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Research Article

Link between Secondhand Smoke Exposure and Obstructive Sleep Apnea among Nonsmoking U.S General Adults: Finding from the National Health and Nutrition Examination Survey 2015-2020

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The association between secondhand smoke exposure (SHSE) and obstructive sleep apnea (OSA) in general adults remains to be explored and therefore is investigated based on the representative National Health and Nutrition Examination Survey (NHANES) in this study. SHSE was assessed by self-reporting of passive exposure to burning cigarette in an indoor area (home, restaurant or bar, etc.), and OSA was defined by self-reporting OSA-related symptoms and frequency. A survey-weighted regression model and stratified analyses were used to estimate the association between SHSE and odds of OSA. The study involved 9,991 participants who had never smoked, representing a weighted number of 449.9 million adults ranging from 20 to 80 years old in the noninstitutionalized U. S population. There was a strong association between several kinds of SHSEs and OSA that compared with participants staying indoors without exposure to secondhand smoke (SHS), the odds of OSA was 1.2 times higher for those with SHSE at home (adjusted odds ratio (AOR) = 1.225, 95% CI: 1.009, 1.484), 1.4 times higher for those with SHSE in car (AOR = 1.404, 95% CI: 1.219, 1.616), and 1.3 times higher for those with e-cigarette SHSE (AOR = 1.302, 95% CI: 1.087, 1.557). Participants with simultaneous exposure to more different SHSs were 36% (one to three kinds of SHSEs (AOR = 1.368, 95% CI: 1.219, 1.534)) and 44% (above four kinds of SHSEs (AOR = 1.444, 95% CI: 1.034, 2.004)) more likely to have OSA, respectively. In general, general adults with SHSE in separate indoor areas, especially those with simultaneous exposure to different SHSs, had higher OSA risk. Identifying causality and health consequences of the association requires future longitudinal studies.

1. Introduction

Obstructive sleep apnea (OSA), characterized by frequent episodes of interrupted breathing (apnea) or a reduction in breaths (hypopnea), is the most common sleep disorder and one of the two major forms of sleep apnea syndrome (SAS). According to the International Classification of Sleep Disorders, Second Edition (ICSD-2) [1], a high prevalence of OSA was found in adults (males: 27.3%; females: 22.5%). It has been found that OSA alone increases the risk of metabolic, neuropsychiatric, and cardiovascular problems, especially in females [2, 3]. Several meta-analyses have also found that OSA correlates significantly with all-cause mortality and cardiovascular mortality [4–7]. Apart from the above medical problem, the impact of OSA extends to nonmedical issues, for example, car accidents, resulting in a

significant financial burden ranging from €10.7 billion to €32.0 billion per year. Additionally, insufficient treatment of OSA, which leads to a reduced quality of life, is estimated to cost between €2.8 billion and €9.0 billion annually [8].

When a person inhales a stream of cigarette smoke, thousands of hazardous chemicals and carcinogens in the tobacco enter the human body and cause various comorbidities, such as metabolic diseases and airway disorders [9]. Currently, the smoking rate among U.S. adults stands at 11.4 percent [10], and there is an increasing number of nonsmokers who are affected by a growing volume of e-cigarette smokers [11]. In other words, nonsmokers were at an increased risk of secondhand smoke exposure (SHSE). Breathing in smoke from a burning cigarette/smoke blown out by smokers is called secondhand smoke (SHS) [12, 13]. Those toxic components in tobacco induce chronic inflammation of the upper respiratory airways by inducing cellular hyperplasia, edema, epithelium thickening, and/or ciliary dysfunction [14]. Exposure to SHS has been linked to an increased risk of tracheal, bronchus, lung cancer, breast cancer, diabetes mellitus, and ischemic heart disease [15]. Recent years have seen a steady increase in the number of years lived with disability (YLDs) attributed to SHSE [15].

SHSE and OSA have been reported to be associated among children, but for general adults, the evidence is still rare with considerable uncertainties. A study has shown that adults with exposure to SHS at home were more likely to have habitual snoring than those without exposure to SHS at home, which suggests the harmful effects of indoor SHSE and emphasizes the need to reduce SHSE in indoor environments, particularly in homes [16]. The relationship between the two was not significant in another study [17]. Moreover, limitations such as a small sample size (a few hundred participants), old data, and special population (e.g., pregnant women) affect the generalization of the findings in these studies to a broader population [16–18], and one study even included smokers as its participants [17]. The most important is that previous studies examining single SHSE only focused on tobacco smoke in family surroundings, without considering SHSE in diverse indoor areas, such as the restaurant, the bar, the public transportation, or others' homes [16, 18, 19]. Accordingly, based on the representative and informative National Health and Nutrition Examination Survey (NHANES) database, we aimed to investigate whether exposure to a wide variety of SHSs was associated with higher odds of OSA among general adults.

2. Materials and Methods

2.1. Study Populations. NHANES is a multiyear, cross-sectional, and national population-based study, comprising a representative sample of the noninstitutionalized civilian population of the United States. NHANES utilizes a sophisticated, multistage probabilistic sampling methodology to choose participants that are representative of the civilian, deinstitutionalized population of the United States. Furthermore, to improve the accuracy and reliability of health status indicators for specific groups within the population, targeted samples are collected. A household interview was conducted to obtain demographic, socioeconomic, lifestyle, and self-reported health information. Approval for the NHANES project was gained from the National Center for Health Statistics Research Ethics Review Board, and participants provided written consent. Three waves (2015-2016, 2017-2018, and 2019-2020) with six years of publicly available datasets were downloaded to define the OSA status. The designated website provides free access to all the data presented in this study (https://www.cdc.gov/nchs/nhanes/index.htm). At first, participants under 20 years old as well as past and current smokers were excluded from the 114,152 evaluated participants. Then, they were checked for OSA status, and 79,042 participants without relevant OSA data were removed. Meanwhile, those without the Interview and Mobile Examination Center sample and weight data (7,267 participants) or with missing related information (17,852 participants), such as education and smoking status, were all screened out. Accordingly, 9,991 participants who met the above criteria were included in the study (Figure 1).

2.2. Secondhand Smoke Exposure. SHSE among never-smokers was identified by their self-reported of passive exposure to burning cigarettes in an indoor area (restaurant, bar, or car). Participants recalled if they had stayed in any indoor area where there were people smoking in the past week based on the following six dichotomous questions: "While you were staying in a home/restaurant/bar/car/other people's homes/other places, was someone smoking indoors?"Moreover, for e-cigarette indoor exposure, another question was put that "In the last 7 days, have you been in an indoor place where someone was using an e-cigarette, e-hookah, vape pen or other similar electronic products?" [12]. We have further combined the above all SHSEs as the total SHSE and stratified it into three groups (without SHSE, one to three kinds of SHSEs, above four kinds of SHSEs) that means how many types of SHSs that he/she has been exposed to simultaneously during the last 7 days.

2.3. Obstructive Sleep Apnea Measures. The American Academy of Sleep Medicine recommends using the Sleep Disorders questionnaire to screen the participants for OSA status, featured by four symptoms: snoring, daytime tiredness, witnessed apneas, and hypertension. NHANES adapted their screening questionnaire from the Sleep Heart Health Study's sleep habits questionnaire in which the OSA included the first three symptoms mentioned above [20]. The definition of OSA involves three dichotomous questions: (1) snoring no less than 3 times by night each week; (2) snorting, gasping, or stopping breathing no less than 3 times by night each week; (3) feeling extremely sleepy 16-30 times by day each month even with roughly 7 or more hours of sleep by night on weekdays [21]. At least one of the following three questions was answered in the affirmative by individuals with symptoms of OSA. These three questions were only available for the 2015-2016, 2017-2018, and 2019-2020 waves.

2.4. Definition of Covariates. To minimize possible confounding effects, the relevant variables from previous studies

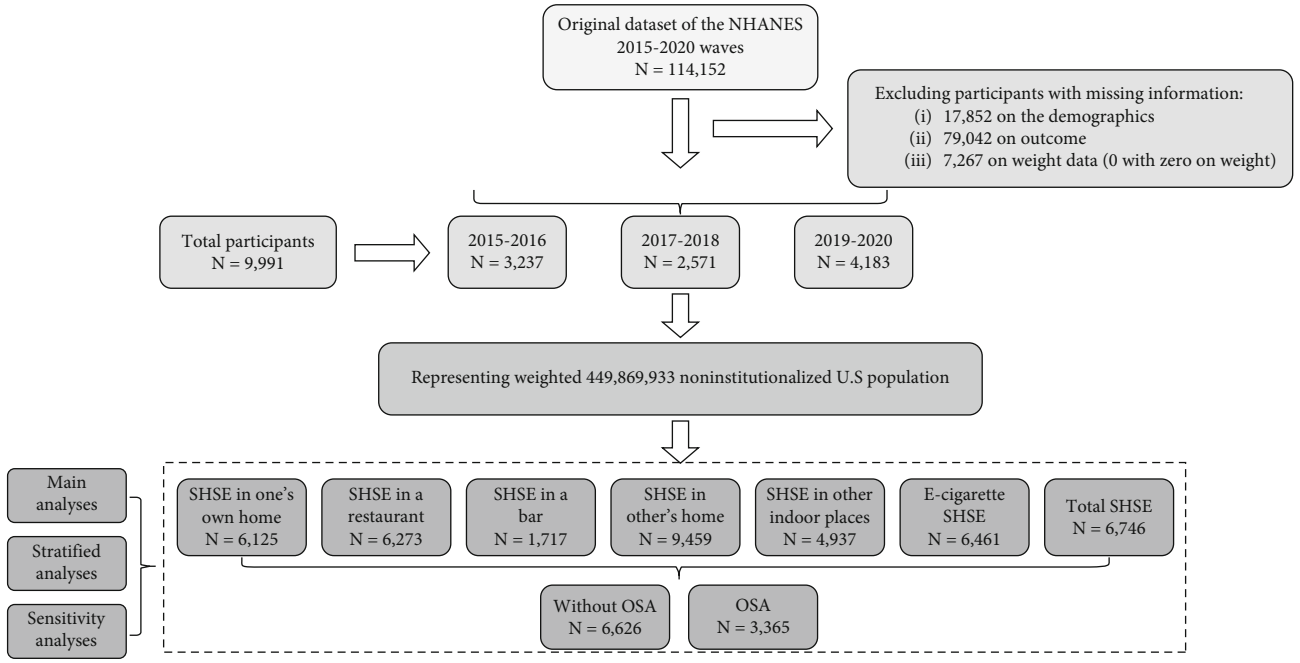

Figure 1: Flow chart of selection of NHANES participants. Abbreviations: NHANES: National Health and Nutrition Examination Survey; OSA: obstructive sleep apnea; SHSE: secondhand smoke exposure. Assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own house, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in other's home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days.

were chosen as predictors for the regression analysis. Under the gender item are "male" and "female." Following the standard proportions for NHANES Population Groupings, respondents were divided into three categories according to their age: 20-39 years old, 40-59 years old, and above 60 years old. For race/ethnicity, we had four divisions: Non-Hispanic White, Non-Hispanic Black, Mexican American, and other races (multiracial and other Hispanic). Education of participants is divided into five levels (below 9th grade, 9th-11th grade (including 12th grade without diploma), high school graduate (GED or equivalent), college graduate or above, and some college or AA degree), and their status of marriage into three categories (divorced/separated/widowed, single/never married, and married/living with partner). The family income was classified according to the federal poverty threshold and the poverty-to-income ratio (PIR). To calculate PIR, the income of a family or individual is divided by the income set in the poverty guidelines that are specific to each survey year [22]. A PIR value of less than 1.0 indicates that a family lives below the poverty threshold [23]. Body mass index (BMI) is determined by dividing a person's weight in kilograms by their squared height in meters (kg/m^2). A questionnaire was used to measure physical activity (PA) in terms of metabolic equivalent minutes (MET-minutes) per week. MET-minutes is a measure of the energy expenditure of an activity, related to the resting metabolic rate. To calculate the energy expenditure of an activity, we use MET-minutes, which is obtained by multiplying the MET score of the activity by the duration (minutes) of the activity. For a person weighing 60 kilograms, the energy expenditure in MET-minutes is equivalent to the number of kilocalories burned [24] and was divided into four quartiles (Q1, Q2, Q3, and Q4).

2.5. Statistical Analyses. Since the NHANES had a multiple-stage sampling procedure, we used the appropriate weights and strata variables for the following analysis. Conducted in accordance with the NHANES analytic guidelines, the analyses took the unequal probability of selection, oversampling of certain subpopulations, and nonresponse adjustments into account to ensure that the estimates were nationally representative. As recommended by NHANES tutorial (https://wwwn.cdc.gov/nchs/nhanes/tutorials/Module3.aspx), the 6-year weights (2015-2016, 2017-2018, and 2019-2020) were calculated using the weights of the individual SHSE. Generally, means and standard deviations are used to represent continuous variables with an approximately normal distribution, whereas those with a skewed distribution are expressed as median and interquartile range. In categorical variables, the sample size is multiplied by a weighted percentage as well as absolute numbers. To compare patients with OSA to control subjects, we utilized either a survey-weighted *t*-test (for normal distribution) or a survey-weighted Mann–Whitney test (for skewed distribution) for continuous variables. Additionally, we used a survey-weighted Chi-square test for categorical variables. Additionally, survey-weighted multivariable logistic regression was utilized to calculate adjusted odds ratios (AORs) and 95% confidence intervals (CIs) for the association between SHSE and OSA. Three models were implemented in our main analysis. The crude model was a model without any covariate adjustments. Model 1 was built to adjust age,

gender, and race/ethnicity. The full-adjustment model 2 was further adjusted for PIR, BMI, education, marital status, PA (quartile), and alcohol consumption.

To investigate the impact of potential variability on the relationship between SHSE and the likelihood of OSA, subgroup analyses were performed based on demographic characteristics (e.g., age, gender, and race). Furthermore, the robustness of our results was also explored through several sensitivity analyses. First, further adjustments were made based on the total energy (quartile). Then, we excluded participants with abnormal PIR and BMI values. All the above statistical analyses were carried out with R statistical programming language (X64 Version 4.1.0, R Foundation for Statistical Computing, Vienna, Austria, https://www.r-project.org/), with statistical significance set at bilateral P -value below 0.05.

3. Results and Discussion

3.1. Results

3.1.1. Sociodemographic Characteristics of Participants. The 9,991 participants from the NHANES database represented a sum of 449,869,933 noninstitutionalized U. S residents, among which the majority were Non-Hispanic White adults (297,913,477, 66.2%). In total, 48.4% (4,835) of the population was females, and 27.8% (2,782) were above 60 years old. The percentage of Non-Hispanic Whites (37.1%) topped the list with other races (26.8%) and Non-Hispanic Blacks (22.8%) followed behind, and Mexican Americans were in the minority (13.3%). A 33.6% age-adjusted prevalence for participants in the sample suffers from OSA while males (37.1%), middle-aged, and older adults (40-59 years old group: 38.3%; above 60 years old group: 37.8%) tended to have higher odds for OSA. The majority of the demographic variables were significant between participants with and without OSA ($P < 0.001$) except race/ethnicity, education, PIR, PA (quartile), and alcohol consumption. Details of more sociodemographic characteristics for included participants categorized by OSA status are presented in Table 1 and Figure 2.

3.1.2. Association between Secondhand Smoke Exposure and Odds of Obstructive Sleep Apnea. Among the seven SHSEs, several SHSEs (SHSE in one's own home, SHSE in a car, SHSE in others' homes, SHSE in other indoor places, e-cigarette SHSE, and total SHSE) were independently associated with OSA based on the crude model (shown in Table 2). After a full adjustment, compared with those who were not exposed to SHS, participants with SHSE in their own home (AOR = 1.225, 95% CI: 1.009, 1.484; $P < 0.05$), in a car (AOR = 1.404, 95% CI: 1.219, 1.616; $P < 0.001$), in others' homes (AOR = 1.221, 95% CI: 1.005, 1.480; $P < 0.05$) and in other indoor places (AOR = 1.272, 95% CI: 1.027, 1.573; $P < 0.05$), and with e-cigarette SHSE (AOR = 1.302, 95% CI: 1.087, 1.557; $P < 0.05$) were 1.2, 1.4, 1.2, 1.2, and 1.3 times more likely to contract OSA among adults, separately. Regarding the total SHSE, participants with simultaneous exposure to different SHSs were 36% (one to three SHSEs (AOR = 1.368, 95% CI: 1.219, 1.534; $P < 0.001$)) and 44% (above four SHSEs (AOR = 1.444, 95% CI: 1.034, 2.004; $P < 0.05$)) more likely to suffer from OSA, respectively. We found no statistically significant association between SHSE in a restaurant (AOR = 1.182, 95% CI: 0.865, 1.603; $P = 0.288$), or in a bar (AOR = 1.102, 95% CI: 0.825, 1.468; $P = 0.510$) and OSA.

3.1.3. Subgroup Analyses and Sensitivity Analyses. Through independent subgroup analyses by various demographic variables, it was found that the association between these SHSEs and OSA persisted, and SHS was significantly associated with OSA in terms of the items of age, gender, and education (P for interaction < 0.05). The association between total SHSE and OSA was not significant among Non-Hispanic Black participants (AOR = 1.175, 95% CI: 0.938, 1.473; $P = 0.510$), but among those that were Non-Hispanic White (AOR = 1.379, 95% CI: 1.134, 1.675; $P < 0.001$), Mexican American (AOR = 1.645, 95% CI: 1.213, 2.232; $P < 0.001$), and other races (AOR = 1.374, 95% CI: 1.080, 1.746; $P < 0.001$). Similarly, participants with total SHSE and a low level of PIR were associated with higher odds of OSA (AOR = 2.647, 95% CI: 1.409, 4.966; $P < 0.001$), but the association was not significant for those with a high level of PIR (AOR = 1.112, 95% CI: 0.858, 2.288; $P = 0.379$; P for interaction < 0.001). The subgroup analyses were shown in Supplementary Table 3 in detail.

Basic results in the sensitivity analyses were the same as those in the main analyses (shown in Supplementary Table 4). Further adjusting the results with total energy of individuals did not substantially change the results either. Moreover, similar results were yielded that the odds of OSA were higher for groups exposed to more SHSs after excluding the extreme BMI values and PIR values.

3.2. Discussion. As a national population-based study, we investigated the association between comprehensive SHSEs and possible OSA. We found a higher likelihood of OSA in the groups with SHSE compared to those without, and the correlation was particularly significant when participants were exposed to SHS in a car or to more SHSs simultaneously, which proves that exposure to SHS is a modifiable risk factor for OSA. This association was stronger in females and older population groups.

Our findings may be consistent with those in an earlier meta-analysis. With a comprehensive search strategy, it eventually selected 26 studies to pool analysis and confirmed that exposure to SHS was associated with higher odds of OSA [9]. Nevertheless, there is still a lack of understanding regarding the detailed biological mechanisms behind the association of tobacco exposure and snoring, but it is assumed to be possibly related to inflammation and irritation in the upper airways [2, 25]. Another hypothetical explanation is that edema and pharyngeal inflammation induced by chemicals bring about obstruction [26]. Also, SHSE is thought to possibly have an influence on neurotransmitters of ventilatory control [27]. What's more, the possible pathological change is because with prolonged exposure to SHS, tissues are less sensitive to hypoxia, and

Table 1: Survey-weighted detailed characteristics of U.S adults aged 20-80 years with obstructive sleep apnea status (National Health and Nutrition Examination Survey 2015-2020 ($N = 9{,}991$)).

Health variables	Age-adjusted OSA prevalence ((weighted, % (SE))	Estimate U.S population (n)	Overall	Without OSA	OSA	P value[a]
Total participants	33.6 (0.71)	449,869,933	9,991 (100.0)	6,626 (66.3)	3,365 (33.7)	—
Age (years)	—	—	45.72 ± 0.43	44.46 ± 0.40	48.24 ± 0.67	<0.001
20-39	26.8 (1.04)	184,361,381	3,813 (38.2)	2,791 (45.1)	1,022 (32.8)	
40-59	38.3 (1.16)	161,269,706	3,396 (34.0)	2,078 (33.2)	1,318 (41.1)	**<0.001**
60	37.8 (1.73)	104,238,846	2,782 (27.8)	1,757 (21.7)	1,025 (26.2)	
Sex						
Male	37.1 (1.05)	229,667,470	5,156 (51.6)	3,229 (48.5)	1,927 (56.1)	**<0.001**
Female	30.0 (1.19)	220,202,463	4,835 (48.4)	3,397 (51.5)	1,438 (43.9)	
Race/ethnicity						
Non-Hispanic White	33.2 (0.93)	297,913,477	3,704 (37.1)	2,470 (66.1)	1,234 (66.4)	
Non-Hispanic Black	33.9 (1.16)	44,721,575	2,280 (22.8)	1,508 (9.9)	772 (10.0)	
Mexican American	37.2 (1.33)	37,611,326	1,325 (13.3)	832 (8.4)	493 (8.2)	0.967
Other race (including Multiracial and other Hispanic)	34.6 (1.41)	69,623,554	2,682 (26.8)	1,816 (15.5)	866 (15.4)	
Education level						
Less than 9th grade	32.6 (2.34)	11,461,354	582 (5.8)	385 (2.5)	197 (2.96)	
9-11th grade (including 12th grade with no diploma)	38.9 (2.95)	25,089,048	909 (9.1)	583 (5.1)	326 (6.4)	
High school grad/GED or equivalent	36.7 (1.57)	109,560,656	2,241 (22.4)	1,470 (23.3)	771 (26.5)	**<0.05**
College graduate or above	29.8 (1.56)	155,977,187	2,857 (28.6)	1,995 (36.5)	862 (30.9)	
Some college or AA degree	34.3 (1.29)	147,781,686	3,402 (34.1)	2,193 (32.5)	1,209 (33.5)	
PIR	—	—	3.22 ± 0.05	3.22 ± 0.05	3.22 ± 0.06	0.946
Below poverty (<1.0)	35.1 (1.86)	54,119,969	1,787 (17.9)	1,213 (12.2)	574 (11.7)	0.602
Above poverty (≥1.0)	33.5 (0.76)	395,749,964	8,204 (82.1)	5,413 (87.8)	2,791 (88.3)	
Marital status						
Widowed/divorced/separated	31.2 (1.84)	69,811,029	1,868 (25.0)	1,246 (19.2)	622 (19.9)	
Never married	29.2 (2.38)	92,066,066	2,082 (27.8)	1,535 (28.5)	547 (19.6)	**<0.001**
Married/living with partner	35.0 (1.28)	197,201,801	3,534 (47.2)	2307 (52.3)	1,227 (60.5)	
BMI (kg/m^2)	—	—	29.38 ± 0.17	28.35 ± 0.19	31.44 ± 0.23	**<0.001**
Alcohol consumption						
Never	25.9 (2.38)	37,354,393	1,123 (11.2)	832 (9.3)	291 (6.3)	
Former	38.7 (4.62)	19,873,952	457 (4.6)	315 (4)	142 (5.3)	**<0.05**
Current	34.1 (0.76)	392,641,587	8,411 (84.2)	5,479 (86.8)	2,932 (88.3)	
Moderate to vigorous PA (MET minutes/week)	—	—	5564.95 ± 152.48	5508.48 ± 161.00	5677.23 ± 254.19	0.527
Quartile 1 (<960 MET)	34.7 (1.70)	108,891,983	2,659 (26.6)	1,751 (23.3)	908 (26.0)	
Quartile 2 (960-2640 MET)	32.7 (1.37)	117,808,316	2,366 (23.67)	1,593 (26.4)	773 (25.8)	**<0.05**
Quartile 3 (2640-7200 MET)	31.0 (1.05)	115,726,862	2,478 (24.8)	1,673 (26.9)	805 (23.3)	
Quartile 4 (>7200 MET)	35.6 (1.77)	107,442,771	2,488 (24.9)	1,609 (23.4)	879 (24.9)	
Total energy intake (kcal)	—	—	2105.52 ± 13.72	2046.57 ± 16.74	2223.85 ± 21.71	**<0.001**
Quartile 1 (<1503 kcal)	27.8 (1.46)	92,921,010	2,098 (25.1)	1,464 (25.4)	634 (20.1)	
Quartile 2 (1503-1958 kcal)	29.4 (1.58)	100,371,847	2,092 (25.0)	1,437 (27)	655 (22.5)	**<0.001**
Quartile 3 (1958-2526.5 kcal)	33.8 (1.75)	99,711,684	2,092 (25.0)	1,370 (25.1)	722 (25.8)	
Quartile 4 (>2526.5 kcal)	41.5 (1.49)	100,191,145	2,093 (25.0)	1,244 (22.4)	849 (31.6)	

Table 1: Continued.

Health variables	Age-adjusted OSA prevalence ((weighted, % (SE))	Estimate U.S population (*n*)	Overall	Without OSA	OSA	*P* value[a]
SHSE in one's own home						
No	32.9 (1.14)	254,378,527	5,334 (87.1)	3,596 (90.0)	1,738 (87.3)	**<0.05**
Yes	40.4 (2.85)	31,080,509	791 (12.9)	473 (10.0)	318 (12.7)	
SHSE in a restaurant						
No	33.5 (0.97)	308,497,922	6,024 (96.0)	3,992 (97.1)	2,032 (97.0)	0.822
Yes	37.2 (4.70)	9,252,616	249 (4.0)	158 (2.9)	91 (3.0)	
SHSE in a bar						
No	35.0 (2.34)	81,428,973	1,303 (75.9)	867 (83.3)	436 (81.0)	0.451
Yes	37.6 (4.51)	17,259,914	414 (24.1)	269 (16.7)	145 (19.0)	
SHSE in a car						
No	33.0 (0.79)	369,729,932	7,864 (83.1)	5,254 (86.0)	2,610 (83.7)	0.152
Yes	38.1 (2.57)	64,024,416	1,595 (16.9)	994 (14.0)	601 (16.3)	
SHSE in others' homes						
No	34.0 (1.08)	212,262,559	4,136 (83.8)	2,772 (87.9)	1,364 (87.1)	0.523
Yes	37.3 (2.24)	30,034,017	801 (16.2)	497 (12.1)	304 (12.9)	
SHSE in other indoor places						
No	33.0 (0.96)	295,103,964	5,872 (90.9)	3,903 (93.4)	1,969 (91.1)	**<0.05**
Yes	41.2 (3.36)	23,385,963	589 (9.1)	373 (6.6)	216 (8.9)	
E-cigarette SHSE						
No	34.6 (1.12)	238,277,087	5,657 (83.9)	3,716 (83.7)	1,941 (83.4)	0.845
Yes	39.5 (2.48)	46,676,875	1,089 (16.1)	678 (16.3)	411 (16.6)	
Total SHSE[b]						
Without SHSE	31.7 (0.94)	314,515,109	6,728 (67.3)	4,576 (71.4)	2,152 (67.0)	
1-3 kinds of SHSE	39.0 (1.42)	126,605,817	3,037 (30.4)	1,914 (26.6)	1,123 (31.2)	**<0.05**
≥4 kinds of SHSE	29.6 (4.03)	8,749,007	226 (2.3)	136 (2.0)	90 (1.8)	
Survey wave						
2015-2016 wave	31.3 (1.12)	164,655,844	3,237 (32.4)	2,226 (37.8)	1,011 (34.2)	
2017-2018 wave	35.0 (1.49)	142,834,637	2,571 (25.7)	1,689 (31.2)	882 (32.9)	0.078
2019-2020 wave	35.1 (1.14)	142,379,452	4,183 (41.9)	2,711 (31.0)	1,472 (32.9)	

Footnotes: Continuous variables were presented as mean ± SE, and categorical variables were presented as *n* (%). [a]*P* values were calculated by *t*-test and chi-square test. [b]Assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own home, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in others' home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days. Abbreviations: AA: associate's degree; BMI: body mass index; GED: general educational development; OSA: obstructive sleep apnea; PA: physical activity; PIR: poverty income ratio; SE: standard error; SHSE: secondhand smoke exposure. The bold *P*-values indicate that the differences are statistically significant.

the capability of recovering from conditions induced by hypoxia is damaged [28, 29]. Similar to most included studies mentioned above, previous studies investigating this association were mainly focused on children. The third edition of the International Classification of Sleep Disorders (ICSD-3) divided OSA into adult and pediatric OSA [30]. The clinical features, risk factors, standard of diagnosis, and polysomnographic findings of OSA between children and adults are not likely the same. General adults, however, have long been ignored by researchers investigating the relationship between SHSE and OSA. Furthermore, limitations in existing studies, such as special population (pregnant women), single SHSE, a small sample size, or absence of key variables, make it hard to extrapolate their findings to general adults. Based on the entire adult population that is nationally representative, this study provided an unprecedented evidence of comprehensive SHSE for identifying its association with OSA. Our study suggests that the odds of developing OSA may vary with the location of SHSE. Specifically, we found a significant association between OSA and exposure to e-cigarette SHS, as well as exposure in one's own or others' home. However, we did not find any association between OSA and SHSE in a restaurant or bar setting. These findings demonstrated the need to consider the location of exposure in the assessment of OSA odds related to SHS. These results could possibly be attributed to the lower frequency and

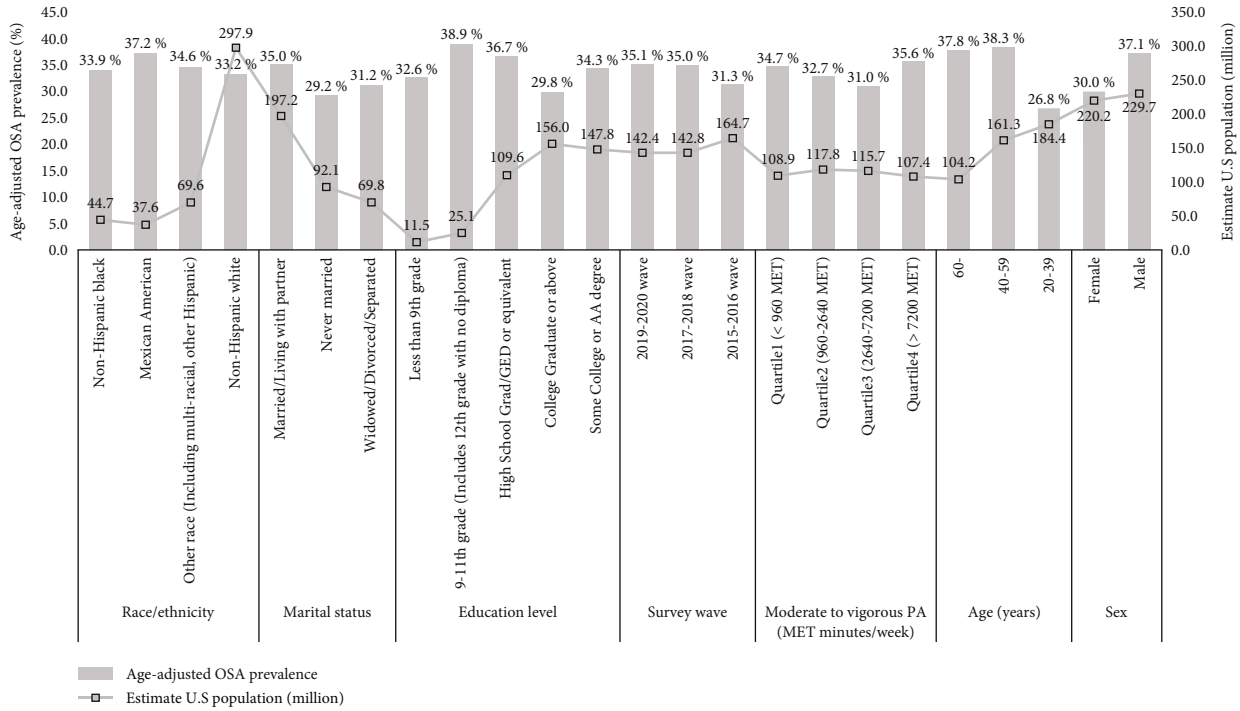

Figure 2: Age-adjusted OSA prevalence and estimate U.S population among U.S population based on demographic characteristics (NHANES 2015-2020 ($N = 9{,}991$)). Abbreviations: NHANES: National Health and Nutrition Examination Survey; AA: associate's degree; GED: general educational development; OSA: obstructive sleep apnea; PA: physical activity; SHSE: secondhand smoke exposure. Assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own home, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in others' home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days.

Table 2: The associations between secondhand smoke exposure and the odds of obstructive sleep apnea in survey-weighted generalized logistic regression models ($N = 9{,}991$).

Exposures	Cases/participants	Crude Model		Model 1		Model 2	
		COR (95%CI)	P-value[a]	AOR (95%CI)	P-value[a]	AOR (95%CI)	P-value[a]
SHSE in one's own home							
No	1,738/5,334	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	318/791	**1.391 (1.193,1.621)**	**< 0.001**	**1.280 (1.093,1.497)**	**< 0.05**	**1.225 (1.009,1.484)**	**< 0.05**
SHSE in a restaurant							
No	2,032/6,024	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	91/249	1.131 (0.867,1.469)	0.358	1.118 (0.853,1.457)	0.412	1.182 (0.865,1.603)	0.288
SHSE in a bar							
No	436/1,303	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	145/414	1.072 (0.848,1.351)	0.558	1.079 (0.845,1.375)	0.539	1.102 (0.825,1.468)	0.510
SHSE in a car							
No	2,610/7,864	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	601/1,595	**1.217 (1.088,1.360)**	**< 0.001**	**1.309 (1.165,1.470)**	**< 0.001**	**1.404 (1.219,1.616)**	**< 0.001**
SHSE in others' homes							
No	1,364/4,136	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	304/801	**1.243 (1.062,1.453)**	**< 0.05**	**1.248 (1.060,1.469)**	**< 0.05**	**1.221 (1.005,1.480)**	**< 0.05**
SHSE in other indoor places							
No	1,969/5,872	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	216/589	1.148 (0.961,1.368)	0.125	1.117 (0.932,1.337)	0.228	**1.272 (1.027,1.573)**	**< 0.05**
E-cigarette SHSE							
No	1,941/5,657	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
Yes	411/1,089	**1.161 (1.014,1.327)**	**< 0.05**	**1.297 (1.128,1.490)**	**< 0.001**	**1.302 (1.087,1.557)**	**< 0.05**
Total SHSE[b]							
without SHSE	2,152/6,728	1 [Reference]	-	1 [Reference]	-	1 [Reference]	-
1-3 kinds of SHSE	1,123/3,037	**1.248 (1.140,1.365)**	**< 0.001**	**1.312 (1.195,1.440)**	**< 0.001**	**1.368 (1.219,1.534)**	**< 0.001**
≥ 4 kinds of SHSE	90/226	**1.407 (1.070,1.842)**	**< 0.05**	**1.512 (1.142,1.994)**	**< 0.05**	**1.444 (1.034,2.004)**	**< 0.05**
P for trend			**< 0.001**		**< 0.001**		**< 0.001**

◆ Significant difference □ Non-significant difference

Footnotes: Crude model was an unadjusted model. Model 1 was adjusted for age, sex, and race/ethnicity. Model 2 was further adjusted for PIR, BMI, education, marital status, alcohol consumption, and PA (quartile). [a]P values, COR, and AOR in bold indicate statistical significance. [b]Assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own home, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in others' home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days. Abbreviations: AOR: adjusted odds ratio; BMI: body mass index; CI: confidence interval; COR: crude odds ratio; PA: physical activity; PIR: poverty income ratio; SHSE: secondhand smoke exposure.

shorter duration of SHSE in restaurants or bars, or the lower concentration of SHSE in these places due to their larger space or better ventilation compared to homes [31]. Our study did not identify a safe threshold level of SHSE to prevent OSA, considering the limitations of using self-reported SHSE data. To better evaluate the relationship between environmental SHS concentrations and OSA, future studies should use passive samplers to monitor nicotine levels in various locations [32]. This will help determine a safety threshold for SHSE and its correlation with OSA. Meanwhile, it is recommended that policies be established to reduce the concentration of SHSE in various environments. Participants with a total SHSE were much more susceptible to OSA than those with no SHSE or with fewer types of SHSEs. Though there has been no clear evidence for this so far, this hints to the possibility that adults who are affected by the external environment, for instance, being driven by alcohol reward [33], and simultaneously experience more than one of these types of SHSEs were more likely to develop OSA compared to those with single SHSE. This finding may have implications for the direction of future studies.

Besides SHSE, several studies highlighted that current smoking and former smoking both contributed to habitual snoring development, and adults with a higher tobacco intake and more passive smoking exposure had an increased frequency of snoring [16, 34–38]. One of these studies also pointed out that women who smoked had a disproportionately higher risk of snoring than men who smoked [16], which was in line with another population-based study with bronchial hyperresponsiveness and related respiratory symptom indicator [39]. Even though the relevant information on SHSE has not been previously documented, our study showed that the odds of OSA appeared to be higher among females than males if both genders were exposed to SHS at home. This is likely related to the different pathogenesis of snores between males and females that males are more affected by structural changes within the upper airways, whereas females are affected by functional changes within those airways [40]. Findings of additional subgroup analyses revealed that the influence extent of ethnic differences in our study was identical to that of geographic differences in another one [16]. Non-Hispanic White and Mexican American respondents seem to have higher odds of developing OSA when they are exposed to SHS. Thus, we hereby put forward an initial hypothesis that ethnic differences are demonstrated both by different living conditions, including financial status, alcohol consumption, PA habit, and the like, and by differences in sensitivity to the mentioned various living conditions.

Previous research on SHSE simply focused on familial settings and has not thoroughly investigated SHSE in various indoor environments, including public transportation, restaurants, bars, and other people's homes [16, 17]. Our study is aimed at filling this gap by conducting a comprehensive examination of the link between SHSE and the likelihood of OSA in different settings, such as homes, cars, bars, restaurants, and exposure from e-cigarettes. The data in our study came from a national sample representative of the U.S. population, thus making our findings generalizable to all the adults without OSA in the U.S. Meanwhile, our use of several indicators of SHSE as a comprehensive evaluation increases the accuracy of exposure classification compared with previous studies with single SHSE. This study offers valuable referential significance for patients, policy maker, and even the health care system. At least, the health care providers and law enforcement agency should implement stronger regulation and policy to prohibit smoking in public indoor areas including e-cigarettes. Several limitations in this study should be noted. First, considering that the study was cross-sectional, it cannot demonstrate a cause-and-effect relationship between SHSE and OSA. Second, the serum cotinine for evaluating the SHSE might provide a more accurate and dose-response association between SHS and OSA. However, since the level of serum cotinine for rating whether a person has exposure to SHS is inconsistent with that of previous studies, to further evaluate various SHSEs, our study defined SHSE based on self-report assessment with dichotomous questions. Our assessment of OSA, relying on self-reported symptoms rather than a clinical diagnostic interview or the polysomnography (PSG), can identify individuals with high OSA risk but may be insufficient for a clinical diagnosis [41]. Unfortunately, PSG, the recommended criteria for diagnosing OSA by the American Association of Sleep Medicine, is often prohibitively expensive and not readily accessible in many areas. Therefore, our assessment was only an alternative measurement, and future research could develop more powerful and valid screening tools to better identify OSA symptoms.

4. Conclusions

Based on the representative NHANES database, we included 9,991 respondents and found a relationship between several SHSEs and OSA. Individuals exposed to SHS in a car or different kinds of SHSs simultaneously have greater odds of OSA. The causal relationship between SHSE and OSA may be better understood through further well-designed prospective cohort studies.

Abbreviations

AA: Associate's degree
AOR: Adjusted odds ratio
BMI: Body mass index
CIs: Confidence intervals
METs: Metabolic equivalent minutes
NHANES: National Health and Nutrition Examination Survey
OSA: Obstructive sleep apnea
PA: Physical activity
PIR: Poverty-to-income ratio
PSG: Polysomnography
SHS: Secondhand smoke
SHSE: Secondhand smoke exposure
SHSEs: Secondhand smoke exposures
YLDs: Years lived with disability.

Data Availability

The datasets generated and analyzed during the present study are available from the NHANES databases (available from https://www.cdc.gov/nchs/nhanes/participant.htm).

Conflicts of Interest

The authors declare no conflict of interest.

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Supplementary Materials

Supplementary Table 1 and Supplementary Table 2 showed survey-weighted detailed characteristics of U.S adults aged 20-80 years with obstructive sleep apnea status. Supplementary Table 1 was stratified by seven kinds of secondhand smoke exposures. Supplementary Table 2 was stratified by year waves. Assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own home, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in others' home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days. Supplementary Table 3 presented stratified analyses of weighted associations between seven kinds of secondhand smoke exposures with obstructive sleep apnea odds. Supplementary Table 4 showed a sensitivity analysis about associations between seven kinds of secondhand smoke exposures and odds of obstructive sleep apnea. All supplementary files include the same following footnotes (assessment of total SHSE was based on seven types of SHSE, including SHSE in one's own home, SHSE in a restaurant, SHSE in a bar, SHSE in a car, SHSE in others' home, SHSE in other indoor places, and e-cigarette SHSE. Total SHSE means how many types of SHSE that he/she has been exposed to simultaneously during the last 7 days). *(Supplementary Materials)*

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