources and methods used to generate and validate the projections of the distribution of BMI categories in South Korea, 2012-2040

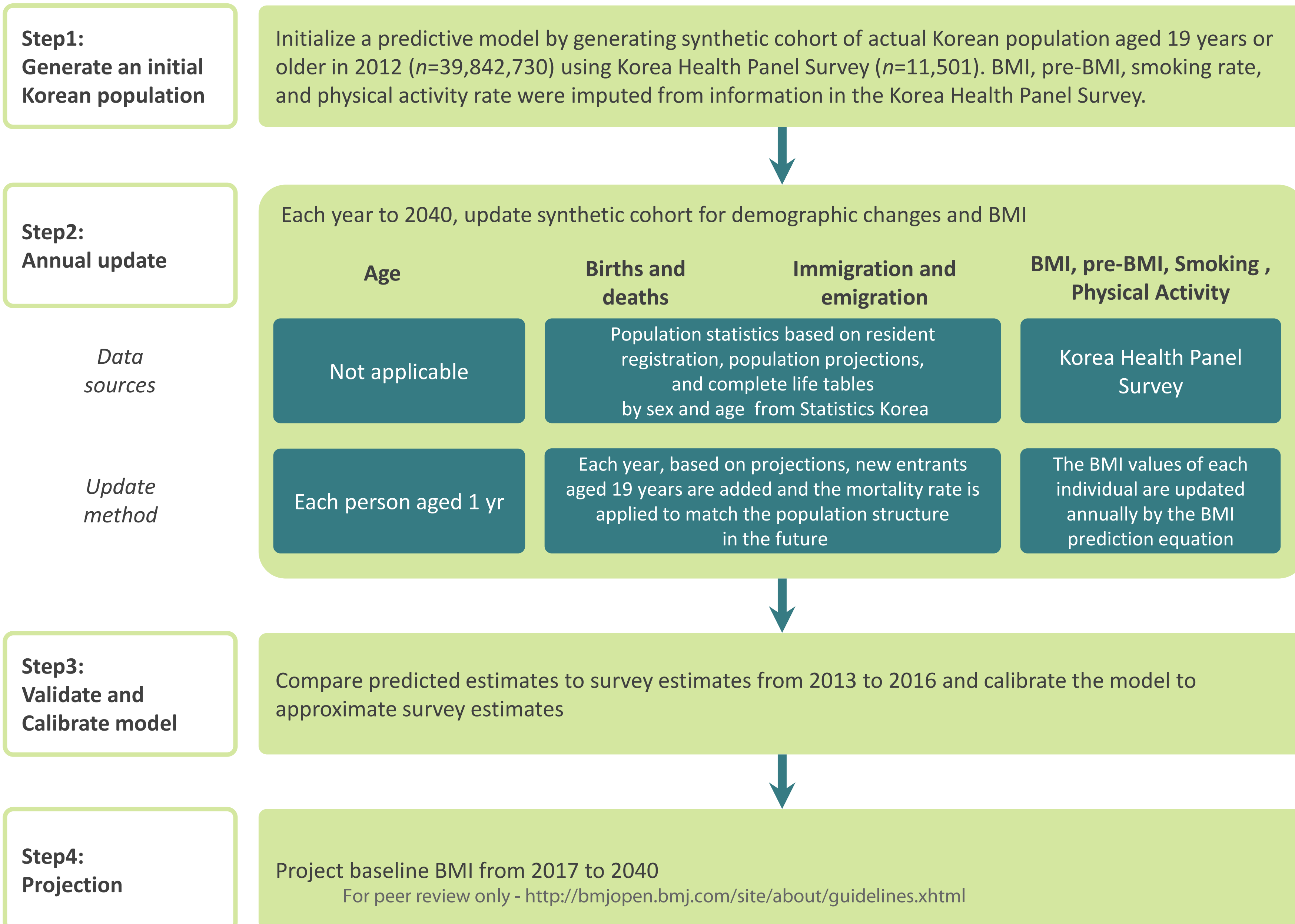


Figure 2 Population Health Model (POHEM) projections of median BMI in South Korea, 2012-2040

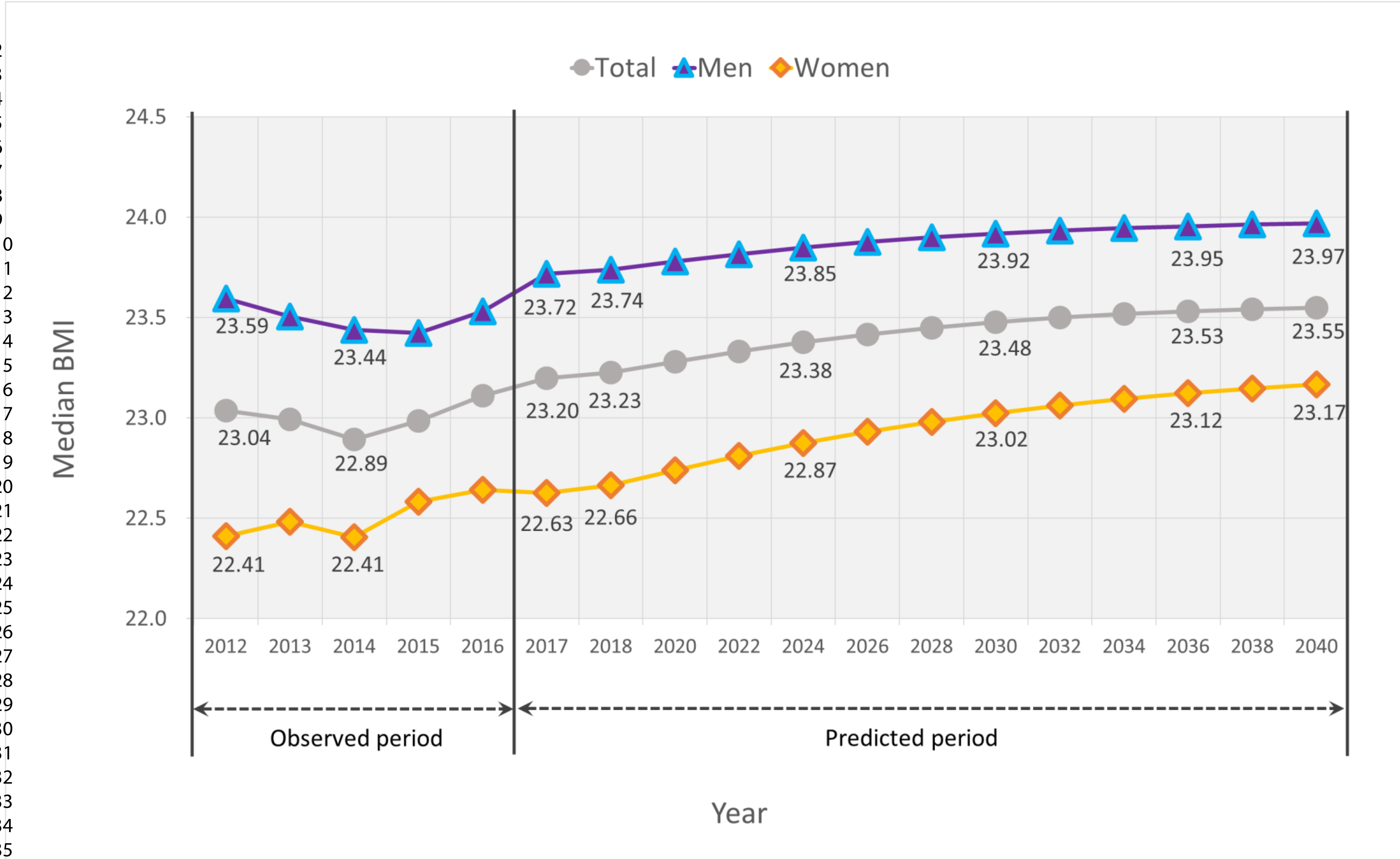
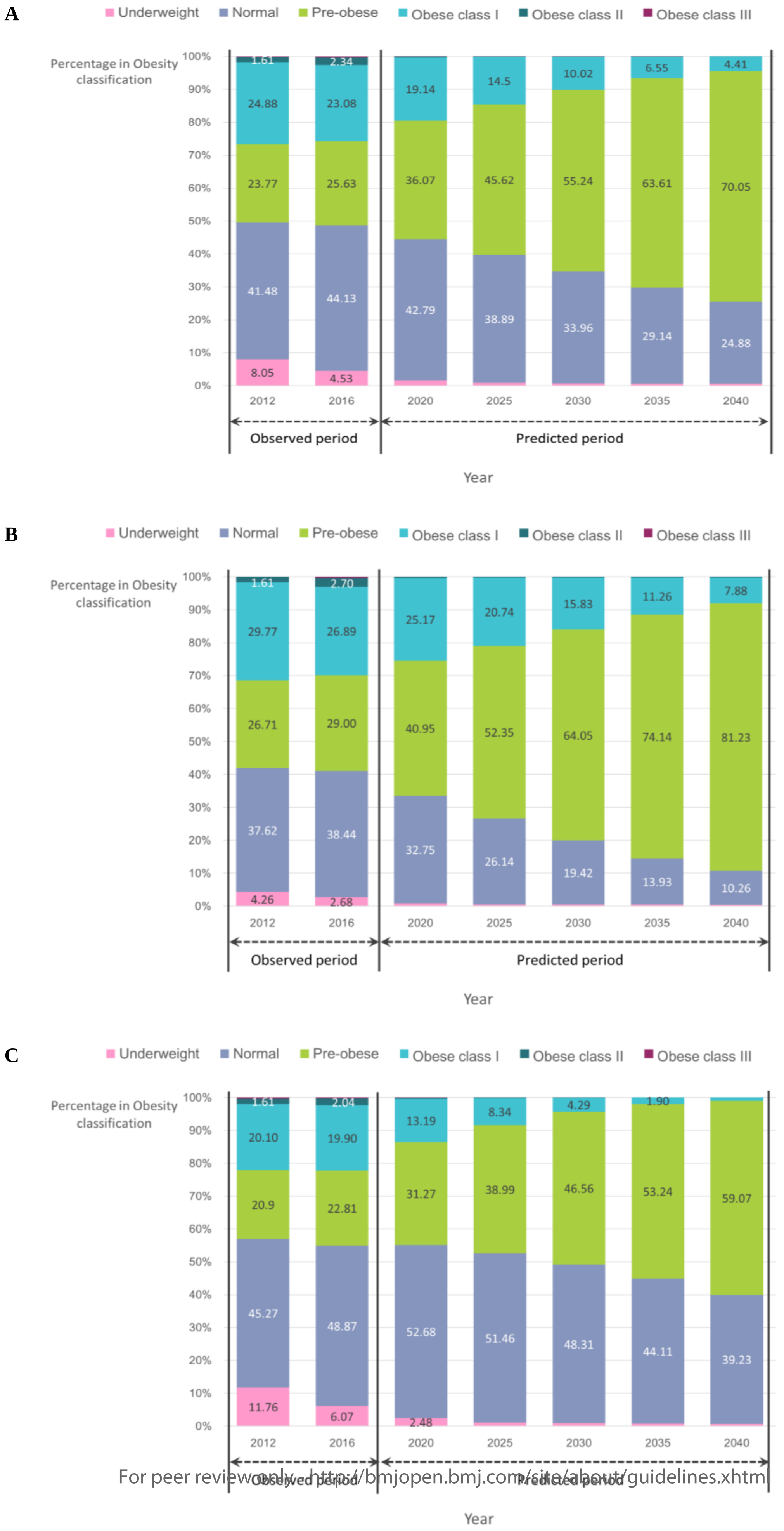


Figure 3 Projection of the distribution of BMI, (A) Adults, (B) Men and (C) Women, aged 19 years and older, South Korea, 2012-2040



STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	7
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	7-8
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	8-9
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	-
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-9
Bias	9	Describe any efforts to address potential sources of bias	9
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7-8
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	7-9
		(*b*) Describe any methods used to examine subgroups and interactions	-
		(*c*) Explain how missing data were addressed	-
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	9
		(*e*) Describe any sensitivity analyses	-

Continued on next page

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	10
		(b) Give reasons for non-participation at each stage	-
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10-13
		(b) Indicate number of participants with missing data for each variable of interest	14
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	10-11
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	14
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	-
		Cross-sectional study—Report numbers of outcome events or summary measures	-
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	13-14
		(*b*) Report category boundaries when continuous variables were categorized	13-14
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	-
Discussion			
Key results	18	Summarise key results with reference to study objectives	15
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	18-19
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	15-19
Generalisability	21	Discuss the generalisability (external validity) of the study results	19
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	19-20

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.