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Trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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STRENGTHS AND LIMITATIONS OF THIS STUDY

- This is the first study to compare the prevalence trends of general obesity by sex, ethnicity (Mexican, European and African American), and age group in adults 20-79 years in the United States using the relative fat mass (RFM) index, a validated surrogate for whole-body fat percentage, and the body mass index.
- We used survey data from nationally representative samples of the non-institutionalized U.S. adults collected by the National Health and Nutrition Examination Survey from 1999 to 2020.
- RFM has a high diagnostic accuracy (91%) for obesity defined by the dual energy X-ray absorptiometry; it requires only measured waist circumference and height; and the diagnosis of general obesity was based on previously validated RFM cutoffs to predict all-cause mortality.
- Estimates of prevalence trends could have been affected by some variability in sampling across survey cycles.
- We did not analyze the prevalence trends for Asian Americans due to the lack of oversampling prior to 2011.

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ABSTRACT

Objectives: The body mass index (BMI) largely underestimates excess body fat, suggesting that the prevalence of obesity could be underestimated. This study aimed to compare the trends of general obesity by sex, ethnicity, and age group among adults in the United States using the relative fat mass (RFM), a validated surrogate for whole-body fat percentage, and the BMI.

Design: Population-based study

Setting: U.S. National Health and Nutrition Examination Survey (NHANES), from 1999-2000 through 2017-March 2020.

Participants: A representative sample of adults 20-79 years in the U.S.

Main outcome measures: Age-adjusted prevalence of general obesity. RFM-defined obesity was diagnosed using validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men. BMI-defined obesity was diagnosed using a cutoff of 30 kg/m^2.

Results: Analysis included 47,667 adults. Among women, RFM-defined obesity prevalence was 64.7% (95% confidence interval, 62.1 to 67.3%) in 2017-2020, a linear increase of 13.9 percentage points (9.0 to 18.9%; P<0.001) relative to 1999-2000. In contrast, the prevalence of BMI-defined obesity was 42.2% (39.4 to 45.0%) in 2017-2020. Among men, the corresponding RFM-defined obesity prevalence was 45.8% (42.0 to 49.7%), a linear increase of 12.0 percentage points (6.6 to 17.3%; P<0.001). In contrast, the prevalence of BMI-defined obesity was 42.0 (37.8 to 46.3%). The highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) and Mexican Americans, in women and men. Conversely, the highest prevalence of BMI-defined obesity across years was observed in middle-age (40-59 years) and older adults, and in African American women.

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Conclusions: The use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women, than that estimated by the BMI, and detected a disproportionate higher prevalence of general obesity in older adults and Mexican Americans.

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INTRODUCTION

The prevalence of obesity (excess body fat) in the United States has doubled from 15.0% in 1976-1980 to 30.9% in 1999-2000 [1], and it continues to increase [2 3]. The age-adjusted prevalence of obesity among adults in the U.S. has been estimated at 41.9% in 2017-March 2020 [4]. Obesity diagnosis is based on the body mass index (BMI), an indirect measure of body fat [5 6]. BMI is calculated as the ratio of body weight in kilograms to the square of the height in meters [7]. BMI does not distinguish between fat mass and fat-free mass and does not account for differences in adiposity between women and men [8-12]. A meta-analysis of 25 international studies comprising nearly 32,000 adults concluded that BMI underestimates ~50% of all individuals with excess body fat percentage determined by reference techniques [11], suggesting that the prevalence of obesity could be largely underestimated among countries.

There is robust evidence linking high whole-body fat percentage with increased risk of death [13-20], supporting the need for a better assessment of body adiposity. Although the limitations of BMI to assess body adiposity are widely acknowledged [6 8-11 21 22], BMI remains the most widely used anthropometric index in clinical practice, epidemiology, and public health, given its simplicity, very low cost, and its association with several clinical conditions and mortality [6]. The high cost and time required to assess body adiposity using more accurate techniques such as dual-energy x-ray absorptiometry (DXA), dual-labeled water, or magnetic resonance, prevents their use in large populations or clinical practice as part of routine screening.

The relative fat mass (RFM) is a simple and low-cost anthropometric index developed to estimate whole-body fat percentage [23]. RFM is a linear equation based on the ratio of height to waist circumference that has been validated in Mexican, European, and African Americans [23], and in other populations [24-26]. Compared with BMI, RFM resulted in lower obesity misclassification when DXA was used as the reference method for diagnosing obesity in adults [24 27]. The accuracy of RFM in diagnosing high body fat percentage is superior to that of BMI

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among men and similar to BMI among women [23]. In an analysis of a representative sample of the U.S. adult population (NHANES 1999-2006), RFM had a diagnostic accuracy of 91% (C-statistic = 0.91) for DXA-defined obesity in women and men [27].

Recent studies have examined the U.S. prevalence trends in obesity using the BMI as diagnostic tool [3 28 29]. Although data on body fat percentage have also been reported for the U.S. adult population [28], no body fat cutoffs were used to diagnose general obesity, and the analyses were limited to adults 20-59 years only, and for the period 2011-2018. In fact, body composition has been inconsistently assessed across NHANES survey cycles and across age groups. In addition, no study has compared the trends of general obesity in the U.S. using the RFM, a surrogate for body fat percentage, and the BMI. Furthermore, no study has examined current obesity trends among U.S. adults over a period of nearly 22 years. The aim of this study was to compare the trends of general obesity by sex, ethnicity, and age group among adults in the U.S. from 1999 to 2020 using the RFM and the BMI.

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MATERIAL AND METHODS

Study design, data source, and participants

In this population-based study, we performed an analysis of cross-sectional individual-level data collected by the National Health and Nutrition Examination Survey (NHANES) through interviews and physical examination in a subset of a representative sample of the U.S. population from 1999-2000 through 2017-March 2020. Initial complete dataset included 107,622 participants of all ages. NHANES suspended data collection in March 2020 as a consequence of the COVID-19 pandemic. Thus, the most current cycle data available are "combined data collected from 2019 to March 2020 with data from the NHANES 2017-2018 cycle to form a nationally representative sample of NHANES 2017-March 2020 pre-pandemic data" [30]. Analysis was restricted to adults 20-79 years of age (n=54,232 potentially eligible) because of three reasons: 1) the diagnosis of obesity in younger adults is based on BMI-for-age percentiles as recommended by the Centers for Disease Control and Prevention (CDC) [7]; 2) in NHANES 2007-2008 and subsequent cycles, the upper age limit was 80 years, whereas in earlier cycles the age limit was 85 years; and 3) to obtain age-adjusted prevalence estimates using 5-year intervals according to the strata for age and sex available from the 2000 US Census Bureau (20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, and 75-79) [31]. Another criterion for inclusion was that individuals had been interviewed and evaluated by physical examination. Women who reported to be pregnant or had a positive urine pregnancy test were excluded from analysis. Observations with missing data on body weight, height, or waist circumference were also excluded.

According to the NHANES physical examination protocol, waist circumference was measured just above the uppermost lateral border of the right ilium (hip bone). Weight and height were measured using standard methods [32]. Information on ethnicity was collected through a questionnaire. The mean unweighted response rate for examined sample across survey cycles

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between 1999-2000 and 2017-March 2020 for individuals 20-79 years was 67.5% (range 50.8-74.5%) [33].

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) [34].

Obesity diagnosis

General obesity was diagnosed based on the RFM, a validated surrogate for whole-body fat percentage [23], and validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men [27]. RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women [23]. BMI-defined obesity was diagnosed if BMI was 30 kg/m^2 or higher [7].

Statistical Analysis

Data collected during the survey cycles from 1999-2000 through 2017-2020 were analyzed using sampling weights following the recommended analytic guidelines, to account for oversampling, nonresponse rates, and subsampling for physical examination [35]. The proportion of missing data was 5.2% of all eligible participants. Given this low percentage of missing data, we performed a complete case analysis [36]. Since age distribution of study samples may vary across survey cycles, all prevalence estimates were adjusted for age to make the estimates more comparable throughout the study period [31]. Estimates across the age categories 20-39, 40-59, and 60-79 years were also adjusted for age using 5-year intervals according to corresponding 2000 US Census Bureau age categories by sex [31]. The changes in obesity prevalence from 1999-2000 to 2017-March 2020 were assessed using the Wald test. For multiple comparisons of prevalence across ethnic groups and age groups, we applied the Bonferroni correction. Because Asian Americans were not oversampled before NHANES 2011,

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our analyses by ethnicity were restricted to Mexican, European, and African Americans. Prevalence trends were tested for the assumption of linearity using logistic regression models, comparing linear and non-linear regression models using the likelihood-ratio test [37]. For the non-linear models, restricted cubic splines with 3 knots were used at years 2001-2002, 2009-2010, and 2017-2020, based on the quantiles recommended by Harrel [38]. Survey cycles were analyzed as a continuous variable. For visualization purposes, trend lines were smoothed using the Lowes method [39]. Statistical significance was set to an alpha level of 0.05. All statistical analyses were performed using Stata 14 for Windows (StataCorp LP, College Station, TX). Prevalence estimates and standard errors were obtained using the survey 'svy' command with Taylor linearization.

Patient and public involvement

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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RESULTS

Clinical characteristics

After applying the inclusion and exclusion criteria, the final sample for analysis comprised 47,667 adults (Supplementary Figure 1). The median age of the study population was 45 years (interquartile range: 33 to 58); 50.6% were women; 67.2% were European Americans, 11.2% were African Americans, and 8.3% were Mexican Americans (Table 1).

Table 1. Characteristics of study participants.*

Characteristic	All 47,667	Women 23,931 (50.6%)	Men 23,736 (49.4%)
Median age (IQR), years	45 (33-58)	46 (33-59)	44 (32-57)
Ethnicity, n (%)			
Mexican American	8,416 (8.3)	4,204 (7.7)	4,212 (9.0)
European American	19,691 (67.2)	9,710 (67.0)	9,981 (67.5)
African American	10,673 (11.2)	5,417 (12.0)	5,256 (10.4)
Other/multi-racial	8,887 (13.3)	4,600 (13.4)	3,928 (13.1)
Body weight (SD), kg	82.6 (21.3)	76.3 (20.5)	89.0 (20.1)
Mean height (SD), cm	168.9 (10.0)	162.1 (6.9)	175.9 (7.5)
Mean waist circumference (SD), cm	98.5 (16.5)	95.9 (16.9)	101.2 (15.6)
Mean BMI (SD), kg/m² †	28.9 (6.8)	29.0 (7.5)	28.7 (5.9)
Mean RFM (SD), % ‡	34.9 (8.5)	41.2 (6.0)	28.4 (5.3)

* Sample size represents unweighted data. Estimates represent weighted data.
BMI, body mass index; IQR, interquartile range; RFM, relative fat mass; SD, standard deviation.
† BMI was calculated as the body weight in kilograms divided by the square of the height in meters.
‡ RFM was calculated as follows: 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women; height and waist circumference measured in the same units.

The characteristics of the population with missing data are shown in Supplementary Table 1.

Obesity prevalence and trends

Our findings indicate a higher proportion of individuals with obesity when RFM was used instead of BMI. The overall age-adjusted prevalence of RFM-defined obesity increased from 42.4% (95% confidence interval, 38.3% to 46.4%) in 1999-2000 to 55.4% (53.0% to 57.9%) in 2017-March 2020. The corresponding BMI-defined obesity prevalence increased from 30.4% (26.7% to 34.0%) to 42.1% (39.4% to 44.8%). We found a linear increase in the overall prevalence of

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obesity during the study period using either RFM (P<0.001; P=0.38 for non-linearity) or BMI (P<0.001; P=0.55 for non-linearity).

Obesity prevalence and trends by sex

We observed a consistently higher prevalence of RFM-defined obesity in women compared with men across years. In contrast, this difference was not consistent for BMI-defined obesity (Figure 1). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in women than in men (P<0.001). In contrast, the prevalence of BMI-defined obesity was similar in women and men (P=0.97). Among women, the prevalence of RFM-defined obesity increased from 50.8% (46.2% to 55.3%) in 1999-2000 to 64.7% (62.1% to 67.3%) in 2017-March 2020, a linear increase of 13.9 percentage points (9.0% to18.9%; P<0.001). For comparison, the prevalence of BMI-defined obesity in women was 42.2% (39.4% to45.0%) in 2017-March 2020, a linear increase of 8.3 percentage points (3.5-13.2%; P<0.001) (Table 2).

Table 2. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by sex: 1999-2000 through 2017-Mach 2020.*

	RFM-defined obesity	BMI-defined obesity
All participants	n=47,667	n=47,667
Prevalence, 95% CI		
1999-2000	42.4 (38.3-46.4)	30.4 (26.7-34)
2001-2002	42.5 (41.1-43.9)	30.0 (27.6-32.4)
2003-2004	46.9 (44.7-49.2)	32.1 (29.3-34.9)
2005-2006	47.1 (43.7-50.5)	34.3 (31.1-37.4)
2007-2008	47.7 (45.0-50.5)	33.7 (31.5-36.0)
2009-2010	48.5 (46.1-50.8)	35.7 (33.6-37.8)
2011-2012	49.8 (46.6-53.0)	35.4 (32.5-38.3)
2013-2014	51.3 (48.7-53.8)	37.8 (35.6-40)
2015-2016	53.7 (49.3-58.0)	40.0 (36.4-43.6)
2017-2020	55.4 (53.0-57.9)	42.1 (39.4-44.8)
Prevalence change†	13.0 (8.5-17.5)	11.8 (7.4-16.1)
P for non-linearity‡	0.38	0.55
P value for trend‡	<0.001	<0.001
Women	n=23,931	n=23,931
Prevalence, 95% CI		
1999-2000	50.8 (46.2-55.3)	33.9 (29.6-38.1)
2001-2002	51.6 (49.2-53.9)	32.9 (29.7-36.0)
2003-2004	55.3 (51.2-59.3)	33.5 (29.7-37.2)
2005-2006	53.9 (50.4-57.4)	34.8 (31.5-38.1)
2007-2008	56.4 (53.5-59.3)	35.4 (32.7-38.0)
2009-2010	58.1 (55.3-60.8)	36.0 (34.0-37.9)
2011-2012	60.8 (56.8-63.6)	36.9 (33.4-40.5)
2013-2014	61.3 (57.9-64.7)	40.0 (36.8-43.2)

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2015-2016	64.4 (60.2-68.6)	41.7 (38.1-45.3)
2017-2020	64.7 (62.1-67.3)	42.2 (39.4-45.0)
Prevalence change†	13.9 (9.0-18.9)	8.3 (3.5-13.2)
P for non-linearity§	0.10	0.39
P value for trend§	<0.001	<0.001
Men	n=23,736	n=23,736
Prevalence, 95% CI		
1999-2000	33.9 (29.9-37.8)	27.0 (23.5-30.4)
2001-2002	33.1 (30.6-35.5)	27.0 (24.8-29.2)
2003-2004	38.4 (35.9-40.8)	30.7 (27.6-33.9)
2005-2006	40.2 (35.9-44.4)	33.5 (29.3-37.8)
2007-2008	38.8 (35.6-42.0)	32.1 (29.3-34.8)
2009-2010	38.7 (35.2-42.2)	35.3 (31.4-39.2)
2011-2012	39.2 (35.9-42.5)	33.8 (30.7-36.9)
2013-2014	41.2 (38.7-43.7)	35.6 (33.2-38.1)
2015-2016	42.7 (37.7-47.7)	38.2 (33.3-43.2)
2017-2020	45.8 (42.0-49.7)	42.0 (37.8-46.3)
Prevalence change†	12.0 (6.6-17.3)	15.1 (9.8-20.4)
P for non-linearity§	0.82	0.84
P value for trend§	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.
† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for age, sex, and ethinicity.
§ Adjusted for age and ethnicity.

Among men, the prevalence of RFM-defined obesity increased from 33.9% (29.9% to 37.8%) in 1999-2000 to 45.8% (42.0% to 49.7%) in 2017-March 2020, a linear increase of 12.0 percentage points (6.6% to 17.3%; P<0.001). The prevalence of BMI-defined obesity in men was 42.0% (37.8% to 46.3%) in 2017-March 2020, a linear increase of 15.1 percentage points (9.8% to 20.4%).

Obesity prevalence and trends by ethnicity

The highest prevalence of RFM-defined obesity across years was observed among Mexican Americans. In contrast, the highest prevalence of BMI-defined obesity was observed among African American women but not men (Figure 2). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in Mexican Americans compared with African Americans (Bonferroni corrected P<0.001) or European Americans (P<0.001). BMI-defined obesity

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prevalence was similar in Mexican and African Americans (P=1.00) and both groups had a higher prevalence than European Americans (P=0.003 and P=0.001, respectively).

The largest increase in the prevalence of RFM-defined obesity from 1999-2000 to 2017-March 2020 occurred in Mexican American men, with a linear increase of 18.3 percentage points (12.0% to 24.5%; P<0.001) (Table 3 and Figure 2). The highest increase in the prevalence of BMI-defined obesity also occurred in Mexican American men, with a linear increase of 21.2 percentage points (15.3% to 27.1%; P<0.001) (Table 3 and Figure 2).

Table 3. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity				BMI-defined obesity		
	Mexican American	European American	African American		Mexican American	European American	African American
All participants	n=8,416	n=19,691	n=10,673		n=8,416	n=19,691	n=10,673
Prevalence, 95% CI							
1999-2000	53.1 (48.5-57.7)	39.4 (34.2-44.6)	48.3 (45.0-51.7)		34.7 (28.9-40.6)	28.3 (23.9-32.7)	39.8 (35.7-43.8)
2001-2002	52.1 (47.1-57.1)	41.0 (38.9-43.1)	46.0 (42.9-49.0)		30.7 (26.7-34.7)	29.8 (27.0-32.6)	38.3 (34.4-42.3)
2003-2004	60.1 (55.2-65.0)	44.8 (41.0-48.6)	52.7 (49.4-56.0)		36.9 (32.2-41.6)	30.6 (27.7-33.4)	45.1 (39.7-50.5)
2005-2006	55.4 (51.8-58.9)	44.9 (40.7-49.2)	51.5 (47.9-55.1)		33.8 (31.2-36.4)	33.1 (29.2-36.9)	45.9 (42.3-49.5)
2007-2008	62.2 (56.2-68.2)	45.7 (41.5-49.9)	52.5 (49.1-56.0)		39.9 (33.8-46.1)	32.4 (28.7-36.0)	43.7 (39.2-48.1)
2009-2010	61.5 (59.4-63.6)	46.4 (43.0-49.8)	56.8 (51.8-61.8)		40.5 (36.7-44.4)	34.2 (31.1-37.2)	49.4 (44.2-54.5)
2011-2012	63.6 (58.6-68.6)	46.8 (42.8-50.9)	57.4 (54.8-60.0)		46.1 (41.3-50.8)	33.0 (29.4-36.5)	48.4 (44.6-52.3)
2013-2014	65.0 (61.2-68.9)	49.4 (46.6-52.3)	55.0 (50.0-59.9)		46.1 (41.0-51.2)	36.6 (33.6-39.5)	47.9 (43.7-52.0)
2015-2016	70.3 (67.0-73.5)	51.2 (46.9-55.4)	56.6 (52.0-61.2)		48.7 (44.3-53.1)	38.5 (34.5-42.5)	48.7 (43.8-53.5)
2017-2020	68.8 (64.5-73.1)	54.1 (50.8-57.4)	57.1 (54.4-59.8)		50.2 (46.8-53.5)	41.7 (37.7-45.6)	49.9 (47.2-52.6)
Prevalence change†	15.7 (9.6-21.7)	14.7 (8.8-20.5)	8.7 (4.6-12.9)		15.4 (9.0-21.9)	13.4 (7.7-19)	10.2 (5.5-14.8)
P for non-linearity‡	0.58	0.97	0.25		0.52	0.10	0.35
P value for trend‡	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Women	n=4,204	n=9,710	n=5,417		n=4,204	n=9,710	n=5,417
Prevalence, 95% CI							
1999-2000	62.8 (55.1-70.5)	46.2 (40.2-52.1)	64.2 (59.6-68.8)		39.8 (31.1-48.5)	30.3 (25.2-35.3)	49.2 (42.5-56.0)
2001-2002	66.4 (58.6-74.3)	47.8 (44.2-51.4)	64.2 (59.0-69.4)		37.0 (30.2-43.8)	31.1 (27.6-34.7)	48.7 (42.8-54.7)

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2003-2004	75.0 (68.3-81.6)	50.6 (43.9-57.2)	70.7 (65.5-75.8)		42.7 (36.0-49.3)	30.3 (25.7-34.8)	53.9 (46.3-61.5)
2005-2006	72.0 (66.4-77.5)	49.9 (45.6-54.2)	66.2 (60.9-71.5)		41.3 (34.8-47.7)	32.8 (28.3-37.3)	52.7 (48.5-56.9)
2007-2008	74.8 (71.2-78.4)	52.3 (47.5-57.2)	67.9 (63.2-72.6)		44.7 (38.8-50.6)	32.8 (28.7-36.9)	49.2 (45.2-53.3)
2009-2010	77.8 (74.8-80.9)	53.4 (49.5-57.2)	74.6 (68.6-80.7)		45.7 (42.0-49.3)	32.1 (29.0-35.3)	58.5 (52.0-64.9)
2011-2012	74.6 (66.2-83.0)	56.3 (51.4-61.3)	74.9 (72.1-77.8)		49.0 (40.4-57.5)	33.3 (28.0-38.7)	57.9 (53.5-62.3)
2013-2014	81.2 (74.7-87.6)	57.3 (53.4-61.2)	72.5 (68.8-76.2)		51.7 (45.2-58.3)	37.6 (33.7-41.6)	56.7 (53.1-60.3)
2015-2016	84.6 (79.7-89.5)	60.0 (56.2-63.8)	72.3 (68.3-76.4)		52.2 (48.4-56.1)	38.5 (34.0-43.0)	57.1 (52.6-61.5)
2017-2020	76.9 (70.8-83.1)	62.3 (59.0-65.7)	72.4 (68.6-76.2)		49.6 (43.1-56.0)	40.3 (36.4-44.2)	57.3 (53.7-60.9)
Prevalence change†	14.1 (4.7-23.6)	16.2 (9.7-22.7)	8.3 (2.5-14.0)		9.8 (-0.6-20.1)	10.0 (3.9-16.1)	8.1 (0.8-15.4)
P for non-linearity§	0.026	0.77	0.34		0.76	0.12	0.71
P value for trend§		<0.001	<0.001		<0.001	<0.001	<0.001
Men	n=4,212	n=9,981	n=5,256		n=4,212	n=9,981	n=5,256
Prevalence, 95% CI							
1999-2000	42.9 (39.4-46.5)	33.2 (28.6-37.7)	27.5 (23.1-31.9)		29.1 (24.6-33.6)	26.8 (22.9-30.6)	26.8 (23.0-30.6)
2001-2002	40.6 (34.7-46.4)	34.1 (30.9-37.4)	25.8 (21.4-30.1)		25.9 (21.9-29.9)	28.3 (25.3-31.4)	26.5 (22.8-30.1)
2003-2004	47.1 (39.3-54.8)	38.9 (35.5-42.4)	31.2 (27.2-35.2)		31.7 (25.0-38.3)	30.9 (27.0-34.7)	34.2 (27.7-40.7)
2005-2006	40.8 (34.1-47.4)	40.0 (35.1-44.9)	34.1 (28.3-39.9)		27.4 (22.7-32.1)	33.3 (28.7-37.9)	37.2 (31.2-43.2)
2007-2008	50.9 (43.3-58.4)	38.8 (34.7-42.9)	33.8 (28.8-38.9)		35.1 (28.0-42.1)	32.0 (27.9-36.0)	36.9 (31.0-42.7)
2009-2010	47.8 (44.6-51.0)	39.4 (34.6-44.3)	35.4 (31.4-39.5)		36.3 (30.9-41.6)	36.1 (30.8-41.3)	38.6 (33.1-44.0)
2011-2012	52.5 (45.6-59.4)	37.6 (34.3-40.9)	36.4 (32.3-40.5)		42.7 (36.0-49.5)	32.5 (29.7-35.3)	37.5 (32.8-42.2)
2013-2014	52.4 (48.6-56.3)	41.7 (38.1-45.3)	35.2 (28.6-41.8)		43.6 (38.2-49.1)	35.6 (31.6-39.5)	37.9 (32.5-43.4)
2015-2016	55.9 (50.9-60.8)	42.3 (36.5-48.1)	38.1 (31.9-44.2)		45.3 (38.5-52.1)	38.4 (32.5-44.3)	38.9 (33.5-44.2)
2017-2020	61.2 (55.8-66.6)	45.8 (40.3-51.2)	39.1 (35.4-42.8)		50.3 (46.1-54.5)	43.1 (36.9-49.2)	41.2 (36.7-45.7)
Prevalence change†	18.3 (12.0-24.5)	12.6 (5.7-19.5)	11.6 (6.1-17.1)		21.2 (15.3-27.1)	16.3 (9.3-23.3)	14.4 (8.7-20.1)
P for non-linearity§	0.21	0.80	0.50		0.24	0.45	0.08
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.

† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).

‡ Adjusted for age and sex.

§ Adjusted for age.

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Obesity prevalence and trends by age group

In women and men, the highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) (Table 4 and Figure 3).

Table 4. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity			BMI-defined obesity		
	20-39 years old	40-59 years old	60-79 years old	20-39 years old	40-59 years old	60-79 years old
All participants	n=16,747	n=16,912	n=14,008	n=16,747	n=16,912	n=14,008
Prevalence, 95% CI						
1999-2000	29.0 (24.5-33.6)	46.9 (40.5-53.4)	61.8 (58.1-65.6)	25.4 (21.5-29.3)	33.2 (26.9-39.4)	35.4 (31.3-39.5)
2001-2002	30.2 (27.2-33.1)	45.0 (42.2-47.8)	63.8 (61.3-66.3)	25.3 (22.4-28.1)	33.2 (29.9-36.4)	33.7 (30.7-36.8)
2003-2004	34.2 (31.2-37.1)	51.2 (47.8-54.6)	65.8 (62.5-69.0)	28.1 (24.6-31.7)	35.9 (32.1-39.7)	33.0 (29.4-36.5)
2005-2006	32.6 (28.7-36.5)	53.2 (47.9-58.5)	66.0 (62.2-69.8)	28.5 (24.1-32.9)	40.1 (35.6-44.6)	34.9 (31.5-38.3)
2007-2008	35.5 (31.1-39.9)	51.6 (48.5-54.7)	66.1 (62.4-69.8)	30.2 (26.2-34.3)	35.7 (32.4-39.1)	37.4 (33.8-40.9)
2009-2010	37.2 (32.8-41.6)	50.5 (47.7-53.4)	68.5 (65.2-71.8)	32.5 (28.7-36.3)	36.0 (33.9-38.2)	41.8 (38.0-45.7)
2011-2012	37.7 (33.1-42.3)	53.6 (49.9-57.3)	68.0 (62.9-73.1)	30.4 (26.2-34.5)	39.3 (36.1-42.5)	38.3 (33.8-42.9)
2013-2014	40.0 (36.2-43.9)	54.5 (50.3-58.7)	68.8 (64.6-73.0)	34.4 (31.3-37.5)	40.6 (36.2-45.1)	39.3 (35.2-43.5)
2015-2016	43.0 (39.0-47.0)	57.1 (50.6-63.6)	69.8 (64.7-74.9)	36.0 (32.2-39.8)	42.8 (37.5-48.2)	42.8 (37.5-48.2)
2017-2020	44.6 (40.5-48.6)	59.4 (56.2-62.7)	70.6 (67.2-74.0)	39.8 (35.6-44.0)	44.3 (41.2-47.4)	42.7 (39.1-46.3)
Prevalence change†	15.5 (9.7-21.3)	12.5 (5.6-19.4)	8.8 (3.9-13.6)	14.5 (8.9-20.0)	11.2 (4.5-17.8)	7.3 (2.0-12.5)
P for non-linearity‡	0.65	0.94	0.25	0.48	0.21	0.46
P value for trend‡	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Women	n=8,295	n=8,684	n=6,952	n=8,295	n=8,684	n=6,952
Prevalence, 95% CI						
1999-2000	36.9 (30.9-42.9)	56.2 (48.9-63.5)	67.7 (63.3-72.2)	28.7 (23.6-33.7)	37.4 (30.2-44.5)	37.4 (31.6-43.2)
2001-2002	39.9 (35.3-44.5)	52.9 (48.1-57.6)	72.0 (69.3-74.7)	28.9 (24.1-33.6)	35.0 (30.2-39.8)	36.6 (32.0-41.2)
2003-2004	42.0 (35.8-48.2)	59.7 (54.9-64.5)	73.0 (68.3-77.7)	29.0 (23.8-34.1)	38.1 (32.3-43.9)	33.6 (28.5-38.7)
2005-2006	40.3 (35.3-45.4)	58.7 (53.5-63.8)	71.3 (66.4-76.2)	29.2 (24.1-34.3)	40.7 (35.9-45.6)	34.8 (28.4-41.2)

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2007-2008	46.1 (40.4-51.7)	60.0 (56.2-63.8)	69.8 (64.5-75.1)		33.0 (27.3-38.6)	37.6 (32.6-42.5)	36.0 (30.0-41.9)
2009-2010	46.4 (40.6-52.2)	59.3 (55.5-63.1)	78.5 (75.8-81.3)		31.8 (28.2-35.4)	35.5 (31.7-39.3)	45.1 (40.7-49.5)
2011-2012	47.6 (42.1-53.1)	64.6 (60.1-69.0)	76.7 (69.8-83.5)		31.9 (28.0-35.9)	39.4 (35.1-43.6)	42.1 (34.4-49.7)
2013-2014	50.8 (46.6-55.1)	63.3 (58.1-68.5)	78.0 (74.6-81.4)		36.6 (33.9-39.3)	43.6 (38.2-48.9)	40.2 (34.1-46.2)
2015-2016	53.3 (48.9-57.8)	69.1 (62.7-75.5)	77.1 (70.6-83.6)		37.1 (33.5-40.7)	44.8 (38.4-51.1)	45.0 (37.3-52.8)
2017-2020	53.3 (48.5-58.0)	67.9 (63.6-72.3)	81.0 (76.4-85.6)		39.9 (35.3-44.4)	42.8 (38.9-46.7)	45.4 (40.9-49.8)
Prevalence change†	16.4 (9.1-23.7)	11.7 (3.6-19.9)	13.3 (7.1-19.5)		11.2 (4.7-17.7)	5.5 (-2.3-13.2)	8.0 (1.0-15.0)
P for non-linearity§	0.16	0.39	0.99		0.44	0.42	0.97
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Men	n=8,452	n=8,228	n=7,056		n=8,452	n=8,228	n=7,056
Prevalence, 95% CI							
1999-2000	22.4 (18.0-26.8)	36.8 (30.4-43.2)	54.7 (49.9-59.5)		22.7 (18.3-27.0)	28.8 (22.8-34.8)	33.2 (28.2-38.1)
2001-2002	20.8 (17.4-24.1)	37.1 (33.5-40.7)	53.5 (49.8-57.1)		21.7 (18.5-24.9)	31.2 (28.0-34.5)	30.4 (26.0-34.8)
2003-2004	26.9 (23.3-30.4)	42.3 (36.7-47.9)	57.2 (52.5-62.0)		27.4 (22.5-32.3)	33.6 (28.4-38.9)	32.3 (27.4-37.2)
2005-2006	25.4 (20.1-30.7)	47.4 (40.5-54.2)	59.8 (54.8-64.7)		27.6 (22.0-33.1)	39.5 (33.1-45.9)	34.7 (29.9-39.5)
2007-2008	25.4 (21.2-29.5)	42.8 (37.8-47.8)	61.8 (57.7-65.9)		27.6 (23.8-31.4)	33.7 (28.8-38.5)	39.2 (34.8-43.5)
2009-2010	28.5 (23.6-33.3)	41.6 (37.7-45.5)	56.9 (51.1-62.7)		33.2 (27.2-39.2)	36.6 (33.0-40.2)	37.5 (32.3-42.8)
2011-2012	28.4 (23.9-33.0)	42.3 (38.0-46.6)	58.1 (52.1-64.2)		28.9 (23.5-34.2)	39.1 (35.6-42.5)	34.2 (29.2-39.2)
2013-2014	30.0 (25.5-34.5)	45.5 (40.3-50.7)	58.6 (51.6-65.5)		32.5 (28.1-36.8)	37.7 (32.2-43.3)	38.6 (30.7-46.4)
2015-2016	33.1 (28.3-38.0)	44.5 (36.5-52.6)	61.4 (55.4-67.5)		35.0 (29.0-41.0)	40.8 (34.6-47.1)	40.2 (34.9-45.5)
2017-2020	35.9 (30.2-41.5)	50.8 (46.2-55.4)	58.8 (54.3-63.3)		39.5 (33.1-46.0)	45.8 (41.1-50.6)	39.7 (34.0-45.4)
Prevalence change†	13.4 (6.5-20.4)	14.0 (6.4-21.6)	4.1 (-2.3-10.5)		16.8 (9.3-24.4)	17.0 (9.7-24.4)	6.5 (-0.7-13.8)
P for non-linearity§	0.47	0.42	0.16		0.97	0.41	0.24
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.

† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).

‡ Adjusted for sex and ethnicity.

§ Adjusted for ethnicity.

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In contrast, no differences were observed in the prevalence of obesity between individuals 60-79 years and 40-59 years when using BMI for the diagnosis of obesity (Figure 3). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in individuals 60-79 years compared with those 40-59 years (Bonferroni corrected P<0.001) or 20-39 years (P<0.001). We found no statistically significant differences in the prevalence of BMI-defined obesity across age groups (P>0.17 for all comparisons).

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DISCUSSION

Our study shows that, compared with BMI, the use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity among adults in the U.S., particularly among women, affecting nearly two-thirds of all women and nearly half of all men in 2017-2020, with an overall prevalence of 55.4%. This is an additional 22.5% of women and 3.8% of men 20-79 years being defined as obese compared with a BMI-based definition with the current criteria.

The use of RFM also revealed that the highest prevalence of general obesity over the study period from 1999 to 2020 occurred among Mexican Americans and not among African Americans, as was observed when BMI was used to diagnose obesity. Likewise, the use of RFM showed that the highest prevalence of general obesity over this study period occurred among older adults (60-79 years) and not among adults 40-59 years, as was observed when BMI was used.

Overall, women had a markedly higher prevalence of RFM-defined obesity across years than men, a difference that was less evident when using BMI. Previous studies have shown no differences in the prevalence of BMI-defined obesity between women and men [3 4 40]. In the present study, the difference in the prevalence of RFM-defined obesity for 2017-2020 between women and men was nearly 20 percentage points.

The highest prevalence of RFM-defined obesity was observed in Mexican Americans, and the increase was linear over the study period, albeit this linear increase was largely driven by a steady increase among men. Among Mexican American women, a decrease was observed since 2015. A previous study reported that, between 2003 and 2006, the prevalence of BMI-defined obesity was higher among African Americans compared with Mexican Americans, but between 2015 and 2018, Mexican American men had a higher prevalence than African American men [29]. In contrast, RFM revealed a consistently higher prevalence of general obesity

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among Mexican Americans over the observed time, in both women and men. Socio-economic characteristics are probably the main determinants of differences in the prevalence of general obesity between ethnic groups [41].

Further research is needed to better understand the clinical implications of our study findings: 1) the much higher prevalence of general obesity among women when RFM is used as opposed to BMI; 2) the higher burden of general obesity on Mexican Americans compared with African and European Americans; and 3) the higher prevalence of general obesity in older individuals. Since RFM is based on waist circumference, and waist circumference is a surrogate for intra-abdominal fat [42 43], RFM could be a surrogate for both general obesity and abdominal obesity. Although RFM has been shown to predict trunk fat percentage, the prediction error is greater for trunk fat percentage than for whole-body fat percentage [23].

The higher prevalence of RFM-defined obesity in older individuals found in our study is consistent with the higher body fat percentage observed in older individuals [12 23 44-48]. Whether the increased whole-body fat percentage in older individuals confers a higher risk on mortality requires further investigation. For instance, age *per se* is a strong risk factor for mortality, and the relationship between obesity and mortality could be mediated by age [49]. Conversely, the high body fat percentage in older individuals could explain the association of BMI-defined obesity with diabetes and cardiovascular disease in older individuals [50-53]. The increase in body adiposity with aging coincides with the high prevalence of many cardiometabolic alterations occurring more often in older individuals, such as glucose intolerance, insulin resistance, dyslipidemia, and hypertension [49]. BMI did not detect a higher prevalence of general obesity in individuals aged 60 years and older compared with younger adults, unlike when RFM was used. These findings further support that notion that BMI is a poor predictor of morbidity and mortality in older individuals [48 54].

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Our study has strengths. First, we used RFM, a previously validated surrogate for whole-body fat percentage in adults in the U.S. [23], which has a high diagnostic accuracy (91%) for DXA-defined obesity [27] and has been shown to result in lower total misclassification of DXA-defined high body adiposity compared with BMI among women (RFM: 12.7%; BMI: 56.5%) and men (RFM: 9.4% BMI: 13.0%) [23]. Second, to define general obesity, we used previously validated RFM cutoffs to predict all-cause mortality in a large U.S. adult population [27]. Previously proposed cutoffs for fat-defined obesity have been based on arbitrary values [55 56] or on corresponding BMI cutoffs [12]. Third, RFM requires only measured waist circumference and height, which allowed us to estimate the prevalence of general obesity in a large adult population of the U.S. (n=44,754) with a wide age range, over a period of nearly 22 years. Fourth, NHANES have used a consistent methodology across survey cycles to measure anthropometrics, reducing the risk of measurement error to influence our results.

Our study also has limitations. First, our analysis was performed using data from a representative sample of the non-institutionalized U.S. population only. Second, our estimates of prevalence trends could have been affected by some variability in sampling across NHANES survey cycles [35]. Third, we did not analyze the prevalence trends for Asian Americans during the period studied because NHANES began oversampling Asian Americans only from 2011-2012 onwards and the RFM cutoffs used to diagnose general obesity have not been validated among Asian populations.

From a public health perspective, we argue that due to the underdiagnosis of obesity when using BMI, the most affected populations are not receiving adequate medical care that they require. Aspects that will need further research are the implications of some possible overdiagnosis of obesity [57] and the stigma that would be associated with it [58].

In conclusion, the use of RFM, a surrogate for whole-body fat percentage, revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women,

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than that estimated by the BMI. RFM, but not BMI, also revealed a disproportionate higher prevalence of general obesity in adults aged 60 years and older and Mexican Americans. Using BMI as the lone measure to define obesity may lead to significant misclassification of large obese subpopulations as non-obese, particularly among women. Our findings may have implications for the use of resources in public health to tackle obesity-related health problems in the most affected populations.

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ETHICS APPROVAL

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) 35.

DATA AVAILABILITY STATEMENT

All data utilized for analysis in this study are fully available at: https://wwwn.cdc.gov/nchs/nhanes/

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AUTHOR CONTRIBUTIONS

OOW was responsible for the conception and design of the study. OOW contributed to the statistical analysis. OOW and TS contributed to the interpretation of data and critical revision of the manuscript. OOW and TS drafted the final version of the manuscript and agreed to the submitted version of the manuscript. OOW is the manuscript's guarantor. OOW accepts full responsibility for the work and the conduct of the study, had access to the data, and controlled the decision to submit for publication.

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COMPETING INTERESTS

The authors declare no conflict of interest.

TRANSPARENCY STATEMENT

OW (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned have been explained.

PATIENT AND PUBLIC INVOLVEMENT

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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FIGURE LEGENDS

Figure 1. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. Body fat-defined obesity was determined using the relative fat mass (RFM). RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 2. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 3. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

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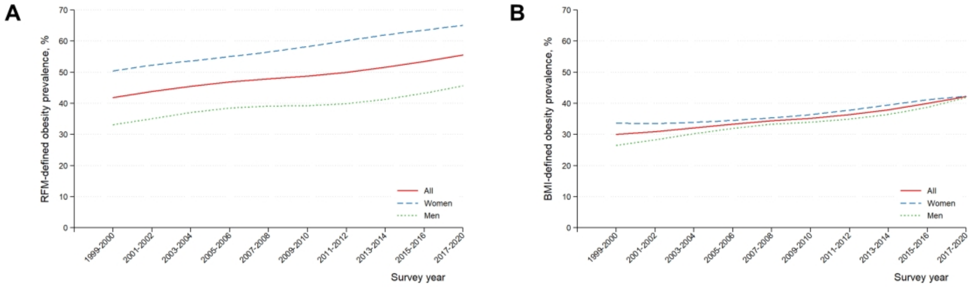

Figure 1. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020.

762x228mm (96 x 96 DPI)

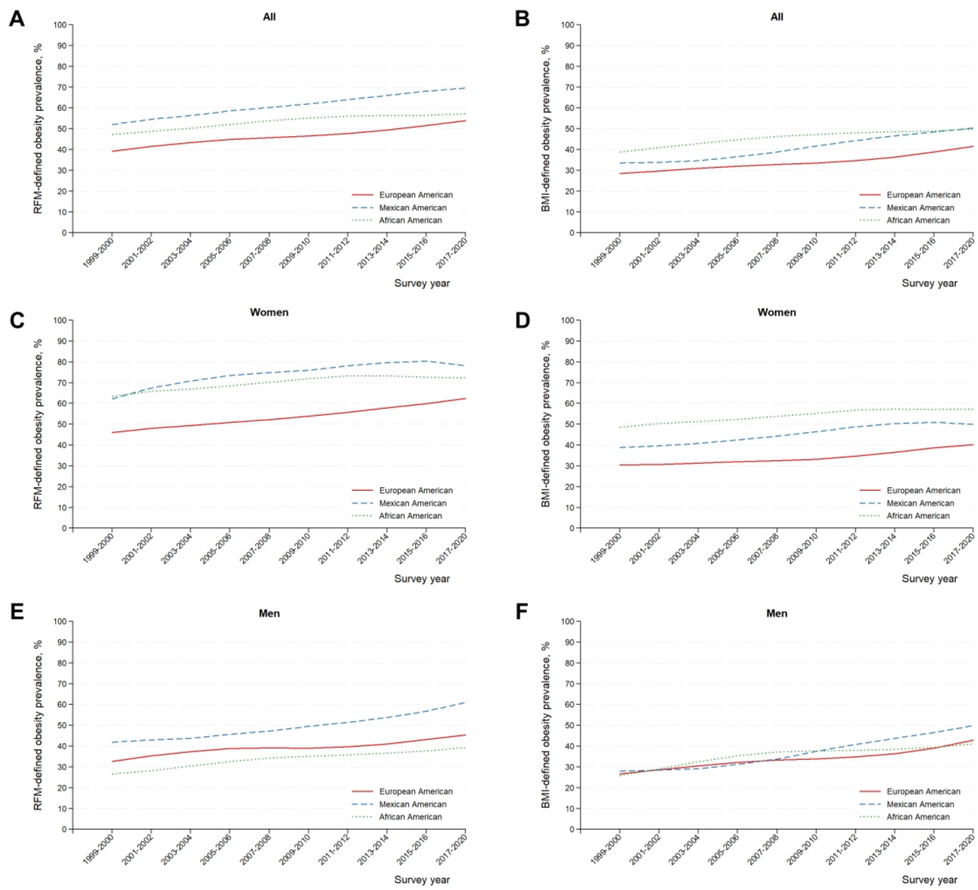

Figure 2. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.

762x711mm (96 x 96 DPI)

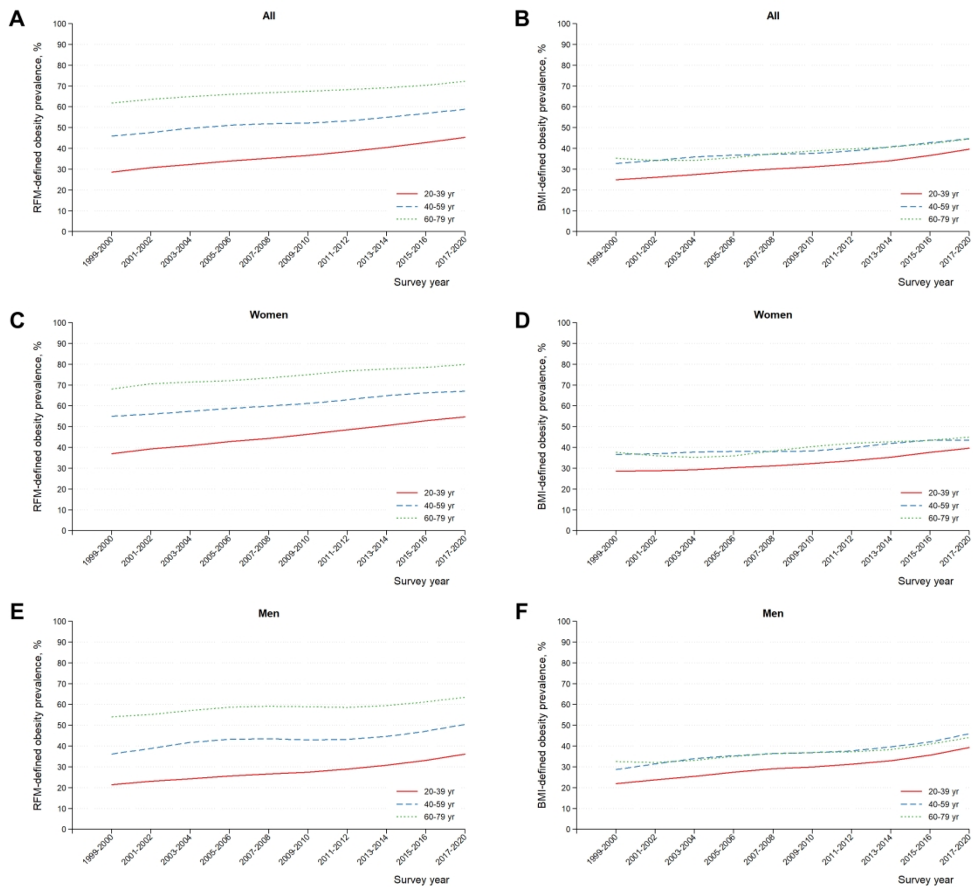

Figure 3. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.

762x711mm (96 x 96 DPI)

Supplementary Material

Trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

Orison O. Woolcott[1,2,*], Till Seuring[3]

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Supplementary Table 1. Characteristics of study participants with missing data.*

Characteristic	All	With complete data	With missing data
Sample size, n (%)	50,283 (100)	47,667 (95.6)	2,616 (4.4)
Median age (IQR), years	45 (33-58)	45 (33-58)	47 (34-63)
Male sex, n (%)	24,954 (49.2)	23,736 (49.4)	1,218 (45.4)
Ethnicity, n (%)			
Mexican American	8,827 (8.3)	8,416 (8.3)	411 (8.6)
European American	20,618 (66.9)	19,691(67.2)	927 (58.6)
African American	11,433 (11.4)	10,673(11.2)	760 (16.7)
Other/multi-racial	9,405 (13.4)	8,887 (13.2)	518 (16.1)

* Sample size represents unweighted data. Estimates represent weighted data.

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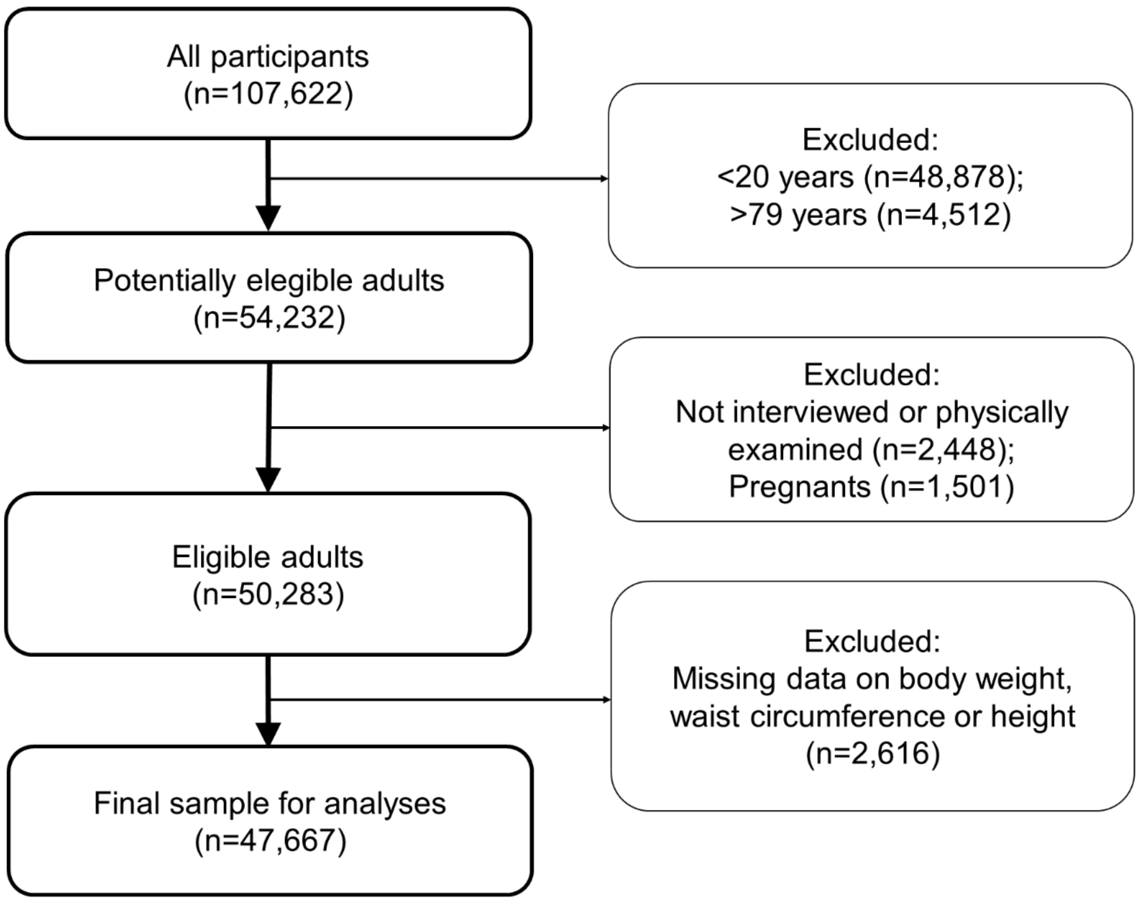
NHANES 1999-March 2020



Supplementary Figure 1

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
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	5-6
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	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	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	8-9
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8-9
		(*b*) Describe any methods used to examine subgroups and interactions	8-9
		(*c*) Explain how missing data were addressed	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	7,9
		(*e*) Describe any sensitivity analyses	NA

Continued on next page

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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	10
		(c) Consider use of a flow diagram	Suppl Fig 1
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10
		(b) Indicate number of participants with missing data for each variable of interest	Suppl Table 1
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	
		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	*10-17*
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	8, 10
		(*b*) Report category boundaries when continuous variables were categorized	15-16
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	12-17
Discussion			
Key results	18	Summarise key results with reference to study objectives	18
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	20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	20-21
Generalisability	21	Discuss the generalisability (external validity) of the study results	20
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	23

*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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BMJ Open

Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Secondary Subject Heading:	Diabetes and endocrinology, General practice / Family practice, Public health
Keywords:	EPIDEMIOLOGY, PUBLIC HEALTH, General endocrinology < DIABETES & ENDOCRINOLOGY, GENERAL MEDICINE (see Internal Medicine), Obesity

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Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Keywords: General Obesity, NHANES, Prevalence, Relative Fat Mass, RFM, Trends.

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ABSTRACT

Objectives: The body mass index (BMI) largely underestimates excess body fat, suggesting that the prevalence of obesity could be underestimated. Biologically, women are known to have higher body fat than men. This study aimed to compare the temporal trends in general obesity by sex, ethnicity, and age among adults in the United States using the relative fat mass (RFM), a validated surrogate for whole-body fat percentage, and BMI.

Design: Population-based study

Setting: U.S. National Health and Nutrition Examination Survey (NHANES), from 1999-2000 through 2017-March 2020.

Participants: A representative sample of adults 20-79 years in the U.S.

Main outcome measures: Age-adjusted prevalence of general obesity. RFM-defined obesity was diagnosed using validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men. BMI-defined obesity was diagnosed using a cutoff of 30 kg/m^2.

Results: Analysis included data from 47,667 adults. Among women, RFM-defined obesity prevalence was 64.7% (95% confidence interval, 62.1-67.3%) in 2017-2020, a linear increase of 13.9 percentage points (9.0-18.9%; P<0.001) relative to 1999-2000. In contrast, the prevalence of BMI-defined obesity was 42.2% (39.4-45.0%) in 2017-2020. Among men, the corresponding RFM-defined obesity prevalence was 45.8% (42.0-49.7%), a linear increase of 12.0 percentage points (6.6-17.3%; P<0.001). In contrast, the prevalence of BMI-defined obesity was 42.0 (37.8-46.3%). The highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) and Mexican Americans, in women and men. Conversely, the highest prevalence of BMI-defined obesity across years was observed in middle-age (40-59 years) and older adults, and in African American women.

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Conclusions: The use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women, than that estimated using BMI, and detected a disproportionate higher prevalence of general obesity in older adults and Mexican Americans.

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STRENGTHS AND LIMITATIONS OF THIS STUDY

- RFM is a validated surrogate for whole-body fat percentage that has a high diagnostic accuracy (91%) for DXA-defined obesity.
- The diagnosis of obesity was based on measured anthropometrics and validated RFM cutoffs associated with increased risk for all-cause mortality.
- RFM requires only waist circumference and height for its calculation.
- The proportion of obesity misclassification is not trivial when using RFM.
- Estimates of temporal trends in obesity was not possible for Asian Americans.

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INTRODUCTION

The prevalence of obesity (excess body fat) in the United States has doubled from 15.0% in 1976-1980 to 30.9% in 1999-2000 [1], and it continues to increase [2 3]. The age-adjusted prevalence of obesity among adults in the U.S. has been estimated at 41.9% in 2017-March 2020 [4]. Obesity diagnosis is based on the body mass index (BMI), an indirect measure of body fat [5 6]. BMI is calculated as the ratio of body weight in kilograms to the square of the height in meters [7]. BMI does not distinguish between fat mass and fat-free mass and does not account for differences in adiposity between women and men. Biologically, women are known to have higher body fat than men [8-12]. A meta-analysis of 25 international studies comprising nearly 32,000 adults concluded that BMI underestimates ~50% of all individuals with excess body fat percentage determined by reference techniques [11], suggesting that the prevalence of obesity could be largely underestimated among countries.

There is robust evidence linking high whole-body fat percentage with increased risk of death [13-20], supporting the need for a better assessment of body adiposity. Although the limitations of BMI to assess body adiposity are widely acknowledged [6 8-11 21 22], BMI remains the most widely used anthropometric index in clinical practice, epidemiology, and public health, given its simplicity, very low cost, and its association with several clinical conditions and mortality [6]. The high cost and time required to assess body adiposity using more accurate techniques such as dual-energy x-ray absorptiometry (DXA), dual-labeled water, or magnetic resonance, prevents their use in large populations or clinical practice as part of routine screening.

The relative fat mass (RFM) is a simple and low-cost anthropometric index developed to estimate whole-body fat percentage [23]. RFM is a linear equation based on the ratio of height to waist circumference that has been validated in Mexican, European, and African Americans [23], and in other populations [24-26]. Compared with BMI, RFM resulted in lower obesity misclassification when DXA was used as the reference method for diagnosing obesity in adults

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[24,27]. The accuracy of RFM in diagnosing high body fat percentage is superior to that of BMI among men and similar to BMI among women [23]. In an analysis of a representative sample of the U.S. adult population (NHANES 1999-2006), RFM had a diagnostic accuracy of 91% (C-statistic = 0.91) for DXA-defined obesity in women and men [27].

Recent studies have examined the U.S. prevalence trends in obesity using BMI as diagnostic tool [3,28,29]. Although data on body fat percentage have also been reported for the U.S. adult population [28], no body fat cutoffs were used to diagnose general obesity, and the analyses were limited to adults 20-59 years only, and for the period 2011-2018. In fact, body composition has been inconsistently assessed across NHANES survey cycles and across age groups. In addition, no study has compared the trends of general obesity in the U.S. using RFM, a surrogate for body fat percentage, and BMI. Furthermore, no study has examined current obesity trends among U.S. adults over a period of nearly 22 years. The aim of this study was to compare the temporal trends in general obesity by sex, ethnicity, and age group among adults in the U.S. from 1999 to 2020 using RFM and BMI.

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MATERIAL AND METHODS

Study design, data source, and participants

In this population-based study, we performed an analysis of cross-sectional individual-level data collected by the National Health and Nutrition Examination Survey (NHANES) through interviews and physical examination in a subset of a representative sample of the U.S. population from 1999-2000 through 2017-March 2020. Initial complete dataset included 107,622 participants of all ages. NHANES suspended data collection in March 2020 as a consequence of the COVID-19 pandemic. Thus, the most current cycle data available are "combined data collected from 2019 to March 2020 with data from the NHANES 2017-2018 cycle to form a nationally representative sample of NHANES 2017-March 2020 pre-pandemic data" [30]. Analysis was restricted to adults 20-79 years of age (n=54,232 potentially eligible) because of three reasons: 1) the diagnosis of obesity in younger adults is based on BMI-for-age percentiles as recommended by the Centers for Disease Control and Prevention (CDC) [7]; 2) in NHANES 2007-2008 and subsequent cycles, the upper age limit was 80 years, whereas in earlier cycles the age limit was 85 years; and 3) to obtain age-adjusted prevalence estimates using 5-year intervals according to the strata for age and sex available from the 2000 US Census Bureau (20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, and 75-79) [31]. Another criterion for inclusion was that individuals had been interviewed and evaluated by physical examination. Women who reported to be pregnant or had a positive urine pregnancy test were excluded from analysis. Observations with missing data on body weight, height, or waist circumference were also excluded.

According to the NHANES physical examination protocol, waist circumference was measured just above the uppermost lateral border of the right ilium (hip bone). Weight and height were measured using standard methods [32]. Information on ethnicity was collected through a questionnaire. The mean unweighted response rate for examined sample across survey cycles

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between 1999-2000 and 2017-March 2020 for individuals 20-79 years was 67.5% (range 50.8-74.5%) [33].

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) [34].

Obesity diagnosis

General obesity was diagnosed using RFM, a validated surrogate for whole-body fat percentage [23], and validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men [27]. RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women [23]. BMI-defined obesity was diagnosed if BMI was 30 kg/m^2 or higher [7].

Statistical Analysis

Data collected during the survey cycles from 1999-2000 through 2017-2020 were analyzed using sampling weights following the recommended analytic guidelines, to account for oversampling, nonresponse rates, and subsampling for physical examination [35]. The proportion of missing data was 5.2% of all eligible participants. Given this low percentage of missing data, we performed a complete case analysis [36]. Since age distribution of study samples may vary across survey cycles, all prevalence estimates were adjusted for age to make the estimates more comparable throughout the study period [31]. Estimates across the age categories 20-39, 40-59, and 60-79 years were also adjusted for age using 5-year intervals according to corresponding 2000 US Census Bureau age categories by sex [31]. The changes in obesity prevalence from 1999-2000 to 2017-March 2020 were assessed using the Wald test. For multiple comparisons of prevalence across ethnic groups and age groups, we applied the

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Bonferroni correction. Because Asian Americans were not oversampled before NHANES 2011, our analyses by ethnicity were restricted to Mexican, European, and African Americans.

To determine the possible role of menopause in the high prevalence of RFM-defined obesity in women, we performed a post hoc analysis. Data related to menopause were self-reported. We defined postmenopausal women as those with natural menopause and no missing information on age at menopause. For this analysis, women were excluded if menopause occurred before age 40 or after age 62 [37], or if they reported oophorectomy (surgical removal of one or two ovaries), treatment with estrogen/progesterone for hysterectomy/oophorectomy, breastfeeding, pregnancy in past year of the interview, or irregular period due to medical conditions or treatment.

Temporal trends in prevalence of obesity were tested for the assumption of linearity using logistic regression models, comparing linear and non-linear regression models using the likelihood-ratio test [38]. For the non-linear models, restricted cubic splines with 3 knots were used at years 2001-2002, 2009-2010, and 2017-2020, based on the quantiles recommended by Harrel [39]. Survey cycles were analyzed as a continuous variable. For visualization purposes, trend lines were smoothed using the Lowes method [40]. Statistical significance was set to an alpha level of 0.05. All statistical analyses were performed using Stata 14 for Windows (StataCorp LP, College Station, TX). Prevalence estimates and standard errors were obtained using the survey ‘svy’ command with Taylor linearization.

<u>Patient and public involvement</u>

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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RESULTS

Clinical characteristics

After applying the inclusion and exclusion criteria, the final sample for analysis comprised 47,667 adults (Supplementary Figure 1). The median age of the study population was 45 years (interquartile range: 33 to 58); 50.6% were women; 67.2% were European Americans, 11.2% were African Americans, and 8.3% were Mexican Americans (Table 1). The overall prevalence of obesity by ethnicity in the study participants is shown in Supplementary Table 1.

Table 1. Characteristics of study participants.*

Characteristic	All 47,667	Women 23,931 (50.6%)	Men 23,736 (49.4%)
Median age (IQR), years	45 (33-58)	46 (33-59)	44 (32-57)
Ethnicity, n (%)			
Mexican American	8,416 (8.3)	4,204 (7.7)	4,212 (9.0)
European American	19,691 (67.2)	9,710 (67.0)	9,981 (67.5)
African American	10,673 (11.2)	5,417 (12.0)	5,256 (10.4)
Other/multi-racial	8,887 (13.3)	4,600 (13.4)	3,928 (13.1)
Body weight (SD), kg	82.6 (21.3)	76.3 (20.5)	89.0 (20.1)
Mean height (SD), cm	168.9 (10.0)	162.1 (6.9)	175.9 (7.5)
Mean waist circumference (SD), cm	98.5 (16.5)	95.9 (16.9)	101.2 (15.6)
Mean BMI (SD), kg/m^2	28.9 (6.8)	29.0 (7.5)	28.7 (5.9)
Mean RFM (SD), %	34.9 (8.5)	41.2 (6.0)	28.4 (5.3)
RFM-defined obesity, % (95% CI) †	50.1 (48.9-50.8)	59.4 (58.4-60.5)	40.6 (39.4-41.8)
BMI-defined obesity, % (95% CI) ‡	36.2 (35.4-37.1)	37.8 (36.8-38.7)	34.6 (33.5-35.8)
Abdominal obesity, % (95% CI) §	54.0 (53.0-55.0)	63.8 (62.8-64.9)	43.9 (42.7-45.1)

* Sample size represents unweighted data. Estimates represent weighted data.
BMI, body mass index; CI, confidence interval; IQR, interquartile range; RFM, relative fat mass; SD, standard deviation.
† Defined as an RFM ≥40% for women and ≥30% for men. RFM was calculated as follows: 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women; height and waist circumference measured in the same units. Estimates are not adjusted for age.
‡ Defined as a BMI ≥30 kg/m2. BMI was calculated as the body weight in kilograms divided by the square of the height in meters. Estimates are not adjusted for age.
§ Defined as a waist circumference >88 cm for women and >102 cm for men, according to the recommendations of the National Cholesterol Education Program (NCEP) Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). Estimates are not adjusted for age.

The characteristics of the population with missing data are shown in Supplementary Table 2.

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Obesity prevalence and temporal trends

Our findings indicate a higher proportion of individuals with obesity when RFM was used instead of BMI. The overall age-adjusted prevalence of RFM-defined obesity increased from 42.4% (95% confidence interval, 38.3% to 46.4%) in 1999-2000 to 55.4% (53.0% to 57.9%) in 2017-March 2020. The corresponding BMI-defined obesity prevalence increased from 30.4% (26.7% to 34.0%) to 42.1% (39.4% to 44.8%). We found a linear increase in the overall prevalence of obesity during the study period using either RFM (P<0.001; P=0.38 for non-linearity) or BMI (P<0.001; P=0.55 for non-linearity).

Obesity prevalence and temporal trends by sex

We observed a consistently higher prevalence of RFM-defined obesity in women compared with men across years. In contrast, this difference was not consistent for BMI-defined obesity (Figure 1). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in women than in men (P<0.001). In contrast, the prevalence of BMI-defined obesity was similar in women and men (P=0.97). Among women, the prevalence of RFM-defined obesity increased from 50.8% (46.2% to 55.3%) in 1999-2000 to 64.7% (62.1% to 67.3%) in 2017-March 2020, a linear increase of 13.9 percentage points (9.0% to18.9%; P<0.001). For comparison, the prevalence of BMI-defined obesity in women was 42.2% (39.4% to 45.0%) in 2017-March 2020, a linear increase of 8.3 percentage points (3.5-13.2%; P<0.001) (Table 2).

Table 2. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by sex: 1999-2000 through 2017-Mach 2020.*

	RFM-defined obesity	BMI-defined obesity
All participants (n=47,667)		
Prevalence, % (95% CI)		
1999-2000	42.4 (38.3-46.4)	30.4 (26.7-34)

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2001-2002	42.5 (41.1-43.9)	30.0 (27.6-32.4)
2003-2004	46.9 (44.7-49.2)	32.1 (29.3-34.9)
2005-2006	47.1 (43.7-50.5)	34.3 (31.1-37.4)
2007-2008	47.7 (45.0-50.5)	33.7 (31.5-36.0)
2009-2010	48.5 (46.1-50.8)	35.7 (33.6-37.8)
2011-2012	49.8 (46.6-53.0)	35.4 (32.5-38.3)
2013-2014	51.3 (48.7-53.8)	37.8 (35.6-40)
2015-2016	53.7 (49.3-58.0)	40.0 (36.4-43.6)
2017-2020	55.4 (53.0-57.9)	42.1 (39.4-44.8)
Prevalence change†	13.0 (8.5-17.5)	11.8 (7.4-16.1)
P for non-linearity‡	0.38	0.55
P value for trend‡	<0.001	<0.001
Women (n=23,931)		
Prevalence, % (95% CI)		
1999-2000	50.8 (46.2-55.3)	33.9 (29.6-38.1)
2001-2002	51.6 (49.2-53.9)	32.9 (29.7-36.0)
2003-2004	55.3 (51.2-59.3)	33.5 (29.7-37.2)
2005-2006	53.9 (50.4-57.4)	34.8 (31.5-38.1)
2007-2008	56.4 (53.5-59.3)	35.4 (32.7-38.0)
2009-2010	58.1 (55.3-60.8)	36.0 (34.0-37.9)
2011-2012	60.8 (56.8-63.6)	36.9 (33.4-40.5)
2013-2014	61.3 (57.9-64.7)	40.0 (36.8-43.2)
2015-2016	64.4 (60.2-68.6)	41.7 (38.1-45.3)
2017-2020	64.7 (62.1-67.3)	42.2 (39.4-45.0)
Prevalence change†	13.9 (9.0-18.9)	8.3 (3.5-13.2)
P for non-linearity§	0.10	0.39
P value for trend§	<0.001	<0.001
Men (n=23,736)		
Prevalence, % (95% CI)		
1999-2000	33.9 (29.9-37.8)	27.0 (23.5-30.4)
2001-2002	33.1 (30.6-35.5)	27.0 (24.8-29.2)
2003-2004	38.4 (35.9-40.8)	30.7 (27.6-33.9)
2005-2006	40.2 (35.9-44.4)	33.5 (29.3-37.8)
2007-2008	38.8 (35.6-42.0)	32.1 (29.3-34.8)
2009-2010	38.7 (35.2-42.2)	35.3 (31.4-39.2)
2011-2012	39.2 (35.9-42.5)	33.8 (30.7-36.9)
2013-2014	41.2 (38.7-43.7)	35.6 (33.2-38.1)
2015-2016	42.7 (37.7-47.7)	38.2 (33.3-43.2)
2017-2020	45.8 (42.0-49.7)	42.0 (37.8-46.3)
Prevalence change†	12.0 (6.6-17.3)	15.1 (9.8-20.4)
P for non-linearity§	0.82	0.84
P value for trend§	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.
† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for age, sex, and ethnicity.
§ Adjusted for age and ethnicity.

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Among men, the prevalence of RFM-defined obesity increased from 33.9% (29.9% to 37.8%) in 1999-2000 to 45.8% (42.0% to 49.7%) in 2017-March 2020, a linear increase of 12.0 percentage points (6.6% to 17.3%; P<0.001). The prevalence of BMI-defined obesity in men was 42.0% (37.8% to 46.3%) in 2017-March 2020, a linear increase of 15.1 percentage points (9.8% to 20.4%).

Obesity prevalence and temporal trends by ethnicity

The highest prevalence of RFM-defined obesity across years was observed among Mexican Americans. In contrast, the highest prevalence of BMI-defined obesity was observed among African American women but not men (Figure 2). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in Mexican Americans compared with African Americans (Bonferroni corrected P<0.001) or European Americans (P<0.001). BMI-defined obesity prevalence was similar in Mexican and African Americans (P=0.99) and both groups had a higher prevalence than European Americans (P=0.003 and P=0.001, respectively).

The largest increase in the prevalence of RFM-defined obesity from 1999-2000 to 2017-March 2020 occurred in Mexican American men, with a linear increase of 18.3 percentage points (12.0% to 24.5%; P<0.001) (Supplementary Table 3 and Figure 2). The highest increase in the prevalence of BMI-defined obesity also occurred in Mexican American men, with a linear increase of 21.2 percentage points (15.3% to 27.1%; P<0.001) (Supplementary Table 3 and Figure 2).

Obesity prevalence and temporal trends by age group

In women and men, the highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) (Figure 3 and Supplementary Table 4).

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In contrast, no differences were observed in the prevalence of obesity between individuals 60-79 years and 40-59 years when using BMI for the diagnosis of obesity (Figure 3). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in individuals 60-79 years compared with those 40-59 years (Bonferroni corrected $P<0.001$) or 20-39 years ($P<0.001$). We found no statistically significant differences in the prevalence of BMI-defined obesity across age groups ($P>0.17$ for all comparisons).

Although our analysis by age showed an increased prevalence of obesity in older women and men (Figure 3), we performed a sensitivity analysis to specifically explore the possible role of menopause. Our findings from this post hoc analysis revealed that the crude prevalence of RFM-defined obesity in 2017-2020 was 56.4% (95% CI, 53.5-59.3%) among premenopausal women (n=1,935) and 76.4% (71.0-81.8%) among postmenopausal women (n=1,406). The mean age at last menstrual period was 49 years in this population. For comparison, among men, the corresponding prevalence of obesity was 39.7% (34.9-44.6%) in those younger than 50 years (n=1,790) and 56.2% (52.9-59.5%) in men 50 years of age and older (n=1,886).

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DISCUSSION

Our study shows that, compared with BMI, the use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity among adults in the U.S., particularly among women, affecting nearly two-thirds of all women and nearly half of all men in 2017-2020, with an overall prevalence of 55.4%. This is an additional 22.5% of women and 3.8% of men 20-79 years being defined as obese compared with a BMI-based definition with the current criteria.

The use of RFM also revealed that the highest prevalence of general obesity over the study period from 1999 to 2020 occurred among Mexican Americans and not among African Americans, as was observed when BMI was used to diagnose obesity. Likewise, the use of RFM showed that the highest prevalence of general obesity over this study period occurred among older adults (60-79 years) and not among adults 40-59 years, as was observed when BMI was used. The higher prevalence of obesity in older individuals does not appear to be fully explained by a loss of skeletal muscle with age, since absolute fat mass also increases with age, although mainly visceral fat [41 42]. However, it is difficult to draw a firm conclusion from cross-sectional data. Our findings are consistent with those from other studies also showing a higher body fat percentage in older individuals [12 23 41 43-46].

Overall, women had a markedly higher prevalence of RFM-defined obesity across years than men, a difference that was less evident when using BMI. Previous studies have shown no differences in the prevalence of BMI-defined obesity between women and men [3 4 47]. In the present study, the difference in the prevalence of RFM-defined obesity for 2017-2020 between women and men was nearly 20 percentage points.

The highest prevalence of RFM-defined obesity was observed in Mexican Americans, and the increase was linear over the study period, albeit this linear increase was largely driven by a steady increase among men. Among Mexican American women, a decrease was observed

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since 2015. A previous study reported that, between 2003 and 2006, the prevalence of BMI-defined obesity was higher among African Americans compared with Mexican Americans, but between 2015 and 2018, Mexican American men had a higher prevalence than African American men [29]. In contrast, RFM revealed a consistently higher prevalence of general obesity among Mexican Americans over the observed time, in both women and men. Socio-economic characteristics are probably the main determinants of differences in the prevalence of general obesity between ethnic groups [48].

It has been argued that the fat mass index (FMI, body fat mass adjusted for the square of the height, expressed in kg/m^2) should be used as a reference of fat mass instead of body fat percentage (body fat mass adjusted for body weight) to avoid including fat mass both in the numerator and the denominator, as this is not mathematically advisable [49]. However, the concept of obesity (excess body fat) and all different forms to express it, for example BMI [6 50 51], FMI [52 53], fat mass/fat-free-mass [54 55], body fat percentage [12 56], to cite a few, should not be seen only as mathematical constructs but also as biological variables with important implications as risk factors for disease and mortality. In the present study, we chose body fat percentage as the reference because numerous studies have shown that body fat percentage is associated with mortality [13-20 57]. What is also important to note is that FMI does not appear to be superior to body fat percentage or BMI as a predictor of cardiovascular mortality [14], all-cause mortality [58 59] or cardiovascular risk factors [60]. Because of its association with mortality, body fat percentage is of great clinical relevance. Recent studies support the utility of RFM to predict type 2 diabetes [61] and heart failure [62].

Further research is needed to better understand the clinical implications of our study findings: 1) the much higher prevalence of general obesity among women when RFM is used as opposed to BMI; 2) the higher burden of general obesity on Mexican Americans compared with African and European Americans; and 3) the higher prevalence of general obesity in older individuals.

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It is difficult to establish whether the higher prevalence of general obesity estimated using RFM would translate into a higher risk of cardiovascular disease (CVD). The association between obesity and CVD is very complex and several factors may mediate this association [63]. Although subcutaneous fat appears to have a relative protective effect against CVD [64], others have shown that subcutaneous fat is also associated with cardiovascular risk factors, although less strongly than visceral fat [65]. A major limitation of these studies, however, is that the analyses involved a small region of the abdominal trunk.

In women, who biologically have a higher body adiposity than men, the possible protective effect of estrogens on metabolism could be attenuated by the high prevalence of RFM-defined obesity. This could help explain for example the very similar relative increase in the U.S. prevalence of diabetes in women and men from 1999 to 2019 (by ~74%) (www.healthdata.org) or the similar prevalence of diabetes in women (14.1% [11.8-16.7%]) and men (15.4% [13.5-17.5%]) in 2017-2020 [66]. Our findings, although cross-sectional, do not appear to support a protective role of estrogens against obesity *per se*.

The temporal trends in RFM- and BMI-defined obesity in both women and men follow a parallel pattern. However, stratified analysis by ethnicity showed some differences. RFM revealed that Mexican Americans have a higher prevalence of obesity than European or African Americans. Although we cannot establish causality, this finding coincides with the higher absolute increase in the prevalence of diabetes and liver disease observed in Mexican Americans from 1999 to 2018 compared with European and African Americans [67].

Whether the increased whole-body fat percentage in older individuals confers a higher risk on mortality also requires further investigation as age *per se* is a strong risk factor for mortality [68], and the relationship between obesity and mortality could be mediated by age [69]. In addition, this can be confounded by concomitant severe disease. For instance, several studies have shown an inverse association between body fat percentage (but also BMI and FMI) and mortality in

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older patients [59 70 71]. Conversely, the high body fat percentage in older individuals could explain the association of BMI-defined obesity with diabetes and cardiovascular disease in older individuals [72-75]. The increase in body adiposity with aging coincides with the high prevalence of many cardiometabolic alterations occurring more often in older individuals, such as glucose intolerance, insulin resistance, dyslipidemia, and hypertension [69]. BMI did not detect a higher prevalence of general obesity in individuals aged 60 years and older compared with younger adults, unlike when RFM was used. These findings further support that notion that BMI is a poor predictor of morbidity and mortality in older individuals [46 76].

Abdominal obesity and general obesity are overall underestimated when using BMI (Table 1 and Supplementary Table 1). It is also important to mention that the prevalence of abdominal obesity is overall higher compared with the prevalence of RFM-defined obesity, except among Mexican Americans (Supplementary Table 1). However, the closer proportions of abdominal obesity and RFM-defined general obesity is expected. Since RFM is based on waist circumference, and waist circumference is a surrogate for intra-abdominal fat [77 78], RFM could be a surrogate for both general obesity and abdominal obesity. Although RFM has been shown to predict trunk fat percentage, the prediction error is greater for trunk fat percentage than for whole-body fat percentage [23].

Our study has strengths. First, we used a previously validated surrogate for whole-body fat percentage in adults in the U.S. [23], which has a high diagnostic accuracy (91%) for DXA-defined obesity [27] and has been shown to result in lower total misclassification of DXA-defined high body adiposity compared with BMI among women (RFM: 12.7%; BMI: 56.5%) and men (RFM: 9.4% BMI: 13.0%) [23]. Second, to define general obesity, we used previously validated RFM cutoffs to predict all-cause mortality in a large U.S. adult population [27]. Previously proposed cutoffs for fat-defined obesity have been based on arbitrary values [79 80] or on corresponding BMI cutoffs [12]. Third, we used measured anthropometrics. RFM requires only waist circumference

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and height for its calculation, which allowed us to estimate the prevalence of general obesity in a large adult population of the U.S. (n=44,754) with a wide age range, over a period of nearly 22 years. Fourth, NHANES have used a consistent methodology across survey cycles to measure anthropometrics, reducing the risk of measurement error that could affect our results.

Our study also has limitations. First, RFM was developed and validated using DXA as the reference method. However, DXA is an indirect method to assess body fatness and is susceptible to bias introduced mainly by age, degree of fatness, and disease [81 82]. Thus, there are limitations to the level of accuracy and precision that RFM can perform. Nevertheless, RFM is an attempt to provide a relatively easy and affordable alternative method to BMI to better assess body fatness. Second, although the overall obesity misclassification has been reported to be lower with RFM than with BMI in American (21) and Korean individuals (20), another limitation is that the proportion of obesity misclassification is not trivial when using RFM. Third, our analysis was performed using data from a representative sample of the non-institutionalized U.S. population only. Fourth, our estimates of prevalence trends could have been affected by some variability in sampling across NHANES survey cycles [35]. Finally, we did not analyze the prevalence trends for Asian Americans during the period studied because NHANES began oversampling Asian Americans only from 2011-2012 onwards and RFM cutoffs used to diagnose general obesity have not been validated among Asian populations.

From a public health perspective, we argue that due to the underdiagnosis of obesity when using BMI, the most affected populations are not receiving adequate medical care that they require. Aspects that will need further research are the implications of some possible overdiagnosis of obesity [83] and the stigma that would be associated with it [84].

In conclusion, the use of RFM, a surrogate for whole-body fat percentage, revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women, than that estimated by BMI. RFM, but not BMI, also revealed a disproportionate higher

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prevalence of general obesity in adults aged 60 years and older and Mexican Americans. Using BMI as the lone measure to define obesity may lead to significant misclassification of large obese subpopulations as non-obese, particularly among women. Our findings may have implications for the use of resources in public health to tackle obesity-related health problems in the most affected populations.

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ETHICS APPROVAL

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) 35.

DATA AVAILABILITY STATEMENT

All data utilized are publicly and freely available from the NHANES website at https://wwwn.cdc.gov/nchs/nhanes/

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AUTHOR CONTRIBUTIONS

OOW was responsible for the conception and design of the study. OOW contributed to the statistical analysis. OOW and TS contributed to the interpretation of data and critical revision of the manuscript. OOW and TS drafted the final version of the manuscript and agreed to the submitted version of the manuscript. OOW is the manuscript's guarantor. OOW accepts full responsibility for the work and the conduct of the study, had access to the data, and controlled the decision to submit for publication.

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COMPETING INTERESTS

OOW is the lead author of the original article describing the development and validation of RFM. OOW currently works as an editor for The Lancet group. TS declares no conflict of interest.

TRANSPARENCY STATEMENT

OW (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned have been explained.

PATIENT AND PUBLIC INVOLVEMENT

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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FIGURE LEGENDS

Figure 1. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. Body fat-defined obesity was determined using the relative fat mass (RFM). RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 2. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 3. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

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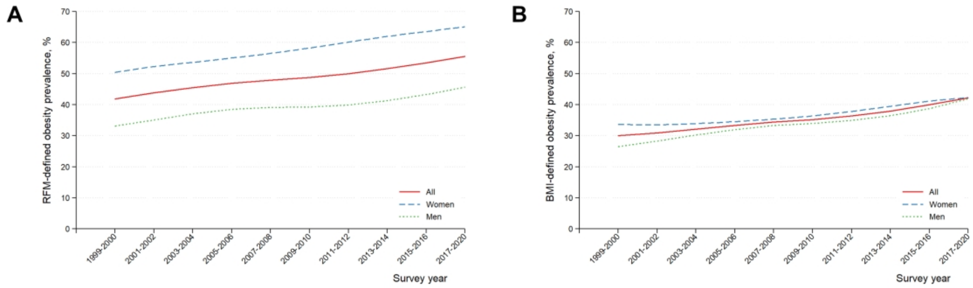

Figure 1. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020.

762x228mm (96 x 96 DPI)

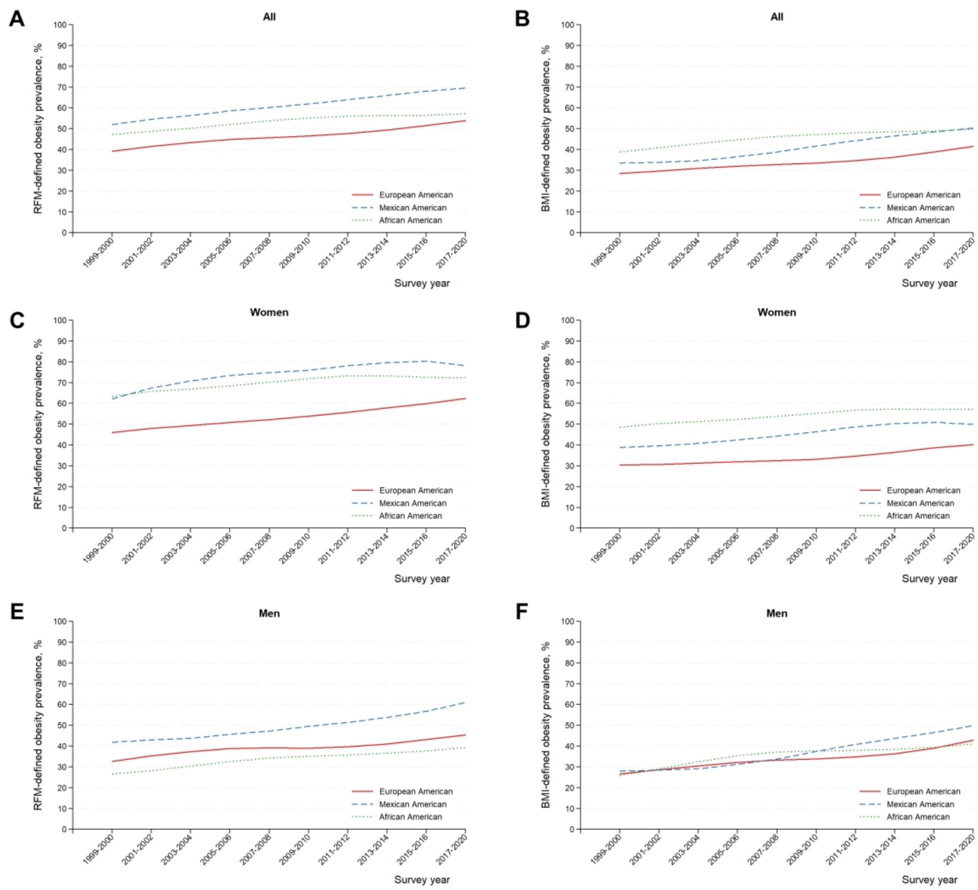

Figure 2. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.

762x711mm (96 x 96 DPI)

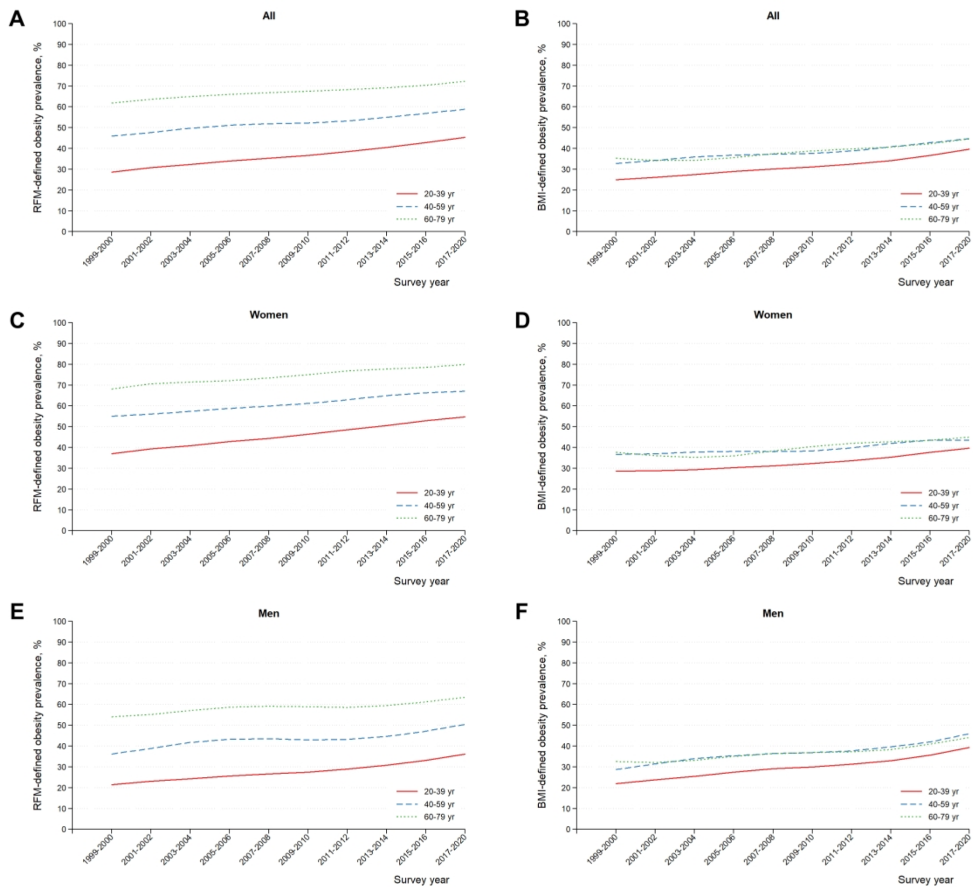

Figure 3. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.

762x711mm (96 x 96 DPI)

Supplementary Material

Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Supplementary Table 1. Prevalence of general and abdominal obesity among study participants by sex and ethnicity.*

	Mexican American	European American	African American
Women	n=4,204	n=9,710	n=5,417
RFM-defined obesity, % (95% CI) †	72.7 (70.3-75.1)	56.6 (55.2-58.0)	69.9 (68.3-71.4)
BMI-defined obesity, % (95% CI) ‡	45.5 (43.2-47.9)	35.4 (34.0-36.7)	54.5 (52.9-56.1)
Abdominal obesity, % (95% CI) §	71.5 (69.2-73.8)	62.8 (61.4-64.1)	75.0 (73.6-76.3)
Men	n=4,212	n=9,981	n=5,256
RFM-defined obesity, % (95% CI) †	47.0 (44.9-49.1)	41.7 (40.3-43.2)	33.7 (32.1-35.3)
BMI-defined obesity, % (95% CI) ‡	38.4 (36.3-40.4)	35.0 (33.6-36.5)	35.9 (34.2-37.6)
Abdominal obesity, % (95% CI) §	41.2 (39.1-43.2)	47.6 (46.2-49.1)	37.5 (35.9-39.0)

* Sample size represents unweighted data. Estimates represent weighted data.
BMI, body mass index; CI, confidence interval IQR, interquartile range; RFM, relative fat mass; SD, standard deviation.
† Defined as an RFM ≥40% for women and ≥30% for men. Estimates are not adjusted for age.
‡ Defined as a BMI ≥30 kg/m^2. Estimates are not adjusted for age.
§ Defined as a waist circumference >88 cm for women and >102 cm for men, according to the recommendations of the National Cholesterol Education Program (NCEP) Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). Estimates are not adjusted for age.

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Supplementary Table 2. Characteristics of study participants with missing data.*

Characteristic	All†	With complete data	With missing data
Sample size, n (%)	50,283 (100)	47,667 (95.6)	2,616 (4.4)
Median age (IQR), years	45 (33-58)	45 (33-58)	47 (34-63)
Male sex, n (%)	24,954 (49.2)	23,736 (49.4)	1,218 (45.4)
Ethnicity, n (%)			
Mexican American	8,827 (8.3)	8,416 (8.3)	411 (8.6)
European American	20,618 (66.9)	19,691(67.2)	927 (58.6)
African American	11,433 (11.4)	10,673(11.2)	760 (16.7)
Other/multi-racial	9,405 (13.4)	8,887 (13.2)	518 (16.1)

* Sample size represents unweighted data. Estimates represent weighted data.
† This group includes participants with complete data and participants with missing data on body weight (n=666), height (n=596), or waist circumference (n=2,340).

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Supplementary Table 3. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity				BMI-defined obesity		
	Mexican American	European American	African American		Mexican American	European American	African American
All participants	n=8,416	n=19,691	n=10,673		n=8,416	n=19,691	n=10,673
Prevalence, % (95% CI)							
1999-2000	53.1 (48.5-57.7)	39.4 (34.2-44.6)	48.3 (45.0-51.7)		34.7 (28.9-40.6)	28.3 (23.9-32.7)	39.8 (35.7-43.8)
2001-2002	52.1 (47.1-57.1)	41.0 (38.9-43.1)	46.0 (42.9-49.0)		30.7 (26.7-34.7)	29.8 (27.0-32.6)	38.3 (34.4-42.3)
2003-2004	60.1 (55.2-65.0)	44.8 (41.0-48.6)	52.7 (49.4-56.0)		36.9 (32.2-41.6)	30.6 (27.7-33.4)	45.1 (39.7-50.5)
2005-2006	55.4 (51.8-58.9)	44.9 (40.7-49.2)	51.5 (47.9-55.1)		33.8 (31.2-36.4)	33.1 (29.2-36.9)	45.9 (42.3-49.5)
2007-2008	62.2 (56.2-68.2)	45.7 (41.5-49.9)	52.5 (49.1-56.0)		39.9 (33.8-46.1)	32.4 (28.7-36.0)	43.7 (39.2-48.1)
2009-2010	61.5 (59.4-63.6)	46.4 (43.0-49.8)	56.8 (51.8-61.8)		40.5 (36.7-44.4)	34.2 (31.1-37.2)	49.4 (44.2-54.5)
2011-2012	63.6 (58.6-68.6)	46.8 (42.8-50.9)	57.4 (54.8-60.0)		46.1 (41.3-50.8)	33.0 (29.4-36.5)	48.4 (44.6-52.3)
2013-2014	65.0 (61.2-68.9)	49.4 (46.6-52.3)	55.0 (50.0-59.9)		46.1 (41.0-51.2)	36.6 (33.6-39.5)	47.9 (43.7-52.0)
2015-2016	70.3 (67.0-73.5)	51.2 (46.9-55.4)	56.6 (52.0-61.2)		48.7 (44.3-53.1)	38.5 (34.5-42.5)	48.7 (43.8-53.5)
2017-2020	68.8 (64.5-73.1)	54.1 (50.8-57.4)	57.1 (54.4-59.8)		50.2 (46.8-53.5)	41.7 (37.7-45.6)	49.9 (47.2-52.6)
Prevalence change†	15.7 (9.6-21.7)	14.7 (8.8-20.5)	8.7 (4.6-12.9)		15.4 (9.0-21.9)	13.4 (7.7-19)	10.2 (5.5-14.8)
P for non-linearity‡	0.58	0.97	0.25		0.52	0.10	0.35
P value for trend‡	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Women	n=4,204	n=9,710	n=5,417		n=4,204	n=9,710	n=5,417
Prevalence, % (95% CI)							
1999-2000	62.8 (55.1-70.5)	46.2 (40.2-52.1)	64.2 (59.6-68.8)		39.8 (31.1-48.5)	30.3 (25.2-35.3)	49.2 (42.5-56.0)
2001-2002	66.4 (58.6-74.3)	47.8 (44.2-51.4)	64.2 (59.0-69.4)		37.0 (30.2-43.8)	31.1 (27.6-34.7)	48.7 (42.8-54.7)
2003-2004	75.0 (68.3-81.6)	50.6 (43.9-57.2)	70.7 (65.5-75.8)		42.7 (36.0-49.3)	30.3 (25.7-34.8)	53.9 (46.3-61.5)
2005-2006	72.0 (66.4-77.5)	49.9 (45.6-54.2)	66.2 (60.9-71.5)		41.3 (34.8-47.7)	32.8 (28.3-37.3)	52.7 (48.5-56.9)
2007-2008	74.8 (71.2-78.4)	52.3 (47.5-57.2)	67.9 (63.2-72.6)		44.7 (38.8-50.6)	32.8 (28.7-36.9)	49.2 (45.2-53.3)
2009-2010	77.8 (74.8-80.9)	53.4 (49.5-57.2)	74.6 (68.6-80.7)		45.7 (42.0-49.3)	32.1 (29.0-35.3)	58.5 (52.0-64.9)
2011-2012	74.6 (66.2-83.0)	56.3 (51.4-61.3)	74.9 (72.1-77.8)		49.0 (40.4-57.5)	33.3 (28.0-38.7)	57.9 (53.5-62.3)
2013-2014	81.2 (74.7-87.6)	57.3 (53.4-61.2)	72.5 (68.8-76.2)		51.7 (45.2-58.3)	37.6 (33.7-41.6)	56.7 (53.1-60.3)
2015-2016	84.6 (79.7-89.5)	60.0 (56.2-63.8)	72.3 (68.3-76.4)		52.2 (48.4-56.1)	38.5 (34.0-43.0)	57.1 (52.6-61.5)
2017-2020	76.9 (70.8-83.1)	62.3 (59.0-65.7)	72.4 (68.6-76.2)		49.6 (43.1-56.0)	40.3 (36.4-44.2)	57.3 (53.7-60.9)
Prevalence change†	14.1 (4.7-23.6)	16.2 (9.7-22.7)	8.3 (2.5-14.0)		9.8 (-0.6-20.1)	10.0 (3.9-16.1)	8.1 (0.8-15.4)

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P for non-linearity§	0.026	0.77	0.34		0.76	0.12	0.71
P value for trend§		<0.001	<0.001		<0.001	<0.001	<0.001
Men	n=4,212	n=9,981	n=5,256		n=4,212	n=9,981	n=5,256
Prevalence, % (95% CI)							
1999-2000	42.9 (39.4-46.5)	33.2 (28.6-37.7)	27.5 (23.1-31.9)		29.1 (24.6-33.6)	26.8 (22.9-30.6)	26.8 (23.0-30.6)
2001-2002	40.6 (34.7-46.4)	34.1 (30.9-37.4)	25.8 (21.4-30.1)		25.9 (21.9-29.9)	28.3 (25.3-31.4)	26.5 (22.8-30.1)
2003-2004	47.1 (39.3-54.8)	38.9 (35.5-42.4)	31.2 (27.2-35.2)		31.7 (25.0-38.3)	30.9 (27.0-34.7)	34.2 (27.7-40.7)
2005-2006	40.8 (34.1-47.4)	40.0 (35.1-44.9)	34.1 (28.3-39.9)		27.4 (22.7-32.1)	33.3 (28.7-37.9)	37.2 (31.2-43.2)
2007-2008	50.9 (43.3-58.4)	38.8 (34.7-42.9)	33.8 (28.8-38.9)		35.1 (28.0-42.1)	32.0 (27.9-36.0)	36.9 (31.0-42.7)
2009-2010	47.8 (44.6-51.0)	39.4 (34.6-44.3)	35.4 (31.4-39.5)		36.3 (30.9-41.6)	36.1 (30.8-41.3)	38.6 (33.1-44.0)
2011-2012	52.5 (45.6-59.4)	37.6 (34.3-40.9)	36.4 (32.3-40.5)		42.7 (36.0-49.5)	32.5 (29.7-35.3)	37.5 (32.8-42.2)
2013-2014	52.4 (48.6-56.3)	41.7 (38.1-45.3)	35.2 (28.6-41.8)		43.6 (38.2-49.1)	35.6 (31.6-39.5)	37.9 (32.5-43.4)
2015-2016	55.9 (50.9-60.8)	42.3 (36.5-48.1)	38.1 (31.9-44.2)		45.3 (38.5-52.1)	38.4 (32.5-44.3)	38.9 (33.5-44.2)
2017-2020	61.2 (55.8-66.6)	45.8 (40.3-51.2)	39.1 (35.4-42.8)		50.3 (46.1-54.5)	43.1 (36.9-49.2)	41.2 (36.7-45.7)
Prevalence change†	18.3 (12.0-24.5)	12.6 (5.7-19.5)	11.6 (6.1-17.1)		21.2 (15.3-27.1)	16.3 (9.3-23.3)	14.4 (8.7-20.1)
P for non-linearity§	0.21	0.80	0.50		0.24	0.45	0.08
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.
† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for age and sex.
§ Adjusted for age.

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Supplementary Table 4. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity				BMI-defined obesity		
	20-39 years old	40-59 years old	60-79 years old		20-39 years old	40-59 years old	60-79 years old
All participants	n=16,747	n=16,912	n=14,008		n=16,747	n=16,912	n=14,008
Prevalence, 95% CI							
1999-2000	29.0 (24.5-33.6)	46.9 (40.5-53.4)	61.8 (58.1-65.6)		25.4 (21.5-29.3)	33.2 (26.9-39.4)	35.4 (31.3-39.5)
2001-2002	30.2 (27.2-33.1)	45.0 (42.2-47.8)	63.8 (61.3-66.3)		25.3 (22.4-28.1)	33.2 (29.9-36.4)	33.7 (30.7-36.8)
2003-2004	34.2 (31.2-37.1)	51.2 (47.8-54.6)	65.8 (62.5-69.0)		28.1 (24.6-31.7)	35.9 (32.1-39.7)	33.0 (29.4-36.5)
2005-2006	32.6 (28.7-36.5)	53.2 (47.9-58.5)	66.0 (62.2-69.8)		28.5 (24.1-32.9)	40.1 (35.6-44.6)	34.9 (31.5-38.3)
2007-2008	35.5 (31.1-39.9)	51.6 (48.5-54.7)	66.1 (62.4-69.8)		30.2 (26.2-34.3)	35.7 (32.4-39.1)	37.4 (33.8-40.9)
2009-2010	37.2 (32.8-41.6)	50.5 (47.7-53.4)	68.5 (65.2-71.8)		32.5 (28.7-36.3)	36.0 (33.9-38.2)	41.8 (38.0-45.7)
2011-2012	37.7 (33.1-42.3)	53.6 (49.9-57.3)	68.0 (62.9-73.1)		30.4 (26.2-34.5)	39.3 (36.1-42.5)	38.3 (33.8-42.9)
2013-2014	40.0 (36.2-43.9)	54.5 (50.3-58.7)	68.8 (64.6-73.0)		34.4 (31.3-37.5)	40.6 (36.2-45.1)	39.3 (35.2-43.5)
2015-2016	43.0 (39.0-47.0)	57.1 (50.6-63.6)	69.8 (64.7-74.9)		36.0 (32.2-39.8)	42.8 (37.5-48.2)	42.8 (37.5-48.2)
2017-2020	44.6 (40.5-48.6)	59.4 (56.2-62.7)	70.6 (67.2-74.0)		39.8 (35.6-44.0)	44.3 (41.2-47.4)	42.7 (39.1-46.3)
Prevalence change†	15.5 (9.7-21.3)	12.5 (5.6-19.4)	8.8 (3.9-13.6)		14.5 (8.9-20.0)	11.2 (4.5-17.8)	7.3 (2.0-12.5)
P for non-linearity‡	0.65	0.94	0.25		0.48	0.21	0.46
P value for trend‡	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Women	n=8,295	n=8,684	n=6,952		n=8,295	n=8,684	n=6,952
Prevalence, 95% CI							
1999-2000	36.9 (30.9-42.9)	56.2 (48.9-63.5)	67.7 (63.3-72.2)		28.7 (23.6-33.7)	37.4 (30.2-44.5)	37.4 (31.6-43.2)
2001-2002	39.9 (35.3-44.5)	52.9 (48.1-57.6)	72.0 (69.3-74.7)		28.9 (24.1-33.6)	35.0 (30.2-39.8)	36.6 (32.0-41.2)
2003-2004	42.0 (35.8-48.2)	59.7 (54.9-64.5)	73.0 (68.3-77.7)		29.0 (23.8-34.1)	38.1 (32.3-43.9)	33.6 (28.5-38.7)
2005-2006	40.3 (35.3-45.4)	58.7 (53.5-63.8)	71.3 (66.4-76.2)		29.2 (24.1-34.3)	40.7 (35.9-45.6)	34.8 (28.4-41.2)
2007-2008	46.1 (40.4-51.7)	60.0 (56.2-63.8)	69.8 (64.5-75.1)		33.0 (27.3-38.6)	37.6 (32.6-42.5)	36.0 (30.0-41.9)
2009-2010	46.4 (40.6-52.2)	59.3 (55.5-63.1)	78.5 (75.8-81.3)		31.8 (28.2-35.4)	35.5 (31.7-39.3)	45.1 (40.7-49.5)
2011-2012	47.6 (42.1-53.1)	64.6 (60.1-69.0)	76.7 (69.8-83.5)		31.9 (28.0-35.9)	39.4 (35.1-43.6)	42.1 (34.4-49.7)
2013-2014	50.8 (46.6-55.1)	63.3 (58.1-68.5)	78.0 (74.6-81.4)		36.6 (33.9-39.3)	43.6 (38.2-48.9)	40.2 (34.1-46.2)
2015-2016	53.3 (48.9-57.8)	69.1 (62.7-75.5)	77.1 (70.6-83.6)		37.1 (33.5-40.7)	44.8 (38.4-51.1)	45.0 (37.3-52.8)
2017-2020	53.3 (48.5-58.0)	67.9 (63.6-72.3)	81.0 (76.4-85.6)		39.9 (35.3-44.4)	42.8 (38.9-46.7)	45.4 (40.9-49.8)

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Prevalence change†	16.4 (9.1-23.7)	11.7 (3.6-19.9)	13.3 (7.1-19.5)		11.2 (4.7-17.7)	5.5 (-2.3-13.2)	8.0 (1.0-15.0)
P for non-linearity§	0.16	0.39	0.99		0.44	0.42	0.97
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Men	n=8,452	n=8,228	n=7,056		n=8,452	n=8,228	n=7,056
Prevalence, 95% CI							
1999-2000	22.4 (18.0-26.8)	36.8 (30.4-43.2)	54.7 (49.9-59.5)		22.7 (18.3-27.0)	28.8 (22.8-34.8)	33.2 (28.2-38.1)
2001-2002	20.8 (17.4-24.1)	37.1 (33.5-40.7)	53.5 (49.8-57.1)		21.7 (18.5-24.9)	31.2 (28.0-34.5)	30.4 (26.0-34.8)
2003-2004	26.9 (23.3-30.4)	42.3 (36.7-47.9)	57.2 (52.5-62.0)		27.4 (22.5-32.3)	33.6 (28.4-38.9)	32.3 (27.4-37.2)
2005-2006	25.4 (20.1-30.7)	47.4 (40.5-54.2)	59.8 (54.8-64.7)		27.6 (22.0-33.1)	39.5 (33.1-45.9)	34.7 (29.9-39.5)
2007-2008	25.4 (21.2-29.5)	42.8 (37.8-47.8)	61.8 (57.7-65.9)		27.6 (23.8-31.4)	33.7 (28.8-38.5)	39.2 (34.8-43.5)
2009-2010	28.5 (23.6-33.3)	41.6 (37.7-45.5)	56.9 (51.1-62.7)		33.2 (27.2-39.2)	36.6 (33.0-40.2)	37.5 (32.3-42.8)
2011-2012	28.4 (23.9-33.0)	42.3 (38.0-46.6)	58.1 (52.1-64.2)		28.9 (23.5-34.2)	39.1 (35.6-42.5)	34.2 (29.2-39.2)
2013-2014	30.0 (25.5-34.5)	45.5 (40.3-50.7)	58.6 (51.6-65.5)		32.5 (28.1-36.8)	37.7 (32.2-43.3)	38.6 (30.7-46.4)
2015-2016	33.1 (28.3-38.0)	44.5 (36.5-52.6)	61.4 (55.4-67.5)		35.0 (29.0-41.0)	40.8 (34.6-47.1)	40.2 (34.9-45.5)
2017-2020	35.9 (30.2-41.5)	50.8 (46.2-55.4)	58.8 (54.3-63.3)		39.5 (33.1-46.0)	45.8 (41.1-50.6)	39.7 (34.0-45.4)
Prevalence change†	13.4 (6.5-20.4)	14.0 (6.4-21.6)	4.1 (-2.3-10.5)		16.8 (9.3-24.4)	17.0 (9.7-24.4)	6.5 (-0.7-13.8)
P for non-linearity§	0.47	0.42	0.16		0.97	0.41	0.24
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.
† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for sex and ethnicity.
§ Adjusted for ethnicity.

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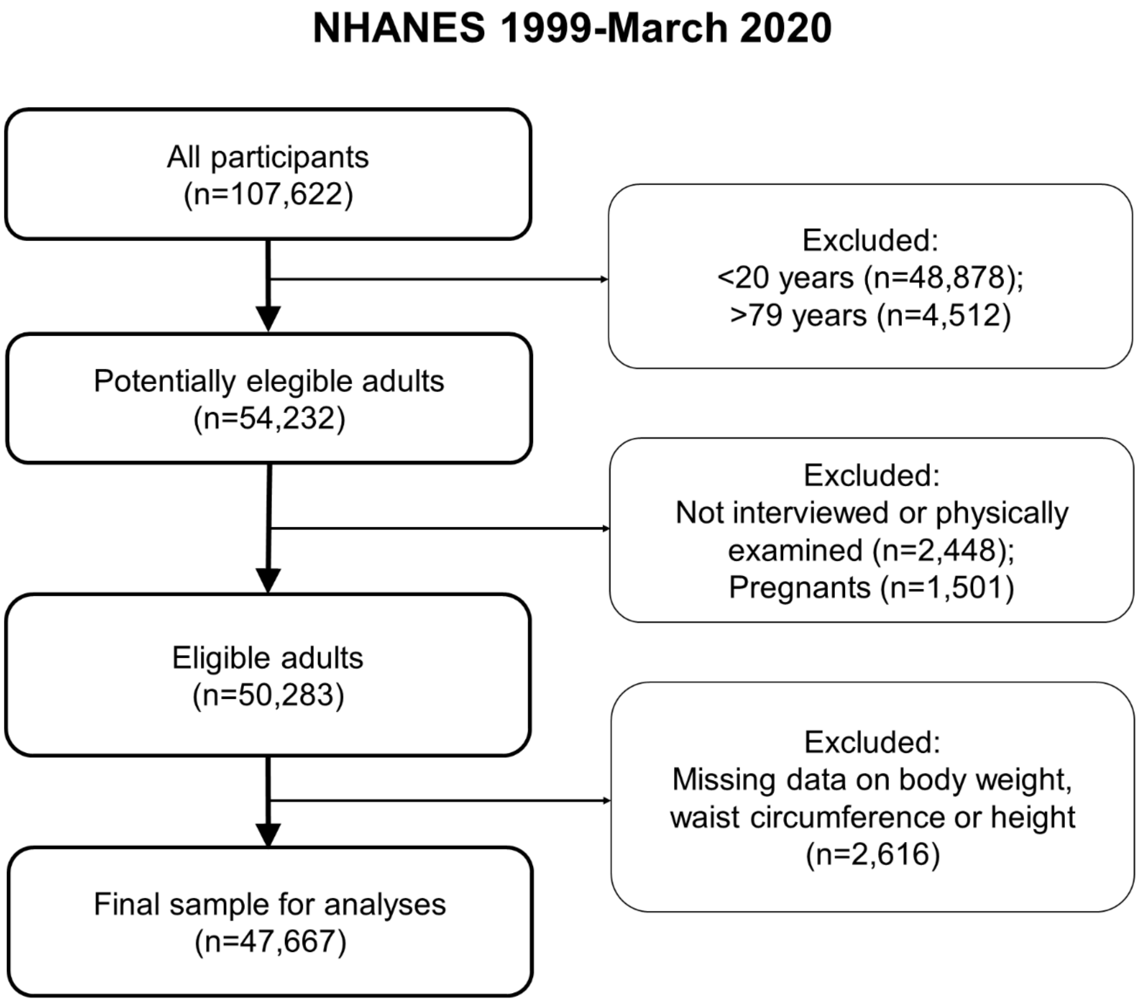

Supplementary Figure 1. Selection of study participants.

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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
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	3-4
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	6-7
Objectives	3	State specific objectives, including any prespecified hypotheses	7
Methods			
Study design	4	Present key elements of study design early in the paper	8
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	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, 10
		(*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	NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	9-10
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	*8-10*
Bias	9	Describe any efforts to address potential sources of bias	9-10
Study size	10	Explain how the study size was arrived at	8
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	9-10
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	9-10
		(*b*) Describe any methods used to examine subgroups and interactions	9-10
		(*c*) Explain how missing data were addressed	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	9-10
		(*e*) Describe any sensitivity analyses	10

Continued on next page

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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	11
		(b) Give reasons for non-participation at each stage	11
		(c) Consider use of a flow diagram	Suppl Fig 1
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	Suppl Table 1
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	NA
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	*NA*
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	*NA*
		Cross-sectional study—Report numbers of outcome events or summary measures	*11-18*
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	NA
		(*b*) Report category boundaries when continuous variables were categorized	12-18
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	11-18
Discussion			
Key results	18	Summarise key results with reference to study objectives	19
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	23-24
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	24
Generalisability	21	Discuss the generalisability (external validity) of the study results	24
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	26

*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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Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Keywords:	EPIDEMIOLOGY, PUBLIC HEALTH, General endocrinology < DIABETES & ENDOCRINOLOGY, GENERAL MEDICINE (see Internal Medicine), Obesity

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Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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ABSTRACT

Objectives: The body mass index (BMI) largely underestimates excess body fat, suggesting that the prevalence of obesity could be underestimated. Biologically, women are known to have higher body fat than men. This study aimed to compare the temporal trends in general obesity by sex, ethnicity, and age among adults in the United States using the relative fat mass (RFM), a validated surrogate for whole-body fat percentage, and BMI.

Design: Population-based study

Setting: U.S. National Health and Nutrition Examination Survey (NHANES), from 1999-2000 through 2017-March 2020.

Participants: A representative sample of adults 20-79 years in the U.S.

Main outcome measures: Age-adjusted prevalence of general obesity. RFM-defined obesity was diagnosed using validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men. BMI-defined obesity was diagnosed using a cutoff of 30 kg/m^2.

Results: Analysis included data from 47,667 adults. Among women, RFM-defined obesity prevalence was 64.7% (95% confidence interval, 62.1-67.3%) in 2017-2020, a linear increase of 13.9 percentage points (9.0-18.9%; P<0.001) relative to 1999-2000. In contrast, the prevalence of BMI-defined obesity was 42.2% (39.4-45.0%) in 2017-2020. Among men, the corresponding RFM-defined obesity prevalence was 45.8% (42.0-49.7%), a linear increase of 12.0 percentage points (6.6-17.3%; P<0.001). In contrast, the prevalence of BMI-defined obesity was 42.0 (37.8-46.3%). The highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) and Mexican Americans, in women and men. Conversely, the highest prevalence of BMI-defined obesity across years was observed in middle-age (40-59 years) and older adults, and in African American women.

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Conclusions: The use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women, than that estimated using BMI, and detected a disproportionate higher prevalence of general obesity in older adults and Mexican Americans.

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STRENGTHS AND LIMITATIONS OF THIS STUDY

- RFM is a validated surrogate for whole-body fat percentage that has a high diagnostic accuracy (91%) for DXA-defined obesity.
- The diagnosis of obesity was based on measured anthropometrics and validated RFM cutoffs associated with increased risk for all-cause mortality.
- RFM requires only waist circumference and height for its calculation.
- The proportion of obesity misclassification is not trivial when using RFM.
- Estimates of temporal trends in obesity was not possible for Asian Americans.

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INTRODUCTION

The prevalence of obesity (excess body fat) in the United States has doubled from 15.0% in 1976-1980 to 30.9% in 1999-2000 [1], and it continues to increase [2 3]. The age-adjusted prevalence of obesity among adults in the U.S. has been estimated at 41.9% in 2017-March 2020 [4]. Obesity diagnosis is based on the body mass index (BMI), an indirect measure of body fat [5 6]. BMI is calculated as the ratio of body weight in kilograms to the square of the height in meters [7]. BMI does not distinguish between fat mass and fat-free mass and does not account for differences in adiposity between women and men. Biologically, women are known to have higher body fat than men [8-12]. A meta-analysis of 25 international studies comprising nearly 32,000 adults concluded that BMI underestimates ~50% of all individuals with excess body fat percentage determined by reference techniques [11], suggesting that the prevalence of obesity could be largely underestimated among countries.

There is robust evidence linking high whole-body fat percentage with increased risk of death [13-20], supporting the need for a better assessment of body adiposity. Although the limitations of BMI to assess body adiposity are widely acknowledged [6 8-11 21 22], BMI remains the most widely used anthropometric index in clinical practice, epidemiology, and public health, given its simplicity, very low cost, and its association with several clinical conditions and mortality [6]. The high cost and time required to assess body adiposity using more accurate techniques such as dual-energy x-ray absorptiometry (DXA), dual-labeled water, or magnetic resonance, prevents their use in large populations or clinical practice as part of routine screening.

The relative fat mass (RFM) is a simple and low-cost anthropometric index developed to estimate whole-body fat percentage [23]. RFM is a linear equation based on the ratio of height to waist circumference that has been validated in Mexican, European, and African Americans [23], and in other populations [24-26]. Compared with BMI, RFM resulted in lower obesity misclassification when DXA was used as the reference method for diagnosing obesity in adults

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[24,27]. The accuracy of RFM in diagnosing high body fat percentage is superior to that of BMI among men and similar to BMI among women [23]. In an analysis of a representative sample of the U.S. adult population (NHANES 1999-2006), RFM had a diagnostic accuracy of 91% (C-statistic = 0.91) for DXA-defined obesity in women and men [27].

Recent studies have examined the U.S. prevalence trends in obesity using BMI as diagnostic tool [3,28,29]. Although data on body fat percentage have also been reported for the U.S. adult population [28], no body fat cutoffs were used to diagnose general obesity, and the analyses were limited to adults 20-59 years only, and for the period 2011-2018. In fact, body composition has been inconsistently assessed across NHANES survey cycles and across age groups. In addition, no study has compared the trends of general obesity in the U.S. using RFM, a surrogate for body fat percentage, and BMI. Furthermore, no study has examined current obesity trends among U.S. adults over a period of nearly 22 years. The aim of this study was to compare the temporal trends in general obesity by sex, ethnicity, and age group among adults in the U.S. from 1999 to 2020 using RFM and BMI.

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MATERIAL AND METHODS

Study design, data source, and participants

In this population-based study, we performed an analysis of cross-sectional individual-level data collected by the National Health and Nutrition Examination Survey (NHANES) through interviews and physical examination in a subset of a representative sample of the U.S. population from 1999-2000 through 2017-March 2020. Initial complete dataset included 107,622 participants of all ages. NHANES suspended data collection in March 2020 as a consequence of the COVID-19 pandemic. Thus, the most current cycle data available are “combined data collected from 2019 to March 2020 with data from the NHANES 2017-2018 cycle to form a nationally representative sample of NHANES 2017-March 2020 pre-pandemic data” [30]. Analysis was restricted to adults 20-79 years of age (n=54,232 potentially eligible) because of three reasons: 1) the diagnosis of obesity in younger adults is based on BMI-for-age percentiles as recommended by the Centers for Disease Control and Prevention (CDC) [7]; 2) in NHANES 2007-2008 and subsequent cycles, the upper age limit was 80 years, whereas in earlier cycles the age limit was 85 years; and 3) to obtain age-adjusted prevalence estimates using 5-year intervals according to the strata for age and sex available from the 2000 US Census Bureau (20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, and 75-79) [31]. Another criterion for inclusion was that individuals had been interviewed and evaluated by physical examination. Women who reported to be pregnant or had a positive urine pregnancy test were excluded from analysis. Observations with missing data on body weight, height, or waist circumference were also excluded.

According to the NHANES physical examination protocol, waist circumference was measured just above the uppermost lateral border of the right ilium (hip bone). Weight and height were measured using standard methods [32]. Information on ethnicity was collected through a questionnaire. The mean unweighted response rate for examined sample across survey cycles

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between 1999-2000 and 2017-March 2020 for individuals 20-79 years was 67.5% (range 50.8-74.5%) [33].

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) [34].

Obesity diagnosis

General obesity was diagnosed using RFM, a validated surrogate for whole-body fat percentage [23], and validated cutoffs to predict all-cause mortality: RFM ≥40% for women and ≥30% for men [27]. RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women [23]. BMI-defined obesity was diagnosed if BMI was 30 kg/m^2 or higher [7].

Statistical Analysis

Data collected during the survey cycles from 1999-2000 through 2017-2020 were analyzed using sampling weights following the recommended analytic guidelines, to account for oversampling, nonresponse rates, and subsampling for physical examination [35]. The proportion of missing data was 5.2% of all eligible participants. Given this low percentage of missing data, we performed a complete case analysis [36]. Since age distribution of study samples may vary across survey cycles, all prevalence estimates were adjusted for age to make the estimates more comparable throughout the study period [31]. Estimates across the age categories 20-39, 40-59, and 60-79 years were also adjusted for age using 5-year intervals according to corresponding 2000 US Census Bureau age categories by sex [31]. The changes in obesity prevalence from 1999-2000 to 2017-March 2020 were assessed using the Wald test. For multiple comparisons of prevalence across ethnic groups and age groups, we applied the

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Bonferroni correction. Because Asian Americans were not oversampled before NHANES 2011, our analyses by ethnicity were restricted to Mexican, European, and African Americans.

To determine the possible role of menopause in the high prevalence of RFM-defined obesity in women, we performed a post hoc analysis. Data related to menopause were self-reported. We defined postmenopausal women as those with natural menopause and no missing information on age at menopause. For this analysis, women were excluded if menopause occurred before age 40 or after age 62 [37], or if they reported oophorectomy (surgical removal of one or two ovaries), treatment with estrogen/progesterone for hysterectomy/oophorectomy, breastfeeding, pregnancy in past year of the interview, or irregular period due to medical conditions or treatment.

Temporal trends in prevalence of obesity were tested for the assumption of linearity using logistic regression models, comparing linear and non-linear regression models using the likelihood-ratio test [38]. For the non-linear models, restricted cubic splines with 3 knots were used at years 2001-2002, 2009-2010, and 2017-2020, based on the quantiles recommended by Harrel [39]. Survey cycles were analyzed as a continuous variable. For visualization purposes, trend lines were smoothed using the Lowes method [40]. Statistical significance was set to an alpha level of 0.05. All statistical analyses were performed using Stata 14 for Windows (StataCorp LP, College Station, TX). Prevalence estimates and standard errors were obtained using the survey 'svy' command with Taylor linearization.

<u>Patient and public involvement</u>

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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RESULTS

Clinical characteristics

After applying the inclusion and exclusion criteria, the final sample for analysis comprised 47,667 adults (online supplemental figure 1). The median age of the study population was 45 years (interquartile range: 33 to 58); 50.6% were women; 67.2% were European Americans, 11.2% were African Americans, and 8.3% were Mexican Americans (Table 1).

Table 1. Characteristics of study participants.*

Characteristic	**All** 47,667	**Women** 23,931 (50.6%)	**Men** 23,736 (49.4%)
Median age (IQR), years	45 (33-58)	46 (33-59)	44 (32-57)
Ethnicity, n (%)			
Mexican American	8,416 (8.3)	4,204 (7.7)	4,212 (9.0)
European American	19,691 (67.2)	9,710 (67.0)	9,981 (67.5)
African American	10,673 (11.2)	5,417 (12.0)	5,256 (10.4)
Other/multi-racial	8,887 (13.3)	4,600 (13.4)	3,928 (13.1)
Body weight (SD), kg	82.6 (21.3)	76.3 (20.5)	89.0 (20.1)
Mean height (SD), cm	168.9 (10.0)	162.1 (6.9)	175.9 (7.5)
Mean waist circumference (SD), cm	98.5 (16.5)	95.9 (16.9)	101.2 (15.6)
Mean BMI (SD), kg/m^2	28.9 (6.8)	29.0 (7.5)	28.7 (5.9)
Mean RFM (SD), %	34.9 (8.5)	41.2 (6.0)	28.4 (5.3)
RFM-defined obesity, % (95% CI) †	50.1 (48.9-50.8)	59.4 (58.4-60.5)	40.6 (39.4-41.8)
BMI-defined obesity, % (95% CI) ‡	36.2 (35.4-37.1)	37.8 (36.8-38.7)	34.6 (33.5-35.8)
Abdominal obesity, % (95% CI) §	54.0 (53.0-55.0)	63.8 (62.8-64.9)	43.9 (42.7-45.1)

BMI, body mass index; CI, confidence interval; IQR, interquartile range; RFM, relative fat mass; SD, standard deviation.
* Sample size represents unweighted data. Estimates represent weighted data.

† Defined as having an RFM of 40% or higher for women and an RFM of 30% or higher for men. RFM was calculated as follows: 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women; height and waist circumference were measured in the same units. Estimates were not adjusted for age.
‡ Defined as a having a BMI of 30 kg/m^2 or higher. BMI was calculated as the body weight in kilograms divided by the square of the height in meters. Estimates were not adjusted for age.
§ Defined as having a waist circumference of more than 88 cm for women and more than 102 cm for men, according to the recommendations of the National Cholesterol Education Program (NCEP) Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). Estimates were not adjusted for age.

The overall prevalence of obesity by ethnicity in the study participants is shown in the supplementary file (online supplemental table 1). The characteristics of the population with missing data are shown in online supplemental table 2.

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Obesity prevalence and temporal trends

Our findings indicate a higher proportion of individuals with obesity when RFM was used instead of BMI. The overall age-adjusted prevalence of RFM-defined obesity increased from 42.4% (95% confidence interval, 38.3% to 46.4%) in 1999-2000 to 55.4% (53.0% to 57.9%) in 2017-March 2020. The corresponding BMI-defined obesity prevalence increased from 30.4% (26.7% to 34.0%) to 42.1% (39.4% to 44.8%). We found a linear increase in the overall prevalence of obesity during the study period using either RFM (P<0.001; P=0.38 for non-linearity) or BMI (P<0.001; P=0.55 for non-linearity).

Obesity prevalence and temporal trends by sex

We observed a consistently higher prevalence of RFM-defined obesity in women compared with men across years. In contrast, this difference was not consistent for BMI-defined obesity (Figure 1). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in women than in men (P<0.001). In contrast, the prevalence of BMI-defined obesity was similar in women and men (P=0.97). Among women, the prevalence of RFM-defined obesity increased from 50.8% (46.2% to 55.3%) in 1999-2000 to 64.7% (62.1% to 67.3%) in 2017-March 2020, a linear increase of 13.9 percentage points (9.0% to18.9%; P<0.001). For comparison, the prevalence of BMI-defined obesity in women was 42.2% (39.4% to 45.0%) in 2017-March 2020, a linear increase of 8.3 percentage points (3.5-13.2%; P<0.001) (Table 2).

Table 2. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by sex: 1999-2000 through 2017-Mach 2020.*

	RFM-defined obesity	BMI-defined obesity
All participants (n=47,667)		
Prevalence, % (95% CI)		
1999-2000	42.4 (38.3-46.4)	30.4 (26.7-34)

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2001-2002	42.5 (41.1-43.9)	30.0 (27.6-32.4)
2003-2004	46.9 (44.7-49.2)	32.1 (29.3-34.9)
2005-2006	47.1 (43.7-50.5)	34.3 (31.1-37.4)
2007-2008	47.7 (45.0-50.5)	33.7 (31.5-36.0)
2009-2010	48.5 (46.1-50.8)	35.7 (33.6-37.8)
2011-2012	49.8 (46.6-53.0)	35.4 (32.5-38.3)
2013-2014	51.3 (48.7-53.8)	37.8 (35.6-40)
2015-2016	53.7 (49.3-58.0)	40.0 (36.4-43.6)
2017-2020	55.4 (53.0-57.9)	42.1 (39.4-44.8)
Prevalence change†	13.0 (8.5-17.5)	11.8 (7.4-16.1)
P for non-linearity‡	0.38	0.55
P value for trend‡	<0.001	<0.001
Women (n=23,931)		
Prevalence, % (95% CI)		
1999-2000	50.8 (46.2-55.3)	33.9 (29.6-38.1)
2001-2002	51.6 (49.2-53.9)	32.9 (29.7-36.0)
2003-2004	55.3 (51.2-59.3)	33.5 (29.7-37.2)
2005-2006	53.9 (50.4-57.4)	34.8 (31.5-38.1)
2007-2008	56.4 (53.5-59.3)	35.4 (32.7-38.0)
2009-2010	58.1 (55.3-60.8)	36.0 (34.0-37.9)
2011-2012	60.8 (56.8-63.6)	36.9 (33.4-40.5)
2013-2014	61.3 (57.9-64.7)	40.0 (36.8-43.2)
2015-2016	64.4 (60.2-68.6)	41.7 (38.1-45.3)
2017-2020	64.7 (62.1-67.3)	42.2 (39.4-45.0)
Prevalence change†	13.9 (9.0-18.9)	8.3 (3.5-13.2)
P for non-linearity§	0.10	0.39
P value for trend§	<0.001	<0.001
Men (n=23,736)		
Prevalence, % (95% CI)		
1999-2000	33.9 (29.9-37.8)	27.0 (23.5-30.4)
2001-2002	33.1 (30.6-35.5)	27.0 (24.8-29.2)
2003-2004	38.4 (35.9-40.8)	30.7 (27.6-33.9)
2005-2006	40.2 (35.9-44.4)	33.5 (29.3-37.8)
2007-2008	38.8 (35.6-42.0)	32.1 (29.3-34.8)
2009-2010	38.7 (35.2-42.2)	35.3 (31.4-39.2)
2011-2012	39.2 (35.9-42.5)	33.8 (30.7-36.9)
2013-2014	41.2 (38.7-43.7)	35.6 (33.2-38.1)
2015-2016	42.7 (37.7-47.7)	38.2 (33.3-43.2)
2017-2020	45.8 (42.0-49.7)	42.0 (37.8-46.3)
Prevalence change†	12.0 (6.6-17.3)	15.1 (9.8-20.4)
P for non-linearity§	0.82	0.84
P value for trend§	<0.001	<0.001

BMI, body mass index; CI, confidence interval; RFM, relative fat mass.
* Prevalence estimates represent weighted data. RFM-defined obesity was diagnosed as having an RFM of 40% or higher for women and having an RFM of 30% or higher for men. RFM was calculated as follows: 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Height and waist circumference were measured in the same units. BMI-defined obesity was diagnosed as having a BMI of 30 kg/m^2 or higher. BMI was calculated as the body weight in kilograms divided by the square of the height in meters. Estimates were not adjusted for age.

† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for age, sex, and ethinicity.
§ Adjusted for age and ethnicity.

Among men, the prevalence of RFM-defined obesity increased from 33.9% (29.9% to 37.8%) in 1999-2000 to 45.8% (42.0% to 49.7%) in 2017-March 2020, a linear increase of 12.0

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percentage points (6.6% to 17.3%; P<0.001). The prevalence of BMI-defined obesity in men was 42.0% (37.8% to 46.3%) in 2017-March 2020, a linear increase of 15.1 percentage points (9.8% to 20.4%).

Obesity prevalence and temporal trends by ethnicity

The highest prevalence of RFM-defined obesity across years was observed among Mexican Americans. In contrast, the highest prevalence of BMI-defined obesity was observed among African American women but not men (Figure 2). In 2017-March 2020, the prevalence of RFM-defined obesity was significantly higher in Mexican Americans compared with African Americans (Bonferroni corrected P<0.001) or European Americans (P<0.001). BMI-defined obesity prevalence was similar in Mexican and African Americans (P=0.99) and both groups had a higher prevalence than European Americans (P=0.003 and P=0.001, respectively).

The largest increase in the prevalence of RFM-defined obesity from 1999-2000 to 2017-March 2020 occurred in Mexican American men, with a linear increase of 18.3 percentage points (12.0% to 24.5%; P<0.001) (online supplemental table 3 and Figure 2). The highest increase in the prevalence of BMI-defined obesity also occurred in Mexican American men, with a linear increase of 21.2 percentage points (15.3% to 27.1%; P<0.001) (online supplemental table 3 and Figure 2).

Obesity prevalence and temporal trends by age group

In women and men, the highest prevalence of RFM-defined obesity across years was observed in older adults (60-79 years) (Figure 3 and online supplemental table 4).

In contrast, no differences were observed in the prevalence of obesity between individuals 60-79 years and 40-59 years when using BMI for the diagnosis of obesity (Figure 3). In 2017-March

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2020, the prevalence of RFM-defined obesity was significantly higher in individuals 60-79 years compared with those 40-59 years (Bonferroni corrected P<0.001) or 20-39 years (P<0.001). We found no statistically significant differences in the prevalence of BMI-defined obesity across age groups (P>0.17 for all comparisons).

Although our analysis by age showed an increased prevalence of obesity in older women and men (Figure 3), we performed a sensitivity analysis to specifically explore the possible role of menopause. Our findings from this post hoc analysis revealed that the crude prevalence of RFM-defined obesity in 2017-2020 was 56.4% (95% CI, 53.5-59.3%) among premenopausal women (n=1,935) and 76.4% (71.0-81.8%) among postmenopausal women (n=1,406). The mean age at last menstrual period was 49 years in this population. For comparison, among men, the corresponding prevalence of obesity was 39.7% (34.9-44.6%) in those younger than 50 years (n=1,790) and 56.2% (52.9-59.5%) in men 50 years of age and older (n=1,886).

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DISCUSSION

Our study shows that, compared with BMI, the use of a surrogate for whole-body fat percentage revealed a much higher prevalence of general obesity among adults in the U.S., particularly among women, affecting nearly two-thirds of all women and nearly half of all men in 2017-2020, with an overall prevalence of 55.4%. This is an additional 22.5% of women and 3.8% of men 20-79 years being defined as obese compared with a BMI-based definition with the current criteria.

The use of RFM also revealed that the highest prevalence of general obesity over the study period from 1999 to 2020 occurred among Mexican Americans and not among African Americans, as was observed when BMI was used to diagnose obesity. Likewise, the use of RFM showed that the highest prevalence of general obesity over this study period occurred among older adults (60-79 years) and not among adults 40-59 years, as was observed when BMI was used. The higher prevalence of obesity in older individuals does not appear to be fully explained by a loss of skeletal muscle with age, since absolute fat mass also increases with age, although mainly visceral fat [41 42]. However, it is difficult to draw a firm conclusion from cross-sectional data. Our findings are consistent with those from other studies also showing a higher body fat percentage in older individuals [12 23 41 43-46].

Overall, women had a markedly higher prevalence of RFM-defined obesity across years than men, a difference that was less evident when using BMI. Previous studies have shown no differences in the prevalence of BMI-defined obesity between women and men [3 4 47]. In the present study, the difference in the prevalence of RFM-defined obesity for 2017-2020 between women and men was nearly 20 percentage points.

The highest prevalence of RFM-defined obesity was observed in Mexican Americans, and the increase was linear over the study period, albeit this linear increase was largely driven by a steady increase among men. Among Mexican American women, a decrease was observed

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since 2015. A previous study reported that, between 2003 and 2006, the prevalence of BMI-defined obesity was higher among African Americans compared with Mexican Americans, but between 2015 and 2018, Mexican American men had a higher prevalence than African American men [29]. In contrast, RFM revealed a consistently higher prevalence of general obesity among Mexican Americans over the observed time, in both women and men. Socio-economic characteristics are probably the main determinants of differences in the prevalence of general obesity between ethnic groups [48].

It has been argued that the fat mass index (FMI, body fat mass adjusted for the square of the height, expressed in kg/m^2) should be used as a reference of fat mass instead of body fat percentage (body fat mass adjusted for body weight) to avoid including fat mass both in the numerator and the denominator, as this is not mathematically advisable [49]. However, the concept of obesity (excess body fat) and all different forms to express it, for example BMI [6 50 51], FMI [52 53], fat mass/fat-free-mass [54 55], body fat percentage [12 56], to cite a few, should not be seen only as mathematical constructs but also as biological variables with important implications as risk factors for disease and mortality. In the present study, we chose body fat percentage as the reference because numerous studies have shown that body fat percentage is associated with mortality [13-20 57]. What is also important to note is that FMI does not appear to be superior to body fat percentage or BMI as a predictor of cardiovascular mortality [14], all-cause mortality [58 59] or cardiovascular risk factors [60]. Because of its association with mortality, body fat percentage is of great clinical relevance. Recent studies support the utility of RFM to predict type 2 diabetes [61] and heart failure [62].

Further research is needed to better understand the clinical implications of our study findings: 1) the much higher prevalence of general obesity among women when RFM is used as opposed to BMI; 2) the higher burden of general obesity on Mexican Americans compared with African and European Americans; and 3) the higher prevalence of general obesity in older individuals.

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It is difficult to establish whether the higher prevalence of general obesity estimated using RFM would translate into a higher risk of cardiovascular disease (CVD). The association between obesity and CVD is very complex and several factors may mediate this association [63]. Although subcutaneous fat appears to have a relative protective effect against CVD [64], others have shown that subcutaneous fat is also associated with cardiovascular risk factors, although less strongly than visceral fat [65]. A major limitation of these studies, however, is that the analyses involved a small region of the abdominal trunk.

In women, who biologically have a higher body adiposity than men, the possible protective effect of estrogens on metabolism could be attenuated by the high prevalence of RFM-defined obesity. This could help explain, for example, the similar relative increase in the U.S. prevalence of diabetes in women and men from 1999 to 2019 (by ~74%) (www.healthdata.org) or the similar prevalence of diabetes in women (14.1% [11.8-16.7%]) and men (15.4% [13.5-17.5%]) in 2017-2020 [66]. Our findings, although cross-sectional, do not appear to support a protective role of estrogens against obesity *per se*.

The temporal trends in RFM- and BMI-defined obesity in both women and men follow a parallel pattern. However, stratified analysis by ethnicity showed some differences. RFM revealed that Mexican Americans have a higher prevalence of obesity than European or African Americans. Although we cannot establish causality, this finding coincides with the higher absolute increase in the prevalence of diabetes and liver disease observed in Mexican Americans from 1999 to 2018 compared with European and African Americans [67].

Whether the increased whole-body fat percentage in older individuals confers a higher risk on mortality also requires further investigation as age *per se* is a strong risk factor for mortality [68], and the relationship between obesity and mortality could be mediated by age [69]. In addition, this can be confounded by concomitant severe disease. For instance, several studies have shown an inverse association between body fat percentage (but also BMI and FMI) and mortality in

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older patients [59 70 71]. Conversely, the high body fat percentage in older individuals could explain the association of BMI-defined obesity with diabetes and cardiovascular disease in older individuals [72-75]. The increase in body adiposity with aging coincides with the high prevalence of many cardiometabolic alterations occurring more often in older individuals, such as glucose intolerance, insulin resistance, dyslipidemia, and hypertension [69]. BMI did not detect a higher prevalence of general obesity in individuals aged 60 years and older compared with younger adults, unlike when RFM was used. These findings further support that notion that BMI is a poor predictor of morbidity and mortality in older individuals [46 76].

Abdominal obesity and general obesity are overall underestimated when using BMI (Table 1 and online supplemental table 1). It is also important to mention that the prevalence of abdominal obesity is overall higher compared with the prevalence of RFM-defined obesity, except among Mexican Americans (online supplementary table 1). However, the closer proportions of abdominal obesity and RFM-defined general obesity is expected. Since RFM is based on waist circumference, and waist circumference is a surrogate for intra-abdominal fat [77 78], RFM could be a surrogate for both general obesity and abdominal obesity. Although RFM has been shown to predict trunk fat percentage, the prediction error is greater for trunk fat percentage than for whole-body fat percentage [23].

It is plausible that the association of fat mass with mortality is, at least partly, reflecting the effect of fat-free mass on mortality. Although body fat percentage is associated with mortality, the implications of fat-free mass percentage, as opposed to body fat percentage, as a predictor of mortality require careful examination. Although the proportion of body FFM is the numeric complement of the proportion of body fat mass (%FM=100%-%FFM), this does not take into account the fact that FFM is not exclusively muscle mass. Unless muscle mass and fat mass are measured accurately, it will be difficult to distinguish the overall contribution of fat mass from the largest metabolically tissue in the body, the skeletal muscle, to predict mortality. The

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problem is that accurate estimates of skeletal muscle mass remain a challenge [79]. The current evidence suggests that increased fat mass is associated with higher mortality whereas increased fat-free mass is associated with lower mortality [13 80 81].

The opposite relationship of fat mass and fat-free mass with mortality could be altered due to weight loss interventions (which induce more fat mass loss than muscle mass loss) or because of loss of muscle mass due to age [82]. In older individuals, increased fat-free mass has been associated with lower mortality, whereas lower fat mass has also been associated with increased risk of mortality [83], suggesting frailty could be a more important factor for mortality risk than body composition. Future studies should focus on comparing the association of fat mass and the metabolic components of fat-free mass with mortality. The muscle-mass centric view of health or disease [84 85], rather than focusing on BMI or body fat percentage, is interesting but requires further research due to the complex interrelationship between fat mass and fat-free mass (and muscle mass).

Our study has strengths. First, we used a previously validated surrogate for whole-body fat percentage in adults in the U.S. [23], which has a high diagnostic accuracy (91%) for DXA-defined obesity [27] and has been shown to result in lower total misclassification of DXA-defined high body adiposity compared with BMI among women (RFM: 12.7%; BMI: 56.5%) and men (RFM: 9.4% BMI: 13.0%) [23]. Second, to define general obesity, we used previously validated RFM cutoffs to predict all-cause mortality in a large U.S. adult population [27]. Previously proposed cutoffs for fat-defined obesity have been based on arbitrary values [86 87] or on corresponding BMI cutoffs [12]. Third, we used measured anthropometrics. RFM requires only waist circumference and height for its calculation, which allowed us to estimate the prevalence of general obesity in a large adult population of the U.S. (n=44,754) with a wide age range, over a period of nearly 22 years. Fourth, NHANES have used a consistent methodology across survey cycles to measure anthropometrics, reducing the risk of measurement error that could affect our results.

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Our study also has limitations. First, RFM was developed and validated using DXA as the reference method. However, DXA is an indirect method to assess body fatness and is susceptible to bias introduced mainly by age, degree of fatness, and disease [88 89]. Thus, there are limitations to the level of accuracy and precision that RFM can perform. Nevertheless, RFM is an attempt to provide a relatively easy and affordable alternative method to BMI to better assess body fatness. Second, although the overall obesity misclassification has been reported to be lower with RFM than with BMI in American (21) and Korean individuals (20), another limitation is that the proportion of obesity misclassification is not trivial when using RFM. Third, our analysis was performed using data from a representative sample of the non-institutionalized U.S. population only. Fourth, our estimates of prevalence trends could have been affected by some variability in sampling across NHANES survey cycles [35]. Finally, we did not analyze the prevalence trends for Asian Americans during the period studied because NHANES began oversampling Asian Americans only from 2011-2012 onwards and RFM cutoffs used to diagnose general obesity have not been validated among Asian populations.

From a public health perspective, we argue that due to the underdiagnosis of obesity when using BMI, the most affected populations are not receiving adequate medical care that they require. Aspects that will need further research are the implications of some possible overdiagnosis of obesity [90] and the stigma that would be associated with it [91].

In conclusion, the use of RFM, a surrogate for whole-body fat percentage, revealed a much higher prevalence of general obesity in the U.S. from 1999 to 2020, particularly among women, than that estimated by BMI. RFM, but not BMI, also revealed a disproportionate higher prevalence of general obesity in adults aged 60 years and older and Mexican Americans. Using BMI as the lone measure to define obesity may lead to significant misclassification of large obese subpopulations as non-obese, particularly among women. Our findings may have

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1 implications for the use of resources in public health to tackle obesity-related health problems in
2 the most affected populations.

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ETHICS APPROVAL

Since this study used publicly available de-identified data, approval from an Institutional Review Board was not required, as indicated in the Federal Policy for the Protection of Human Subjects (detailed in 45 CFR part 46) 35.

DATA AVAILABILITY STATEMENT

All data utilized are publicly and freely available from the NHANES website at https://wwwn.cdc.gov/nchs/nhanes/

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AUTHOR CONTRIBUTIONS

OOW was responsible for the conception and design of the study. OOW contributed to the statistical analysis. OOW and TS contributed to the interpretation of data and critical revision of the manuscript. OOW and TS drafted the final version of the manuscript and agreed to the submitted version of the manuscript. OOW is the manuscript's guarantor. OOW accepts full responsibility for the work and the conduct of the study, had access to the data, and controlled the decision to submit for publication.

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COMPETING INTERESTS

OOW is the lead author of the original article describing the development and validation of RFM. OOW currently works as an editor for The Lancet group. TS declares no conflict of interest.

TRANSPARENCY STATEMENT

OW (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned have been explained.

PATIENT AND PUBLIC INVOLVEMENT

Patients and the public were not involved in this study. This study will be available to the public once it is published in the scientific literature.

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FIGURE LEGENDS

Figure 1. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. Body fat-defined obesity was determined using the relative fat mass (RFM). RFM was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 2. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

Figure 3. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020. Trend lines were smoothed using the Lowes method on weighted prevalence estimates. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men.

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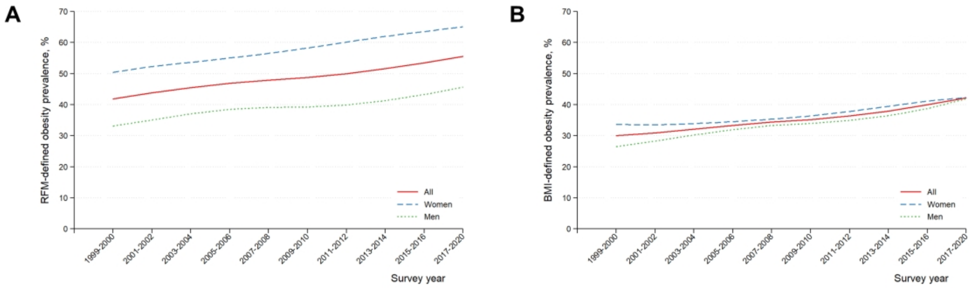

Figure 1. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by sex: 1999-2000 through 2017-March 2020.

762x228mm (96 x 96 DPI)

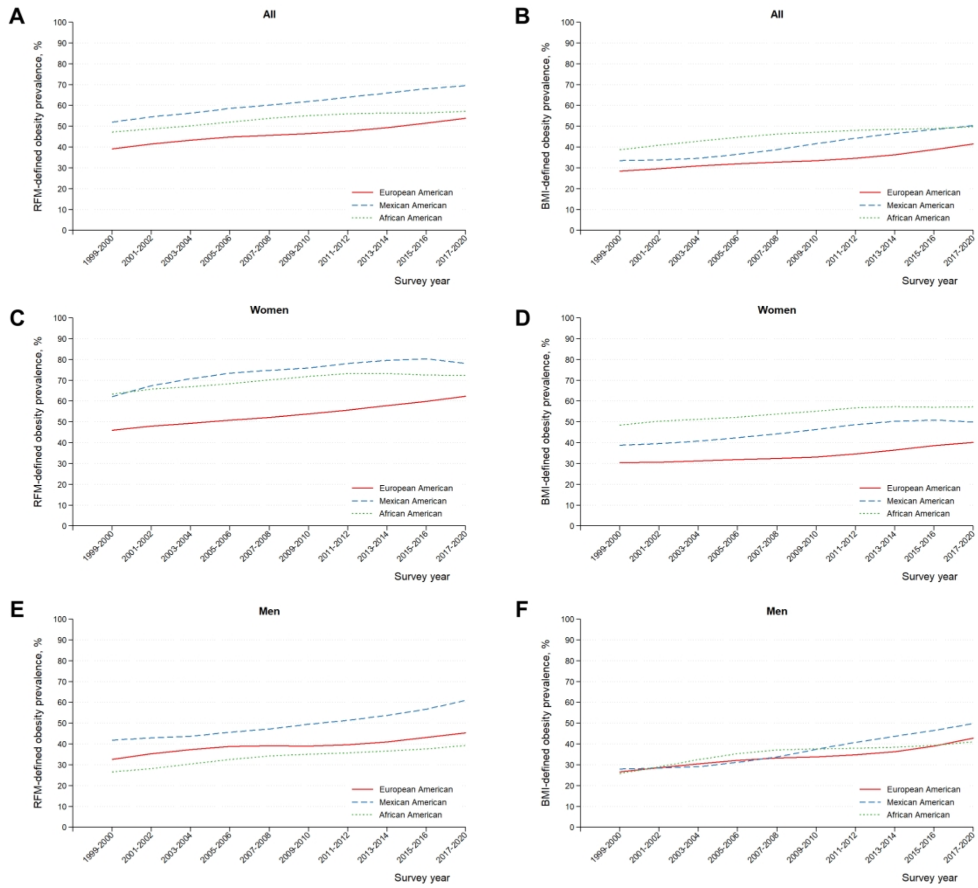

Figure 2. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.

762x711mm (96 x 96 DPI)

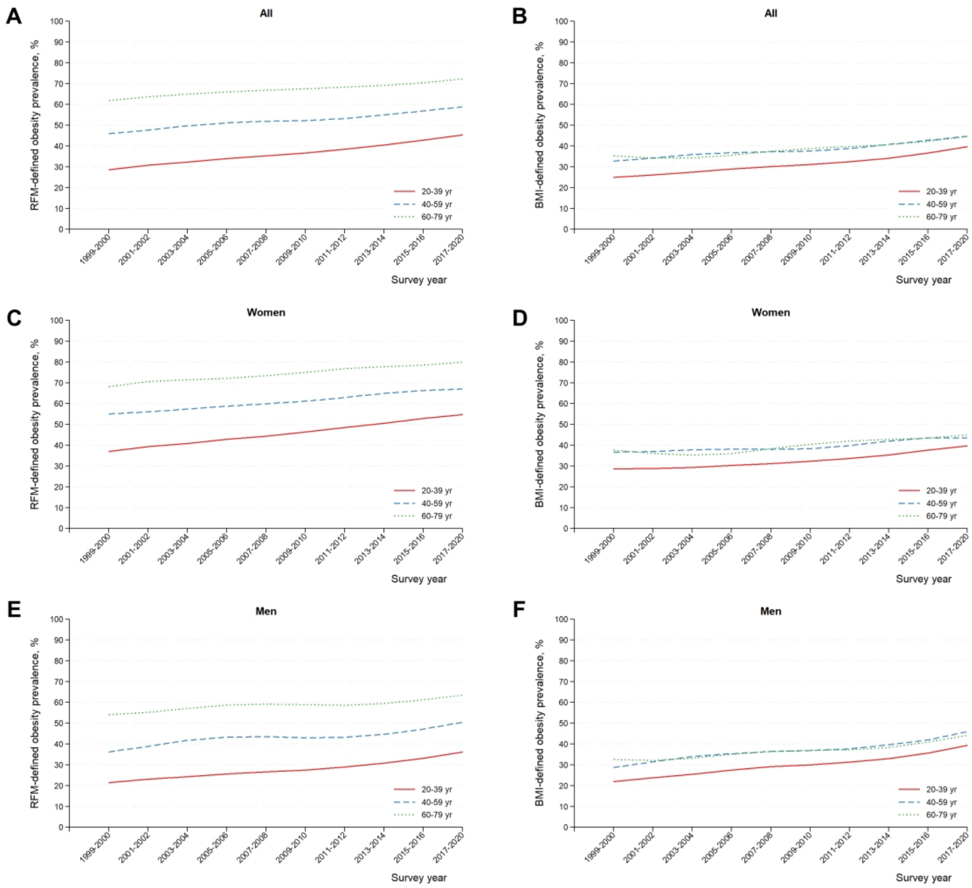

Figure 3. Age-adjusted U.S. adult prevalence trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.

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Supplemental material

Temporal trends in obesity defined by the relative fat mass (RFM) index among adults in the United States from 1999 to 2020: population-based study

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Supplemental Table 1. Prevalence of general and abdominal obesity among study participants by sex and ethnicity.*

	Mexican American	European American	African American
Women	n=4,204	n=9,710	n=5,417
RFM-defined obesity, % (95% CI) †	72.7 (70.3-75.1)	56.6 (55.2-58.0)	69.9 (68.3-71.4)
BMI-defined obesity, % (95% CI) ‡	45.5 (43.2-47.9)	35.4 (34.0-36.7)	54.5 (52.9-56.1)
Abdominal obesity, % (95% CI) §	71.5 (69.2-73.8)	62.8 (61.4-64.1)	75.0 (73.6-76.3)
Men	n=4,212	n=9,981	n=5,256
RFM-defined obesity, % (95% CI) †	47.0 (44.9-49.1)	41.7 (40.3-43.2)	33.7 (32.1-35.3)
BMI-defined obesity, % (95% CI) ‡	38.4 (36.3-40.4)	35.0 (33.6-36.5)	35.9 (34.2-37.6)
Abdominal obesity, % (95% CI) §	41.2 (39.1-43.2)	47.6 (46.2-49.1)	37.5 (35.9-39.0)

* Sample size represents unweighted data. Estimates represent weighted data.
BMI, body mass index; CI, confidence interval; IQR, interquartile range; RFM, relative fat mass; SD, standard deviation.
† Defined as an RFM ≥40% for women and ≥30% for men. Estimates are not adjusted for age.
‡ Defined as a BMI ≥30 kg/m^2. Estimates are not adjusted for age.
§ Defined as a waist circumference >88 cm for women and >102 cm for men, according to the recommendations of the National Cholesterol Education Program (NCEP) Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). Estimates are not adjusted for age.

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Supplemental Table 2. Characteristics of study participants with missing data.*

Characteristic	All†	With complete data	With missing data
Sample size, n (%)	50,283 (100)	47,667 (95.6)	2,616 (4.4)
Median age (IQR), years	45 (33-58)	45 (33-58)	47 (34-63)
Male sex, n (%)	24,954 (49.2)	23,736 (49.4)	1,218 (45.4)
Ethnicity, n (%)			
Mexican American	8,827 (8.3)	8,416 (8.3)	411 (8.6)
European American	20,618 (66.9)	19,691(67.2)	927 (58.6)
African American	11,433 (11.4)	10,673(11.2)	760 (16.7)
Other/multi-racial	9,405 (13.4)	8,887 (13.2)	518 (16.1)

* Sample size represents unweighted data. Estimates represent weighted data.
† This group includes participants with complete data and participants with missing data on body weight (n=666), height (n=596), and waist circumference (n=2,340).

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Supplemental Table 3. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by ethnicity: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity			BMI-defined obesity		
	Mexican American	European American	African American	Mexican American	European American	African American
All participants	n=8,416	n=19,691	n=10,673	n=8,416	n=19,691	n=10,673
Prevalence, % (95% CI)						
1999-2000	53.1 (48.5-57.7)	39.4 (34.2-44.6)	48.3 (45.0-51.7)	34.7 (28.9-40.6)	28.3 (23.9-32.7)	39.8 (35.7-43.8)
2001-2002	52.1 (47.1-57.1)	41.0 (38.9-43.1)	46.0 (42.9-49.0)	30.7 (26.7-34.7)	29.8 (27.0-32.6)	38.3 (34.4-42.3)
2003-2004	60.1 (55.2-65.0)	44.8 (41.0-48.6)	52.7 (49.4-56.0)	36.9 (32.2-41.6)	30.6 (27.7-33.4)	45.1 (39.7-50.5)
2005-2006	55.4 (51.8-58.9)	44.9 (40.7-49.2)	51.5 (47.9-55.1)	33.8 (31.2-36.4)	33.1 (29.2-36.9)	45.9 (42.3-49.5)
2007-2008	62.2 (56.2-68.2)	45.7 (41.5-49.9)	52.5 (49.1-56.0)	39.9 (33.8-46.1)	32.4 (28.7-36.0)	43.7 (39.2-48.1)
2009-2010	61.5 (59.4-63.6)	46.4 (43.0-49.8)	56.8 (51.8-61.8)	40.5 (36.7-44.4)	34.2 (31.1-37.2)	49.4 (44.2-54.5)
2011-2012	63.6 (58.6-68.6)	46.8 (42.8-50.9)	57.4 (54.8-60.0)	46.1 (41.3-50.8)	33.0 (29.4-36.5)	48.4 (44.6-52.3)
2013-2014	65.0 (61.2-68.9)	49.4 (46.6-52.3)	55.0 (50.0-59.9)	46.1 (41.0-51.2)	36.6 (33.6-39.5)	47.9 (43.7-52.0)
2015-2016	70.3 (67.0-73.5)	51.2 (46.9-55.4)	56.6 (52.0-61.2)	48.7 (44.3-53.1)	38.5 (34.5-42.5)	48.7 (43.8-53.5)
2017-2020	68.8 (64.5-73.1)	54.1 (50.8-57.4)	57.1 (54.4-59.8)	50.2 (46.8-53.5)	41.7 (37.7-45.6)	49.9 (47.2-52.6)
Prevalence change†	15.7 (9.6-21.7)	14.7 (8.8-20.5)	8.7 (4.6-12.9)	15.4 (9.0-21.9)	13.4 (7.7-19)	10.2 (5.5-14.8)
P for non-linearity‡	0.58	0.97	0.25	0.52	0.10	0.35
P value for trend‡	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Women	n=4,204	n=9,710	n=5,417	n=4,204	n=9,710	n=5,417
Prevalence, % (95% CI)						
1999-2000	62.8 (55.1-70.5)	46.2 (40.2-52.1)	64.2 (59.6-68.8)	39.8 (31.1-48.5)	30.3 (25.2-35.3)	49.2 (42.5-56.0)
2001-2002	66.4 (58.6-74.3)	47.8 (44.2-51.4)	64.2 (59.0-69.4)	37.0 (30.2-43.8)	31.1 (27.6-34.7)	48.7 (42.8-54.7)
2003-2004	75.0 (68.3-81.6)	50.6 (43.9-57.2)	70.7 (65.5-75.8)	42.7 (36.0-49.3)	30.3 (25.7-34.8)	53.9 (46.3-61.5)
2005-2006	72.0 (66.4-77.5)	49.9 (45.6-54.2)	66.2 (60.9-71.5)	41.3 (34.8-47.7)	32.8 (28.3-37.3)	52.7 (48.5-56.9)
2007-2008	74.8 (71.2-78.4)	52.3 (47.5-57.2)	67.9 (63.2-72.6)	44.7 (38.8-50.6)	32.8 (28.7-36.9)	49.2 (45.2-53.3)
2009-2010	77.8 (74.8-80.9)	53.4 (49.5-57.2)	74.6 (68.6-80.7)	45.7 (42.0-49.3)	32.1 (29.0-35.3)	58.5 (52.0-64.9)
2011-2012	74.6 (66.2-83.0)	56.3 (51.4-61.3)	74.9 (72.1-77.8)	49.0 (40.4-57.5)	33.3 (28.0-38.7)	57.9 (53.5-62.3)
2013-2014	81.2 (74.7-87.6)	57.3 (53.4-61.2)	72.5 (68.8-76.2)	51.7 (45.2-58.3)	37.6 (33.7-41.6)	56.7 (53.1-60.3)
2015-2016	84.6 (79.7-89.5)	60.0 (56.2-63.8)	72.3 (68.3-76.4)	52.2 (48.4-56.1)	38.5 (34.0-43.0)	57.1 (52.6-61.5)
2017-2020	76.9 (70.8-83.1)	62.3 (59.0-65.7)	72.4 (68.6-76.2)	49.6 (43.1-56.0)	40.3 (36.4-44.2)	57.3 (53.7-60.9)
Prevalence change†	14.1 (4.7-23.6)	16.2 (9.7-22.7)	8.3 (2.5-14.0)	9.8 (-0.6-20.1)	10.0 (3.9-16.1)	8.1 (0.8-15.4)
P for non-linearity§	0.026	0.77	0.34	0.76	0.12	0.71
P value for trend§		<0.001	<0.001	<0.001	<0.001	<0.001
Men	n=4,212	n=9,981	n=5,256	n=4,212	n=9,981	n=5,256
Prevalence, % (95% CI)						
1999-2000	42.9 (39.4-46.5)	33.2 (28.6-37.7)	27.5 (23.1-31.9)	29.1 (24.6-33.6)	26.8 (22.9-30.6)	26.8 (23.0-30.6)
2001-2002	40.6 (34.7-46.4)	34.1 (30.9-37.4)	25.8 (21.4-30.1)	25.9 (21.9-29.9)	28.3 (25.3-31.4)	26.5 (22.8-30.1)
2003-2004	47.1 (39.3-54.8)	38.9 (35.5-42.4)	31.2 (27.2-35.2)	31.7 (25.0-38.3)	30.9 (27.0-34.7)	34.2 (27.7-40.7)
2005-2006	40.8 (34.1-47.4)	40.0 (35.1-44.9)	34.1 (28.3-39.9)	27.4 (22.7-32.1)	33.3 (28.7-37.9)	37.2 (31.2-43.2)
2007-2008	50.9 (43.3-58.4)	38.8 (34.7-42.9)	33.8 (28.8-38.9)	35.1 (28.0-42.1)	32.0 (27.9-36.0)	36.9 (31.0-42.7)
2009-2010	47.8 (44.6-51.0)	39.4 (34.6-44.3)	35.4 (31.4-39.5)	36.3 (30.9-41.6)	36.1 (30.8-41.3)	38.6 (33.1-44.0)
2011-2012	52.5 (45.6-59.4)	37.6 (34.3-40.9)	36.4 (32.3-40.5)	42.7 (36.0-49.5)	32.5 (29.7-35.3)	37.5 (32.8-42.2)
2013-2014	52.4 (48.6-56.3)	41.7 (38.1-45.3)	35.2 (28.6-41.8)	43.6 (38.2-49.1)	35.6 (31.6-39.5)	37.9 (32.5-43.4)
2015-2016	55.9 (50.9-60.8)	42.3 (36.5-48.1)	38.1 (31.9-44.2)	45.3 (38.5-52.1)	38.4 (32.5-44.3)	38.9 (33.5-44.2)
2017-2020	61.2 (55.8-66.6)	45.8 (40.3-51.2)	39.1 (35.4-42.8)	50.3 (46.1-54.5)	43.1 (36.9-49.2)	41.2 (36.7-45.7)
Prevalence change†	18.3 (12.0-24.5)	12.6 (5.7-19.5)	11.6 (6.1-17.1)	21.2 (15.3-27.1)	16.3 (9.3-23.3)	14.4 (8.7-20.1)
P for non-linearity§	0.21	0.80	0.50	0.24	0.45	0.08
P value for trend§	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.

† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).

‡ Adjusted for age and sex.

§ Adjusted for age.

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Supplemental Table 4. Age-adjusted U.S. adult prevalence temporal trends in RFM-defined obesity by age group: 1999-2000 through 2017-March 2020.*

	RFM-defined obesity				BMI-defined obesity		
	20-39 years old	40-59 years old	60-79 years old		20-39 years old	40-59 years old	60-79 years old
All participants	n=16,747	n=16,912	n=14,008		n=16,747	n=16,912	n=14,008
Prevalence, 95% CI							
1999-2000	29.0 (24.5-33.6)	46.9 (40.5-53.4)	61.8 (58.1-65.6)		25.4 (21.5-29.3)	33.2 (26.9-39.4)	35.4 (31.3-39.5)
2001-2002	30.2 (27.2-33.1)	45.0 (42.2-47.8)	63.8 (61.3-66.3)		25.3 (22.4-28.1)	33.2 (29.9-36.4)	33.7 (30.7-36.8)
2003-2004	34.2 (31.2-37.1)	51.2 (47.8-54.6)	65.8 (62.5-69.0)		28.1 (24.6-31.7)	35.9 (32.1-39.7)	33.0 (29.4-36.5)
2005-2006	32.6 (28.7-36.5)	53.2 (47.9-58.5)	66.0 (62.2-69.8)		28.5 (24.1-32.9)	40.1 (35.6-44.6)	34.9 (31.5-38.3)
2007-2008	35.5 (31.1-39.9)	51.6 (48.5-54.7)	66.1 (62.4-69.8)		30.2 (26.2-34.3)	35.7 (32.4-39.1)	37.4 (33.8-40.9)
2009-2010	37.2 (32.8-41.6)	50.5 (47.7-53.4)	68.5 (65.2-71.8)		32.5 (28.7-36.3)	36.0 (33.9-38.2)	41.8 (38.0-45.7)
2011-2012	37.7 (33.1-42.3)	53.6 (49.9-57.3)	68.0 (62.9-73.1)		30.4 (26.2-34.5)	39.3 (36.1-42.5)	38.3 (33.8-42.9)
2013-2014	40.0 (36.2-43.9)	54.5 (50.3-58.7)	68.8 (64.6-73.0)		34.4 (31.3-37.5)	40.6 (36.2-45.1)	39.3 (35.2-43.5)
2015-2016	43.0 (39.0-47.0)	57.1 (50.6-63.6)	69.8 (64.7-74.9)		36.0 (32.2-39.8)	42.8 (37.5-48.2)	42.8 (37.5-48.2)
2017-2020	44.6 (40.5-48.6)	59.4 (56.2-62.7)	70.6 (67.2-74.0)		39.8 (35.6-44.0)	44.3 (41.2-47.4)	42.7 (39.1-46.3)
Prevalence change†	15.5 (9.7-21.3)	12.5 (5.6-19.4)	8.8 (3.9-13.6)		14.5 (8.9-20.0)	11.2 (4.5-17.8)	7.3 (2.0-12.5)
P for non-linearity‡	0.65	0.94	0.25		0.48	0.21	0.46
P value for trend‡	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Women	n=8,295	n=8,684	n=6,952		n=8,295	n=8,684	n=6,952
Prevalence, 95% CI							
1999-2000	36.9 (30.9-42.9)	56.2 (48.9-63.5)	67.7 (63.3-72.2)		28.7 (23.6-33.7)	37.4 (30.2-44.5)	37.4 (31.6-43.2)
2001-2002	39.9 (35.3-44.5)	52.9 (48.1-57.6)	72.0 (69.3-74.7)		28.9 (24.1-33.6)	35.0 (30.2-39.8)	36.6 (32.0-41.2)
2003-2004	42.0 (35.8-48.2)	59.7 (54.9-64.5)	73.0 (68.3-77.7)		29.0 (23.8-34.1)	38.1 (32.3-43.9)	33.6 (28.5-38.7)
2005-2006	40.3 (35.3-45.4)	58.7 (53.5-63.8)	71.3 (66.4-76.2)		29.2 (24.1-34.3)	40.7 (35.9-45.6)	34.8 (28.4-41.2)
2007-2008	46.1 (40.4-51.7)	60.0 (56.2-63.8)	69.8 (64.5-75.1)		33.0 (27.3-38.6)	37.6 (32.6-42.5)	36.0 (30.0-41.9)
2009-2010	46.4 (40.6-52.2)	59.3 (55.5-63.1)	78.5 (75.8-81.3)		31.8 (28.2-35.4)	35.5 (31.7-39.3)	45.1 (40.7-49.5)
2011-2012	47.6 (42.1-53.1)	64.6 (60.1-69.0)	76.7 (69.8-83.5)		31.9 (28.0-35.9)	39.4 (35.1-43.6)	42.1 (34.4-49.7)
2013-2014	50.8 (46.6-55.1)	63.3 (58.1-68.5)	78.0 (74.6-81.4)		36.6 (33.9-39.3)	43.6 (38.2-48.9)	40.2 (34.1-46.2)
2015-2016	53.3 (48.9-57.8)	69.1 (62.7-75.5)	77.1 (70.6-83.6)		37.1 (33.5-40.7)	44.8 (38.4-51.1)	45.0 (37.3-52.8)
2017-2020	53.3 (48.5-58.0)	67.9 (63.6-72.3)	81.0 (76.4-85.6)		39.9 (35.3-44.4)	42.8 (38.9-46.7)	45.4 (40.9-49.8)
Prevalence change†	16.4 (9.1-23.7)	11.7 (3.6-19.9)	13.3 (7.1-19.5)		11.2 (4.7-17.7)	5.5 (-2.3-13.2)	8.0 (1.0-15.0)
P for non-linearity§	0.16	0.39	0.99		0.44	0.42	0.97
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Men	n=8,452	n=8,228	n=7,056		n=8,452	n=8,228	n=7,056
Prevalence, 95% CI							
1999-2000	22.4 (18.0-26.8)	36.8 (30.4-43.2)	54.7 (49.9-59.5)		22.7 (18.3-27.0)	28.8 (22.8-34.8)	33.2 (28.2-38.1)
2001-2002	20.8 (17.4-24.1)	37.1 (33.5-40.7)	53.5 (49.8-57.1)		21.7 (18.5-24.9)	31.2 (28.0-34.5)	30.4 (26.0-34.8)
2003-2004	26.9 (23.3-30.4)	42.3 (36.7-47.9)	57.2 (52.5-62.0)		27.4 (22.5-32.3)	33.6 (28.4-38.9)	32.3 (27.4-37.2)
2005-2006	25.4 (20.1-30.7)	47.4 (40.5-54.2)	59.8 (54.8-64.7)		27.6 (22.0-33.1)	39.5 (33.1-45.9)	34.7 (29.9-39.5)
2007-2008	25.4 (21.2-29.5)	42.8 (37.8-47.8)	61.8 (57.7-65.9)		27.6 (23.8-31.4)	33.7 (28.8-38.5)	39.2 (34.8-43.5)
2009-2010	28.5 (23.6-33.3)	41.6 (37.7-45.5)	56.9 (51.1-62.7)		33.2 (27.2-39.2)	36.6 (33.0-40.2)	37.5 (32.3-42.8)
2011-2012	28.4 (23.9-33.0)	42.3 (38.0-46.6)	58.1 (52.1-64.2)		28.9 (23.5-34.2)	39.1 (35.6-42.5)	34.2 (29.2-39.2)
2013-2014	30.0 (25.5-34.5)	45.5 (40.3-50.7)	58.6 (51.6-65.5)		32.5 (28.1-36.8)	37.7 (32.2-43.3)	38.6 (30.7-46.4)
2015-2016	33.1 (28.3-38.0)	44.5 (36.5-52.6)	61.4 (55.4-67.5)		35.0 (29.0-41.0)	40.8 (34.6-47.1)	40.2 (34.9-45.5)
2017-2020	35.9 (30.2-41.5)	50.8 (46.2-55.4)	58.8 (54.3-63.3)		39.5 (33.1-46.0)	45.8 (41.1-50.6)	39.7 (34.0-45.4)
Prevalence change†	13.4 (6.5-20.4)	14.0 (6.4-21.6)	4.1 (-2.3-10.5)		16.8 (9.3-24.4)	17.0 (9.7-24.4)	6.5 (-0.7-13.8)
P for non-linearity§	0.47	0.42	0.16		0.97	0.41	0.24
P value for trend§	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

* Prevalence estimates represent weighted data. The relative fat mass (RFM) was calculated as follows: RFM = 64 − (20 × height/waist circumference) + (12 × sex); sex equals 0 for men and 1 for women. Obesity was diagnosed if RFM was 40% or higher for women and RFM was 30% or higher for men. CI denotes confidence interval.
† Absolute difference (prevalence in 2017-2020 minus the prevalence in 1999-2000).
‡ Adjusted for sex and ethnicity.
§ Adjusted for ethnicity.

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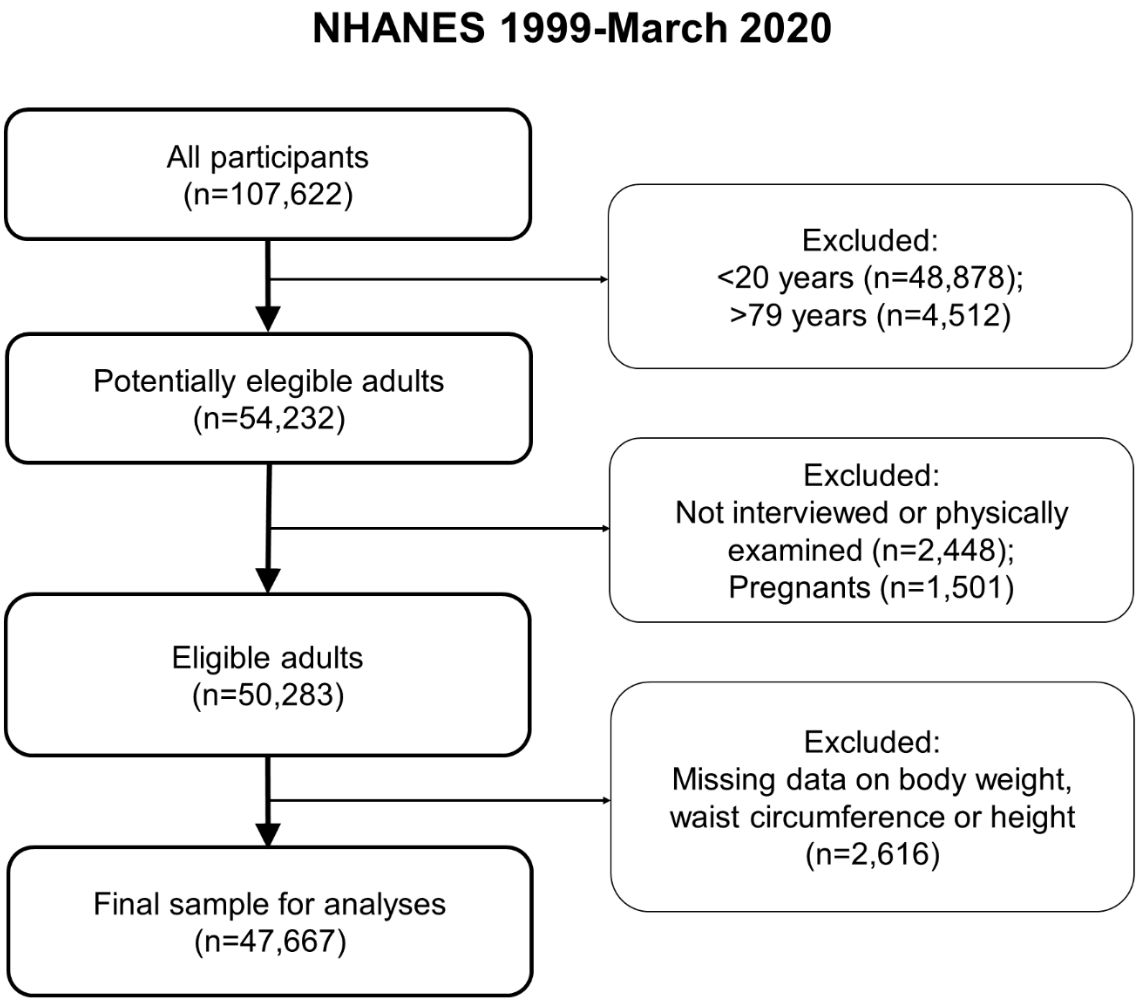

Supplemental Figure 1. Selection of study participants.

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
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	3-4
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	6-7
Objectives	3	State specific objectives, including any prespecified hypotheses	7
Methods			
Study design	4	Present key elements of study design early in the paper	8
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	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, 10
		(*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	NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	9-10
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	*8-10*
Bias	9	Describe any efforts to address potential sources of bias	9-10
Study size	10	Explain how the study size was arrived at	8
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	9-10
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	9-10
		(*b*) Describe any methods used to examine subgroups and interactions	9-10
		(*c*) Explain how missing data were addressed	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	9-10
		(*e*) Describe any sensitivity analyses	10

Continued on next page

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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	11
		(b) Give reasons for non-participation at each stage	11
		(c) Consider use of a flow diagram	Suppl Fig 1
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	Suppl Table 1
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	NA
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	*NA*
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	*NA*
		Cross-sectional study—Report numbers of outcome events or summary measures	*11-18*
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	NA
		(*b*) Report category boundaries when continuous variables were categorized	12-18
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	11-18
Discussion			
Key results	18	Summarise key results with reference to study objectives	19
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	23-24
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	24
Generalisability	21	Discuss the generalisability (external validity) of the study results	24
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	26

*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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