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Association of the Alternative Healthy Eating Index with osteoporosis and muscle mass among U.S. adults aged 50 years and older

Asociación del Índice de Alimentación Saludable Alternativa con la osteoporosis y la masa muscular en adultos estadounidenses de 50 años o más

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Artificial intelligence: The authors declare not to have used artificial intelligence (AI) or any AI-assisted technologies in the elaboration of the article.

ABSTRACT

Objective: this study aimed to explore the association between the Alternative Healthy Eating Index (AHEI) and both osteoporosis and muscle mass among U.S. adults aged 50 years and older, using data from the National Health and Nutrition Examination Survey (NHANES).

Methods: data from 9,466 participants were analyzed to examine the association between AHEI and osteoporosis, defined as a bone mineral density (BMD) T-score ≤ -2.5 . Another 2,233 participants were included to evaluate the association between AHEI and muscle mass, measured by appendicular lean mass index (ALMI). Weighted multivariable logistic and linear regression analyses, restricted cubic

spline (RCS) models, and subgroup analyses were conducted to investigate the relationships of AHEI with both outcomes.

Results: compared with the lowest AHEI tertile (Q1), the highest tertile (Q3) was significantly associated with both a lower prevalence of osteoporosis (OR = 0.55, 95 % CI: 0.38-0.80; $p = 0.002$) and a reduced ALMI ($\beta = -0.18$, 95 % CI: -0.34 to -0.01; $p = 0.039$). The RCS analysis observed no significant nonlinear association, and subgroup analyses showed consistency across different population groups.

Conclusion: a higher AHEI is significantly associated with a lower prevalence of osteoporosis and a lower ALMI among middle-aged and older U.S. adults, underscoring the necessity of developing more precise and personalized dietary interventions aimed at delaying age-related decline in both skeletal and muscular systems.

Keywords: Alternative Healthy Eating Index. Osteoporosis. Appendicular Lean Mass Index. NHANES. Dietary patterns. Aging.

RESUMEN

Objetivo: este estudio tuvo como objetivo explorar la asociación entre el Índice de Alimentación Saludable Alternativa (AHEI) y la osteoporosis y la masa muscular entre adultos estadounidenses de 50 años o más, utilizando datos de la Encuesta Nacional de Examen de Salud y Nutrición (NHANES).

Métodos: se analizaron los datos de 9466 participantes para examinar la asociación entre el AHEI y la osteoporosis, definida como una puntuación T de la densidad mineral ósea (DMO) $\leq -2,5$. Se incluyeron otros 2233 participantes para evaluar la asociación entre el AHEI y la masa muscular, medida mediante el índice de masa magra

apendicular (IMMA). Se realizaron análisis de regresión logística y lineal multivariable ponderados, modelos de spline cúbico restringido (RCS) y análisis de subgrupos para investigar la relación del AHEI con ambos resultados.

Resultados: en comparación con el tercil más bajo de AHEI (Q1), el tercil más alto (Q3) se asoció significativamente con una menor prevalencia de osteoporosis (OR = 0,55; IC del 95 %: 0,38-0,80; $p = 0,002$) y un menor ALMI ($\beta = -0,18$; IC del 95 %: -0,34 a -0,01; $p = 0,039$). El análisis RCS no observó una asociación no lineal significativa, y los análisis de subgrupos mostraron consistencia entre los diferentes grupos poblacionales.

Conclusión: un AHEI más alto se asocia significativamente con una menor prevalencia de osteoporosis y un ALMI más bajo entre los adultos estadounidenses de mediana edad y mayores, lo que subraya la necesidad de desarrollar intervenciones dietéticas más precisas y personalizadas destinadas a retrasar el deterioro relacionado con la edad en los sistemas esquelético y muscular.

Palabras clave: Índice de Alimentación Saludable Alternativa. Osteoporosis. Índice de Masa Magra Apendicular. NHANES. Patrones dietéticos. Envejecimiento.

INTRODUCTION

With the global population aging rapidly, age-related musculoskeletal disorders have become a significant public health concern. Osteoporosis is a chronic metabolic bone disease characterized by reduced bone mineral density and impaired bone microarchitecture,

substantially increasing the risk of fractures, disability, and mortality (1). An estimated 54 million U.S. adults aged 50 and older have osteoporosis or low bone mass, placing them at higher risk of fractures (2). This number continues to grow (3). Sarcopenia, a geriatric syndrome involving progressive loss of skeletal muscle mass and function, also significantly increases the risk of falls, disability, and hospitalization, greatly diminishing the quality of life and independence in older adults (4). Recent studies indicate that osteoporosis and sarcopenia often coexist, giving rise to the emerging concept of “osteosarcopenia.” This combined condition has compounded adverse effects, further increasing the health burden and demand for healthcare resources among middle-aged and older adults (5). Therefore, exploring effective interventions to delay skeletal and muscular decline is essential for promoting healthy aging.

Dietary modification is recognized as a cost-effective and modifiable strategy to prevent age-related diseases. Increasing evidence links dietary patterns to bone and muscle health, indicating that appropriate dietary habits may help reduce the risk of bone loss and muscle atrophy (6). For example, the Mediterranean diet, the Dietary Approaches to Stop Hypertension (DASH) diet, and diets high in protein, fruits, vegetables, and whole grains have been associated with greater bone mineral density, improved muscle mass, and a lower risk of fractures (7-9). These dietary patterns are rich in vitamin D, calcium, magnesium, antioxidants, and polyunsaturated fatty acids, which may exert anti-inflammatory and antioxidant effects, enhance bone metabolism, and stimulate muscle protein synthesis (10). In contrast, the Western dietary pattern, characterized by high intakes of saturated fats, refined sugars, and sodium, has been

associated with a higher risk of osteoporosis and sarcopenia (11).

The Alternative Healthy Eating Index (AHEI) is a validated tool for assessing dietary quality, developed from epidemiological evidence to reflect adherence to evidence-based dietary guidelines (12). It emphasizes the intake of whole grains, fruits, vegetables, nuts, long-chain (*n*-3) fatty acids, and polyunsaturated fats, while restricting red and processed meats, sugar-sweetened beverages, trans fats, and sodium. Alcohol consumption is assessed based on moderation (13). Numerous studies have shown that greater adherence to the AHEI is linked to a lower risk of cardiovascular disease (14), type 2 diabetes (15), and certain cancers (16). Moreover, AHEI scores are inversely associated with all-cause mortality (17). Increasing evidence supports the AHEI as a reliable indicator of dietary quality and a predictor of long-term health outcomes.

Given the increasing combined burden of osteoporosis and sarcopenia, growing attention has been directed toward dietary patterns as potential preventive strategies. Although previous studies have begun to investigate the association between AHEI and bone health, research on its link with muscle mass remains limited—especially comprehensive analyses assessing both bone and muscle health concurrently in middle-aged and older adults. Therefore, this study aims to examine the association between AHEI and both osteoporosis and muscle mass index among U.S. adults aged 50 years and older, using nationally representative data from the National Health and Nutrition Examination Survey (NHANES). The findings are expected to inform clinical practice and guide the development of targeted dietary strategies.

METHODS

Population

Because bone- and muscle-related data were collected during different NHANES survey cycles, two separate analyses were performed. Osteoporosis-related data were obtained from the 2005-2010, 2013-2014, and 2017-2018 NHANES cycles, including adults aged ≥ 50 years with complete information on bone mineral density and dietary intake. Muscle mass data were obtained from the 2011-2018 NHANES cycles, including adults aged ≥ 50 years with complete data on muscle mass, height, and dietary intake. The detailed data selection process is shown in figure 1.

Alternative Healthy Eating Index (AHEI)

The AHEI was calculated using two 24-hour dietary recall interviews from NHANES and includes 11 components: fruits, vegetables, whole grains, nuts and legumes, long-chain (*n*-3) fatty acids, polyunsaturated fatty acids, sugar-sweetened beverages and fruit juice, red and processed meats, trans fats, sodium, and alcohol. The detailed calculation method can be found in the original publication (15). Participants were divided into tertiles based on their total AHEI scores for subsequent analyses.

Osteoporosis and muscle mass definitions

Osteoporosis was defined using three bone mineral density (BMD) measurements: total femur BMD, femoral neck BMD, and trochanteric BMD. A diagnosis of osteoporosis was assigned when BMD at any of the three sites was ≥ 2.5 standard deviations below the mean BMD of healthy young adults aged 20-29 years, in individuals aged ≥ 50 years (18). The reference BMD values for this definition are provided in supplementary table I. Muscle mass was evaluated using

the appendicular lean mass index (ALMI), calculated as appendicular lean mass divided by height squared (kg/m^2) (19). Appendicular lean mass was defined as the total lean soft tissue mass of the arms and legs.

Covariates

Covariates were selected based on prior literature related to osteoporosis and muscle mass, including sex, race/ethnicity, education level, marital status, poverty income ratio (PIR), serum cotinine level, alcohol consumption, and self-reported hypertension and diabetes. Body mass index (BMI) was additionally included as a covariate in the analysis of AHEI and osteoporosis. PIR was used as an indicator of socioeconomic status, and serum cotinine concentration served as a proxy for smoking status (20). Marital status was categorized as non-single for individuals who were married or living with a partner, and as single for those who were widowed, divorced, separated, or never married. Regarding alcohol consumption, individuals reporting no alcohol intake in the past year were classified as non-drinkers, and all others were classified as drinkers.

Statistical analysis

Categorical and continuous variables were compared using the chi-square test and Student's t-test, respectively. Sampling weights (WTDR2D) were applied, with appropriate adjustments made according to the NHANES survey cycles included in the analysis. Multivariable logistic and linear regression models were used to investigate the associations of AHEI scores with osteoporosis and ALMI, respectively. Subgroup analyses were conducted to examine whether these associations varied across different population strata.

Restricted cubic spline (RCS) models were used to explore potential nonlinear associations between AHEI and both osteoporosis and muscle mass. The R packages used in this study included *survey* (version 4.4.2), *forestplotter* (1.1.2), *gtsummary* (2.0.2), and *dietaryindex* (2.0.0) (21). All statistical analyses were conducted using the R software (version 4.4.3).

RESULTS

AHEI and osteoporosis

Participant characteristics

A total of 9,466 U.S. adults aged ≥ 50 years were included in the study. Participants were stratified into three groups according to AHEI score tertiles: low (Q1: 8.52-32.25), moderate (Q2: 32.25-45.13), and high (Q3: 45.13-81.38) adherence. Table I summarizes the distribution of demographic and clinical characteristics across the three AHEI adherence groups.

Significant differences in several covariates were observed across the three AHEI groups. Mean age increased slightly with higher AHEI scores (64 years in Q1 vs. 65 years in Q3). The proportion of female participants increased from 43 % in Q1 to 52 % in Q3. In terms of racial/ethnic distribution, the proportion of non-Hispanic white participants was highest in Q3 (54 %), while the proportion of non-Hispanic black participants declined markedly from 27 % in Q1 to 14 % in Q3.

Educational attainment was positively associated with AHEI scores, as 63 % of participants in Q3 had completed high school or higher education, compared to 38 % in Q1. The proportion of non-single participants also increased with higher AHEI scores (59 % in Q1 vs. 66 % in Q3). Additionally, the poverty income ratio (PIR) was

significantly higher among participants in the highest AHEI tertile, suggesting a strong association between socioeconomic status and dietary quality.

The prevalence of osteoporosis was slightly lower among participants with higher AHEI scores; however, the difference was not statistically significant ($p = 0.117$). In addition, both BMI and the proportion of participants classified as obese showed a decreasing trend across AHEI tertiles. Serum cotinine levels ($\log_2$ cotinine), a biomarker of tobacco exposure, were substantially lower in Q3 compared to Q1 (-0.6 vs. -4.1). Accordingly, the proportion of participants classified as having low exposure increased from 64 % in Q1 to 89 % in Q3. The proportion of alcohol consumers was significantly higher in the highest AHEI tertile, increasing from 64 % in Q1 to 89 % in Q3. Regarding chronic conditions, participants in the highest AHEI tertile had a significantly lower prevalence of both diabetes ($p = 0.003$) and hypertension ($p < 0.001$).

In summary, middle-aged and older adults with higher AHEI scores were more likely to be married or cohabiting, have higher levels of education and socioeconomic status, engage in healthier behaviors (e.g., lower tobacco exposure, healthier body weight), and exhibit lower prevalence of hypertension and diabetes. These characteristics stress the association between dietary quality and overall health behaviors, and support further investigation into the relationship between AHEI and osteoporosis.

Risk factors for osteoporosis

After adjusting for potential confounders using weighted multivariable logistic regression models, the results are shown in figure 2. Compared with the lowest AHEI tertile (Q1), the highest tertile (Q3)

was significantly associated with a lower prevalence of osteoporosis (OR = 0.55, 95 % CI: 0.38-0.80; $p = 0.002$), suggesting that greater adherence to the AHEI may confer a protective effect on bone health and reduce osteoporosis risk among middle-aged and older adults. No statistically significant association was observed between the middle AHEI tertile (Q2) and osteoporosis prevalence (OR = 0.87, 95 % CI: 0.61-1.22; $p = 0.407$). These findings suggest a potential threshold effect, indicating that the protective benefits of AHEI on bone health may only become evident when dietary quality reaches a relatively high level.

Nonlinear association

We constructed a restricted cubic spline (RCS) regression model to further assess whether a linear association exists between AHEI scores and osteoporosis prevalence.

As shown in figure 3, AHEI scores were significantly and inversely associated with osteoporosis prevalence (p -overall < 0.001), while the test for nonlinearity was not statistically significant (p -nonlinear = 0.575). Specifically, the risk of osteoporosis declined progressively with increasing AHEI scores, with the odds ratio falling below the reference level (OR = 1) once the AHEI score exceeded 40, and continuing to decrease thereafter. These findings indicate that higher AHEI scores are associated with a lower risk of osteoporosis in adults aged 50 years and older, and that the association follows an overall linear decreasing trend.

Subgroup analysis

Subsequently, we conducted multivariable subgroup analyses to assess the association between AHEI and osteoporosis across specific

population strata (Supplementary Figure 1). In most subgroups, higher AHEI scores were consistently associated with a lower prevalence of osteoporosis. This inverse association was particularly evident among participants with a PIR ≥ 1 , $\log_2$ cotinine < 0.05 , obesity, female sex, non-Hispanic black ethnicity, alcohol consumption, and self-reported diabetes. Although the within-group associations were statistically significant in these subgroups, none of the interaction terms between subgroup categories and the reference group reached statistical significance (p for interaction > 0.05). These findings indicate that the association between AHEI and osteoporosis prevalence did not differ significantly across population subgroups.

AHEI and Appendicular Lean Mass Index (ALMI)

Participant characteristics

A total of 2,233 middle-aged and older adults (aged ≥ 50 years) were included in this analysis. Participants were categorized into three groups according to AHEI tertiles: low (Q1: 9.38-34.46), moderate (Q2: 34.46-44.89), and high (Q3: 44.90-76.82). Table II summarizes the demographic and clinical characteristics of participants across the three AHEI categories.

Significant differences in demographic and lifestyle characteristics were observed across the three AHEI groups. Similar to the trends observed in the osteoporosis analysis, participants with higher AHEI scores were more likely to be women who were not single, have higher levels of education and socioeconomic status, engage in healthier behaviors, and exhibit a lower prevalence of diabetes and hypertension.

Notably, the mean ALMI decreased with increasing AHEI scores, declining from 8.06 kg/m² in Q1 to 7.62 kg/m² in Q3 ($p < 0.001$),

indicating an unexpected inverse association between AHEI and standardized appendicular lean mass index. This finding suggests that, within this study population, participants with higher AHEI scores tended to have lower ALMI. This observation warrants further investigation to clarify the underlying factors and potential mechanisms.

Factors associated with Appendicular Lean Mass Index

After adjusting for all covariates, we constructed a weighted multivariable linear regression model (Fig. 4). Compared with the lowest AHEI tertile (Q1), the highest tertile (Q3) was significantly associated with a lower ALMI value ($\beta = -0.18$, 95 % CI: -0.34 to -0.01; $p = 0.039$). No significant difference in ALMI was observed between the middle tertile (Q2) and Q1 ($\beta = -0.14$, 95 % CI: -0.31 to 0.04; $p = 0.12$). Contrary to expectations, participants with higher AHEI scores tended to have slightly lower ALMI values, and this inverse association remained statistically significant after adjusting for covariates. These findings point to a potentially complex relationship between AHEI and ALMI, warranting further exploration using nonlinear and subgroup analyses.

Nonlinear association

To further assess the pattern of association between AHEI scores and ALMI, a RCS model was fitted (Fig. 5). The analysis demonstrated a statistically significant overall association between AHEI and ALMI (p -overall = 0.035), with no evidence of nonlinearity (p -nonlinear = 0.827), indicating a predominantly linear relationship. Based on the shape of the curve, ALMI values declined steadily with increasing AHEI scores and dropped below the reference line ($\beta = 0$) at approximately

40, then remained at a relatively low and stable level. This linear decreasing pattern was consistent with the inverse association observed in the multivariable regression analysis and further supporting a stable association between higher dietary quality scores and lower ALMI.

Additionally, multivariable subgroup analyses were conducted to assess whether the observed inverse association differed across specific population subgroups. Statistically significant inverse associations were observed among participants with diabetes ($\beta = -0.03$, 95 % CI: -0.04 to -0.01; $p = 0.004$), $\log_2$ cotinine < 0.05 ($\beta = -0.01$, 95 % CI: -0.02 to 0.00; $p = 0.034$), and those who were not single ($\beta = -0.01$, 95 % CI: -0.02 to 0.00; $p = 0.011$). However, the effect sizes were small, and none of the interaction terms reached statistical significance (p for interaction > 0.05), indicating that the association was relatively consistent across subgroups. Detailed results are provided in supplementary figure 2.

DISCUSSION

This study found a significant inverse association between the Alternative Healthy Eating Index (AHEI) and the prevalence of osteoporosis among U.S. adults aged 50 years and older. Specifically, participants in the highest AHEI tertile (Q3) had a 45 % lower prevalence of osteoporosis compared to those in the lowest tertile (Q1) (OR = 0.55, 95 % CI: 0.38-0.80; $p = 0.002$). No significant association was observed in the middle tertile (Q2) (OR = 0.87, 95 % CI: 0.61-1.22; $p = 0.407$), suggesting that the bone-protective effect of AHEI may exhibit a potential threshold effect. Restricted cubic spline (RCS) analysis demonstrated a linear inverse association between AHEI and osteoporosis prevalence (p -overall < 0.001), with

no significant evidence of nonlinearity (p -nonlinear = 0.575). According to the RCS curve, the odds of osteoporosis dropped below the reference level (OR = 1) when the AHEI score exceeded approximately 40. This finding reinforces the results from the multivariable logistic regression, suggesting that a high level of dietary quality maybe a prerequisite for achieving bone-protective benefits. No significant interactions were observed across population subgroups, indicating that the inverse association remained relatively consistent across strata. Additionally, an unexpected inverse association was observed between AHEI and appendicular lean mass index (ALMI). After adjustment for multiple covariates and RCS modeling, participants in the highest AHEI tertile (Q3) (β = -0.18, 95 % CI: -0.34 to -0.01; p = 0.039), as well as those with AHEI scores near 40, tended to have lower ALMI values. Subgroup analyses also showed no significant heterogeneity across population subgroups. In summary, this cross-sectional study demonstrates that higher AHEI scores are significantly associated with a lower prevalence of osteoporosis and a lower appendicular lean mass index among middle-aged and older U.S. adults.

The observed association between AHEI and osteoporosis may be related to its nutritional composition, which influences bone metabolism, inflammation, and hormonal regulation. A previous longitudinal study among Puerto Rican adults reported that AHEI was associated with higher spine and hip BMD, as well as a lower incidence of osteoporosis (22), consistent with our results. First, AHEI encourages high intake of fruits and vegetables, which are rich in vitamin C, potassium, and provitamin A (β -carotene). These nutrients are known to support bone health by promoting collagen synthesis, reducing calcium loss, and maintaining bone matrix stability (23). In

particular, dark green leafy vegetables are rich in vitamin K, which facilitates γ -carboxylation of osteocalcin, thereby enhancing calcium deposition and reducing bone resorption (24). Additionally, AHEI promotes the consumption of whole grains, nuts, and legumes, which are rich in magnesium and zinc—two minerals involved in bone metabolism (25). Magnesium, a key mineral component of the bone matrix, directly participates in bone formation (26). Zinc acts as a cofactor for vitamin D activation and contributes to the regulation of bone metabolism (27). Phytoestrogens in legumes, such as isoflavones, have also been shown to alleviate postmenopausal bone metabolic imbalance and reduce the risk of osteoporosis and fractures (28). Moreover, long-chain (*n*-3) and polyunsaturated fatty acids emphasized in AHEI possess anti-inflammatory properties that may support bone health by modulating osteoclast and osteoblast activity (29). Finally, AHEI limits the intake of Western dietary components such as soft drinks, red and processed meats, and fried foods. These foods are often high in trans fats, sodium, added sugars, and phosphorus (30). These components may disrupt calcium homeostasis (31), impair osteoblast differentiation and bone development (32), and contribute to increased systemic inflammation and acid load (33), ultimately leading to bone loss and osteoporosis (34). In summary, AHEI may contribute to a bone-supportive dietary environment through its nutrient profile and regulatory properties. However, in contrast to prior studies, we observed that a significant association between AHEI and osteoporosis was only evident when AHEI scores exceeded a certain threshold, which may have practical implications for informing dietary recommendations in osteoporosis prevention.

Currently, evidence regarding the association between AHEI and

muscle mass or sarcopenia remains limited. A previous cross-sectional study among older adults in Iran found no significant association between AHEI and either ALMI or the prevalence of sarcopenia (35). However, the study did not conduct stratified analyses based on AHEI levels, which may have limited interpretation of how variations in dietary quality are associated with muscle-related outcomes. In contrast, our study stratified participants into AHEI tertiles and found that those in the highest adherence group (Q3) unexpectedly had lower ALMI values. This finding indicates that among middle-aged and older adults with higher dietary quality scores, muscle mass may not increase correspondingly and may even show an inverse trend.

This unexpected result warrants further attention and suggests that the mechanisms through which AHEI influences muscle mass may differ from those underlying its effects on bone health. Chronic low-grade inflammation is recognized as one of the primary drivers to sarcopenia development (36). Prior studies have shown that pro-inflammatory cytokines negatively affect muscle protein metabolism and skeletal muscle maintenance (37). A meta-analysis by Xie et al. (38) reported that a higher Dietary Inflammatory Index (DII) was significantly associated with reduced skeletal muscle strength and mass, and with a higher prevalence of sarcopenia. The authors suggested that increasing the intake of fruits and vegetables, and limiting the consumption of sugar-sweetened beverages and processed meats, may reduce systemic inflammation and help preserve skeletal muscle health. However, this perspective appears to contrast with our findings. Although the AHEI promotes similar dietary strategies—such as greater fruit and vegetable intake and reduced consumption of processed and sugary foods—we did not observe a positive association between AHEI and muscle mass. In fact, higher

AHEI scores were associated with lower ALMI values. We speculate that this discrepancy may not result from the AHEI's insufficient anti-inflammatory potential, but rather from its specific nutrient composition. Bian et al. proposed that the DII includes a broader range of nutrients directly involved in muscle protein synthesis, and suggested that insufficient intake of high-quality protein may be a key factor in the development of sarcopenia(39). This may partially explain the inverse association observed in our study. Unlike the DII, the AHEI—although focused on overall dietary quality—does not specifically emphasize foods rich in high biological value protein, vitamin D, or B vitamins, such as lean meats, dairy products, and eggs. Both vitamin D and B vitamins are not only essential for protein metabolism and synthesis but also play a central role in regulating muscle regeneration and repair (40). If participants in the highest AHEI tertile consumed suboptimal amounts of dairy or other protein-rich foods, a potential “nutritional gap” in anabolic support may have attenuated or even offset the expected muscle-protective effects of higher AHEI adherence. Therefore, we suggest that the potential role of AHEI in maintaining muscle health should not be dismissed outright. Instead, its current nutrient composition should be acknowledged as potentially limited in modulating muscle metabolism. Furthermore, due to the cross-sectional nature of this study, causal inferences cannot be made, and reverse causality cannot be ruled out. For instance, individuals with lower muscle mass might adopt healthier diets to improve their overall health, potentially leading to the observed “apparent inverse association” between high AHEI scores and low ALMI levels.

The AHEI dietary pattern has been shown in numerous studies to have various positive effects on human health. However, epidemiological

evidence regarding the association between AHEI and musculoskeletal health remains limited, with most existing research focusing on either bone or muscle outcomes in isolation. This study is novel in that it addresses osteosarcopenia, which is a condition defined by concurrent deterioration of both bone and muscle, and simultaneously evaluates the independent associations of AHEI with skeletal and muscular health. Meanwhile, the use of data from the National Health and Nutrition Examination Survey (NHANES), a nationally representative and large-scale dataset with comprehensive information on health, nutrition, and lifestyle factors, enhances the generalizability and robustness of our findings. Notably, the observed dose-response relationships may provide valuable insights for developing dietary strategies to delay musculoskeletal decline in middle-aged and older adults through targeted nutritional interventions.

Several limitations of this study should be acknowledged. First, the cross-sectional design precludes causal inference between AHEI and either osteoporosis or ALMI. Secondly, AHEI was calculated based on two 24-hour dietary recall interviews, which may be affected by recall bias. Finally, due to limitations of the publicly available dataset and standardized protocols, bone and muscle health were assessed using BMD and ALMI, respectively. Although DXA-derived bone mineral density is considered the gold standard for evaluating bone health and diagnosing osteoporosis (18), and ALMI is widely used based on international sarcopenia guidelines to assess muscle mass (19), these measures may not comprehensively reflect the overall condition of the musculoskeletal system or their combined effects in older adults. Therefore, it is necessary to conduct large-scale prospective cohort studies in the future that additionally incorporate assessments of falls,

frailty, muscle strength, and physical function, in order to provide a more comprehensive evaluation of skeletal and muscular status and their combined effects.

CONCLUSION

Higher adherence to the AHEI is significantly associated with a lower prevalence of osteoporosis and a lower ALMI among U.S. adults aged 50 years and older. Future research should focus on longitudinal designs to validate the causal relationships between AHEI and musculoskeletal health. In addition, efforts should be directed toward the development of more precise and personalized dietary interventions that aim to delay age-related decline in both skeletal and muscular systems.

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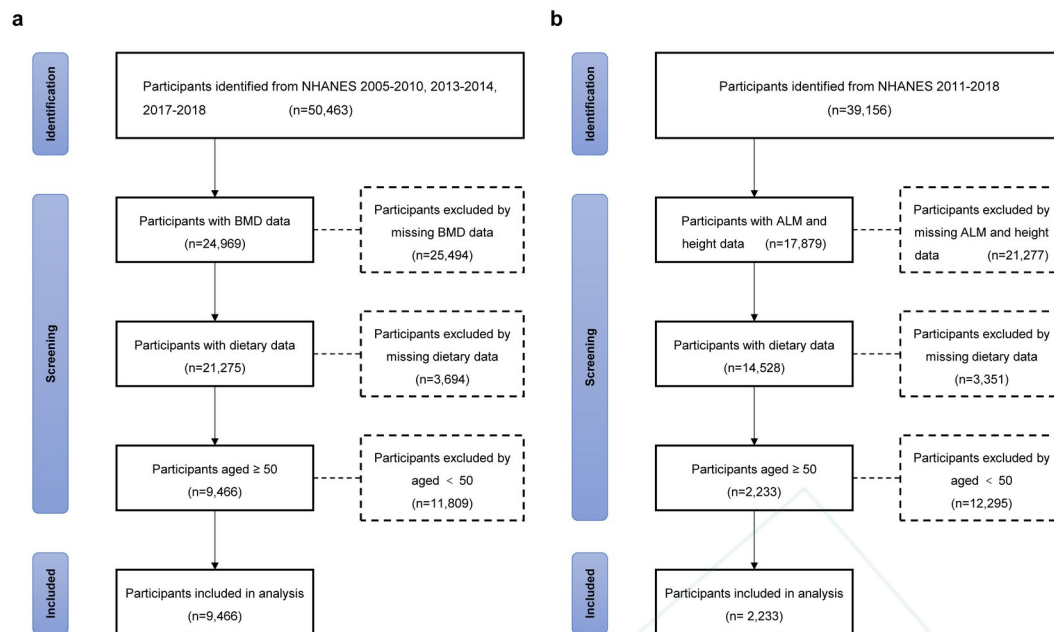


Figure 1. Participants screening process. A. Osteoporosis. B. Muscle mass.

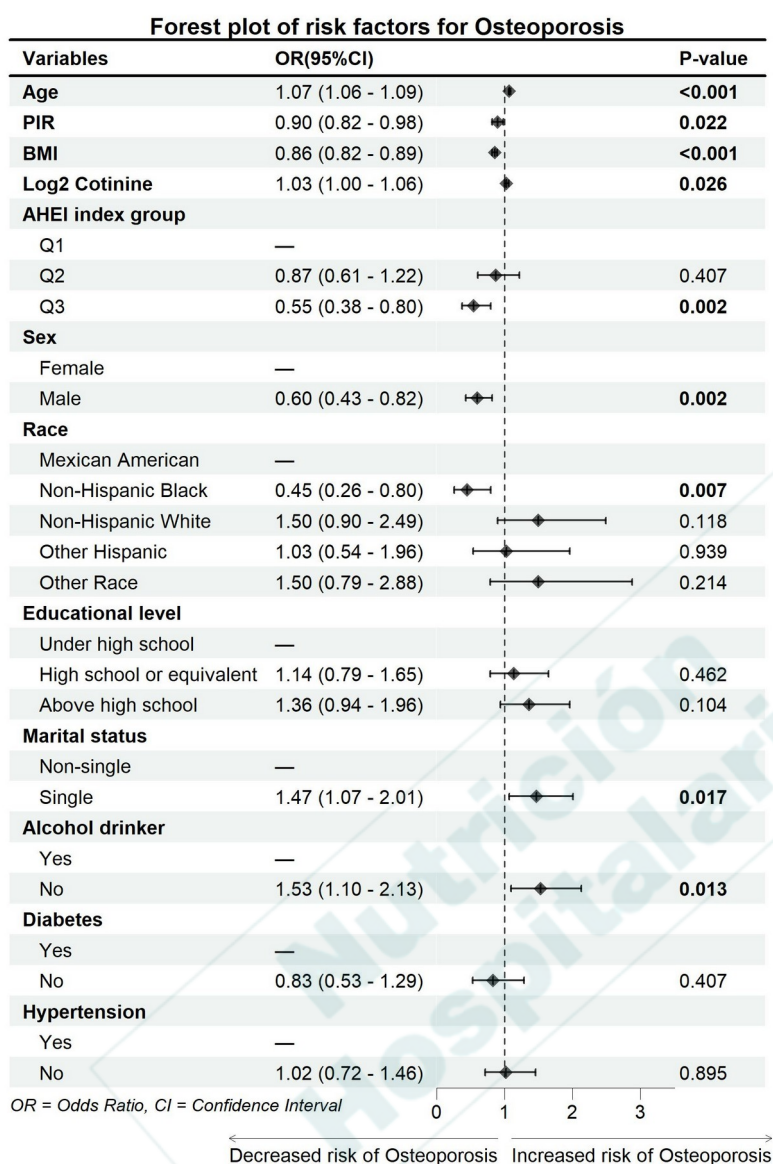


Figure 2. Forest plot of risk factors for osteoporosis (PIR: poverty impact ratio; BMI: body mass index; Log2 Cotinine: log₂-transformed serum cotinine).

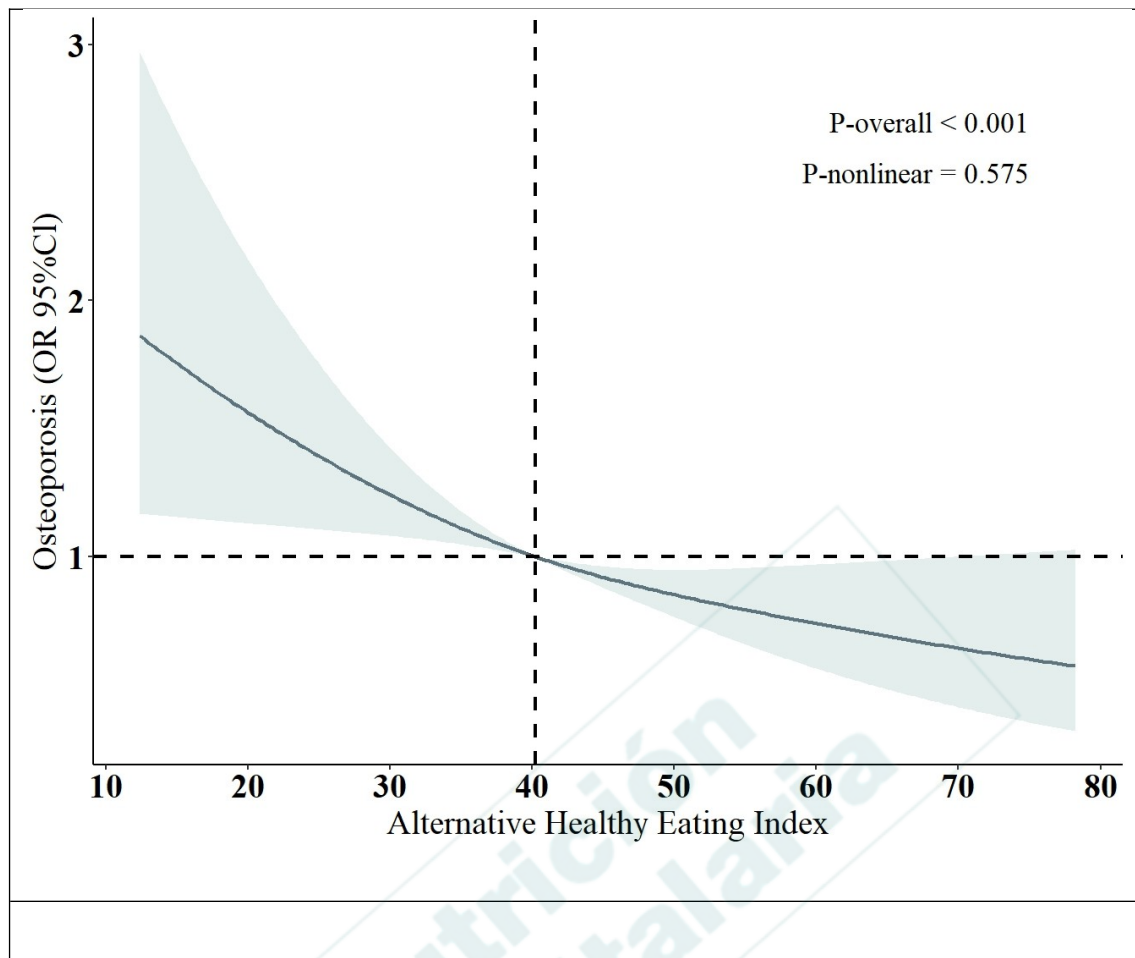


Figure 3. Restricted cubic spline models for the relationship between Alternative Healthy Eating Index and risk of osteoporosis.

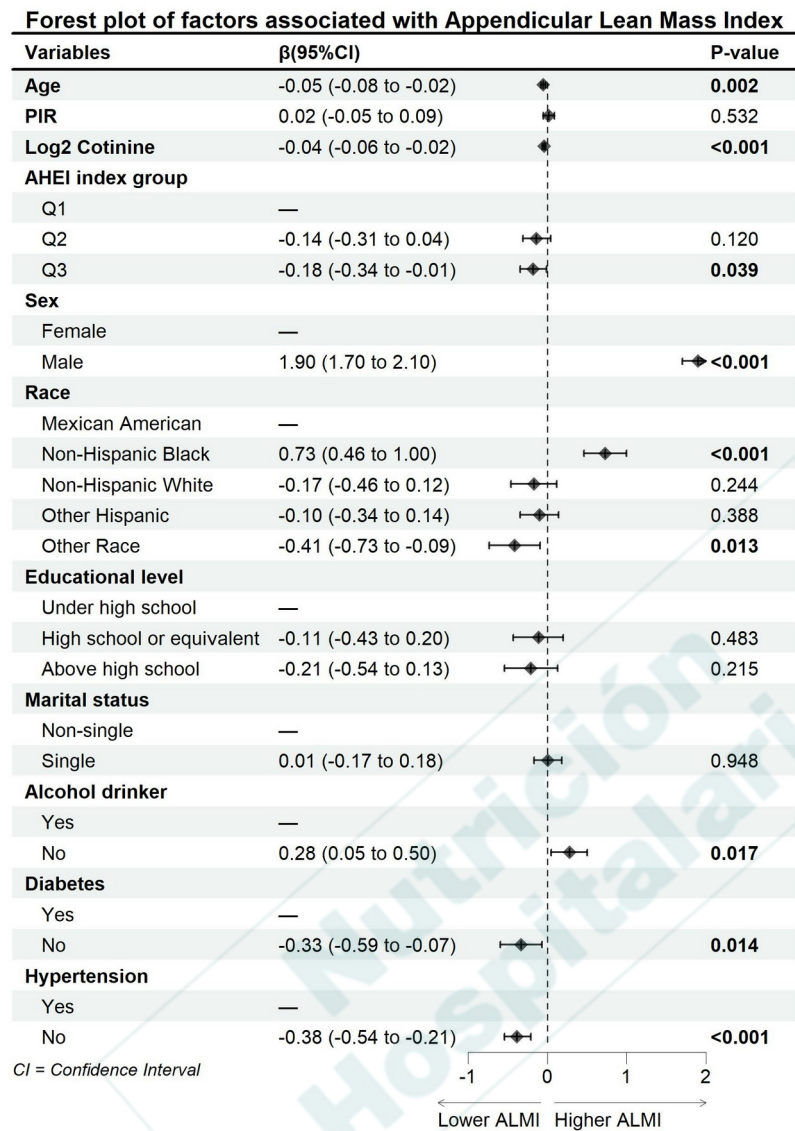


Figure 4. Forest plot of factors associated with Appendicular Lean Mass Index.

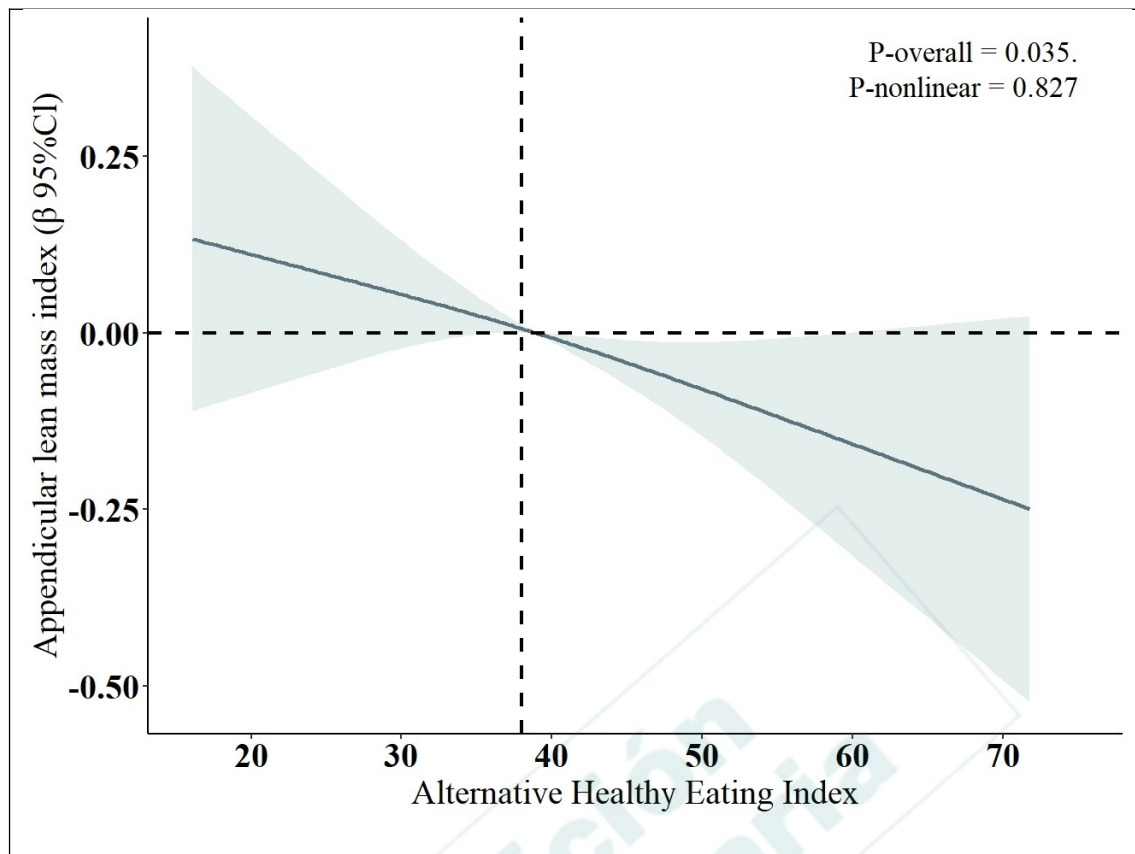


Figure 5. Restricted cubic spline models for the relationship between Alternative Healthy Eating Index and Appendicular Lean Mass Index.

Table I. Characteristics of the participants assessed for osteoporosis

Characteristic	Overall <i>n</i> = 9,466	Q1 <i>n</i> = 3,156	Q2 <i>n</i> = 3,155	Q3 <i>n</i> = 3,155	<i>p</i>-value*
Age, mean (SD)	65 (9)	64 (9)	65 (10)	65 (9)	< 0.001
<i>Sex, n (%)</i>					< 0.001
Female	4,630 (49 %)	1,372 (43 %)	1,614 (51 %)	1,644 (52 %)	
Male	4,836 (51 %)	1,784 (57 %)	1,541 (49 %)	1,511 (48 %)	
<i>Osteoporosis, n (%)</i>					0.117
Yes	872 (9.2 %)	295 (9.3 %)	312 (9.9 %)	265 (8.4 %)	
No	8,594 (91 %)	2,861 (91 %)	2,843 (90 %)	2,890 (92 %)	
AHEI index, mean (SD)	41 (11)	29 (5)	40 (3)	53 (7)	< 0.001
<i>Race, n (%)</i>					< 0.001
Mexican American	1,244 (13 %)	364 (12 %)	487 (15 %)	393 (12 %)	
Non-Hispanic white	4,883 (52 %)	1,555 (49 %)	1,620 (51 %)	1,708 (54 %)	
Non-Hispanic black	1,888 (20 %)	840 (27 %)	597 (19 %)	451 (14 %)	
Other Hispanic	802 (8.5 %)	268 (8.5 %)	266 (8.4 %)	268 (8.5 %)	
Other race	649 (6.9 %)	129 (4.1 %)	185 (5.9 %)	335 (11 %)	
<i>Educational level, n (%)</i>					< 0.001
Under high school	2,458 (26 %)	1,033 (33 %)	841 (27 %)	584 (19 %)	

High school or equivalent	2,303 (24 %)	915 (29 %)	804 (26 %)	584 (19 %)	
Above high school	4,694 (50 %)	1,207 (38 %)	1,504 (48 %)	1,983 (63 %)	
<i>Marital status, n (%)</i>					< 0.001
Non-single	5,910 (62 %)	1,872 (59 %)	1,954 (62 %)	2,084 (66 %)	
Single	3,549 (38 %)	1,281 (41 %)	1,199 (38 %)	1,069 (34 %)	
PIR, mean (SD)	2.76 (1.61)	2.34 (1.51)	2.75 (1.59)	3.19 (1.61)	< 0.001
<i>PIR group, n (%)</i>					< 0.001
< 1	1,291 (15 %)	598 (21 %)	407 (14 %)	286 (9.9 %)	
≥ 1	7,352 (85 %)	2,298 (79 %)	2,452 (86 %)	2,602 (90 %)	
BMI, mean (SD)	28.7 (5.6)	29.3 (6.0)	28.9 (5.5)	27.9 (5.2)	< 0.001
<i>BMI group, n (%)</i>					< 0.001
Under weight	125 (1.3 %)	61 (1.9 %)	29 (0.9 %)	35 (1.1 %)	
Normal weight	2,312 (25 %)	667 (21 %)	750 (24 %)	895 (29 %)	
Overweight	3,591 (38 %)	1,102 (35 %)	1,219 (39 %)	1,270 (40 %)	
Obesity	3,393 (36 %)	1,311 (42 %)	1,145 (36 %)	937 (30 %)	
Log2 cotinine, mean (SD)	-2.5 (5.3)	-0.6 (6.0)	-2.6 (5.3)	-4.1 (4.0)	< 0.001
<i>Log2 cotinine group, n (%)</i>					< 0.001
< 0.05	7,080 (77 %)	1,951 (64 %)	2,411 (79 %)	2,718 (89 %)	

0.05-3	245 (2.7 %)	136 (4.5 %)	61 (2.0 %)	48 (1.6 %)	
≥ 3	1,828 (20 %)	940 (31 %)	597 (19 %)	291 (9.5 %)	
<i>Alcohol drinker, n (%)</i>					< 0.001
Yes	5,541 (69 %)	1,678 (63 %)	1,834 (69 %)	2,029 (76 %)	
No	2,440 (31 %)	986 (37 %)	816 (31 %)	638 (24 %)	
<i>Diabetes, n (%)</i>					0.003
Yes	1,770 (19 %)	594 (19 %)	641 (20 %)	535 (17 %)	
No	7,693 (81 %)	2,560 (81 %)	2,513 (80 %)	2,620 (83 %)	
<i>Hypertension, n (%)</i>					< 0.001
Yes	5,019 (53 %)	1,733 (55 %)	1,716 (54 %)	1,570 (50 %)	
No	4,447 (47 %)	1,423 (45 %)	1,439 (46 %)	1,585 (50 %)	
*Kruskal-Wallis rank sum test; Pearson's Chi-squared; χ^2 test; poverty impact ratio; BMI: body mass index; Log2 cotinine: log ₂ -transformed serum cotinine.					

Table II. Characteristics of the participants assessed for Appendicular Lean Mass Index

Characteristic	Overall <i>n</i> = 2,233	Q1 <i>n</i> = 745	Q2 <i>n</i> = 744	Q3 <i>n</i> = 744	p-value*
Age, mean (SD)	54 (3)	54 (3)	54 (3)	54 (3)	0.132
<i>Sex, n (%)</i>					0.002
Female	1,191 (53 %)	361 (48 %)	403 (54 %)	427 (57 %)	
Male	1,042 (47 %)	384 (52 %)	341 (46 %)	317 (43 %)	
ALM (kg), mean (SD)	22.0 (6.1)	22.8 (6.1)	21.8 (6.2)	21.3 (6.1)	< 0.001
Height (m), mean (SD)	1.66 (0.10)	1.67 (0.10)	1.66 (0.10)	1.66 (0.10)	0.056
ALMI (kg/m ²), mean (SD)	7.83 (1.64)	8.06 (1.67)	7.80 (1.63)	7.62 (1.60)	< 0.001
AHEI index, mean (SD)	40 (12)	28 (5)	39 (3)	53 (7)	< 0.001
<i>Race, n (%)</i>					< 0.001
Mexican American	283 (13 %)	76 (10 %)	122 (16 %)	85 (11 %)	
Non-Hispanic black	527 (24 %)	230 (31 %)	158 (21 %)	139 (19 %)	
Non-Hispanic white	804 (36 %)	293 (39 %)	255 (34 %)	256 (34 %)	
Other Hispanic	261 (12 %)	87 (12 %)	88 (12 %)	86 (12 %)	
Other race	358 (16 %)	59 (7.9 %)	121 (16 %)	178 (24 %)	
<i>Educational level, n (%)</i>					< 0.001
Under high school	428 (19 %)	195 (26 %)	135 (18 %)	98 (13 %)	

High school or equivalent	527 (24 %)	222 (30 %)	183 (25 %)	122 (16 %)	
Above high school	1,278 (57 %)	328 (44 %)	426 (57 %)	524 (70 %)	
<i>Marital status, n (%)</i>					< 0.001
Non-single	1,421 (64 %)	432 (58 %)	474 (64 %)	515 (69 %)	
Single	812 (36 %)	313 (42 %)	270 (36 %)	229 (31 %)	
PIR, mean (SD)	2.78 (1.70)	2.21 (1.55)	2.78 (1.71)	3.35 (1.66)	< 0.001
<i>PIR group, n (%)</i>					< 0.001
< 1	391 (19 %)	175 (26 %)	140 (21 %)	76 (11 %)	
≥ 1	1,645 (81 %)	506 (74 %)	540 (79 %)	599 (89 %)	
BMI, mean (SD)	30 (7)	30 (7)	29 (6)	29 (6)	< 0.001
<i>BMI group, n (%)</i>					< 0.001
Under weight	29 (1.3 %)	16 (2.1 %)	8 (1.1 %)	5 (0.7 %)	
Normal weight	543 (24 %)	145 (19 %)	180 (24 %)	218 (29 %)	
Overweight	756 (34 %)	221 (30 %)	256 (34 %)	279 (38 %)	
Obesity	905 (41 %)	363 (49 %)	300 (40 %)	242 (33 %)	
Log2 Cotinine, mean (SD)	-1.7 (5.9)	0.6 (6.4)	-2.1 (5.7)	-3.7 (4.6)	< 0.001
<i>Log2 Cotinine group, n (%)</i>					< 0.001
< 0.05	1,529 (71 %)	382 (54 %)	530 (74 %)	617 (85 %)	

0.05-3	52 (2.4 %)	27 (3.8 %)	14 (2.0 %)	11 (1.5 %)	
≥ 3	569 (26 %)	301 (42 %)	173 (24 %)	95 (13 %)	
<i>Alcohol drinker, n (%)</i>					< 0.001
Yes	1,462 (79 %)	478 (73 %)	488 (81 %)	496 (82 %)	
No	399 (21 %)	173 (27 %)	118 (19 %)	108 (18 %)	
<i>Diabetes, n (%)</i>					0.043
Yes	342 (15 %)	113 (15 %)	132 (18 %)	97 (13 %)	
No	1,888 (85 %)	630 (85 %)	612 (82 %)	646 (87 %)	
<i>Hypertension, n (%)</i>					< 0.001
Yes	945 (42 %)	352 (47 %)	318 (43 %)	275 (37 %)	
No	1,288 (58 %)	393 (53 %)	426 (57 %)	469 (63 %)	
*Kruskal-Wallis rank sum test; Pearson's Chi-squared; χ^2 test; poverty impact ratio; BMI: body mass index; Log2 cotinine: log ₂ -transformed serum cotinine.					

