Cooking oil/fat consumption and deaths from cardiometabolic diseases and other causes: prospective analysis of 521,120 individuals

Yu Zhang1*, Pan Zhuang1, Fei Wu2, Wei He3, Lei Mao2, Wei Jia1, Yiju Zhang1, Xiaqian Chen1 and Jingjing Jiao2*

Abstract

**Background:** Increasing evidence highlights healthy dietary patterns and links daily cooking oil intake with chronic diseases including cardiovascular disease (CVD) and diabetes. However, food-based evidence supporting the consumption of cooking oils in relation to total and cardiometabolic mortality remains largely absent. We aim to prospectively evaluate the relations of cooking oils with death from cardiometabolic (CVD and diabetes) and other causes.

**Methods:** We identified and prospectively followed 521,120 participants aged 50–71 years from the National Institutes of Health-American Association of Retired Persons Diet and Health Study. Individual cooking oil/fat consumption was assessed by a validated food frequency questionnaire. Hazard ratios (HRs) and 95% confidence intervals (CIs) were estimated for mortality through the end of 2011.

**Results:** Overall, 129,328 deaths were documented during a median follow-up of 16 years. Intakes of butter and margarine were associated with higher total mortality while intakes of canola oil and olive oil were related to lower total mortality. After multivariate adjustment for major risk factors, the HRs of cardiometabolic mortality for each 1-tablespoon/day increment were 1.08 (95% CI 1.05–1.10) for butter, 1.06 (1.05–1.08) for margarine, 0.99 (0.95–1.03) for corn oil, 0.98 (0.94–1.02) for canola oil, and 0.96 (0.92–0.99) for olive oil. Besides, butter consumption was positively associated with cancer mortality. Substituting corn oil, canola oil, or olive oil for equal amounts of butter and margarine was related to lower all-cause mortality and mortality from certain causes, including CVD, diabetes, cancer, respiratory disease, and Alzheimer’s disease.

(Continued on next page)
Conclusions: Consumption of butter and margarine was associated with higher total and cardiometabolic mortality. Replacing butter and margarine with canola oil, corn oil, or olive oil was related to lower total and cardiometabolic mortality. Our findings support shifting the intake from solid fats to non-hydrogenated vegetable oils for cardiometabolic health and longevity.

Keywords: Cooking oils, Cardiometabolic mortality, Total mortality, AARP Diet and Health Study

Background
Cooking oils/fats are known as edible oils from vegetable or animal origin and used for cuisine or salad preparation worldwide. To meet consumption needs, global vegetable oil production was closed to 198 million metric tons in 2018–2019. For animal or artificial cooking fats, 187.1 million Americans used margarine or margarine spread while butter consumption in the USA reached 5.8 pounds per capita in 2019 [1]. Growing controversy focused on the role of cooking oils/fats in the incidence of various chronic disorders including cardiovascular disease (CVD) events. Importantly, the well-known functions of saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs), or polyunsaturated fatty acids (PUFAs) could not apparently translate to cardiometabolic health effects of cooking oils/fats [2]. Thus, increasing evidence supports shifting away from isolated fatty acids toward food-based patterns for linking dietary cooking oils/fats with all-cause mortality, fatal and nonfatal CVD events [3, 4]. Vegetable cooking oils are regarded as the healthier choice as they contain more unsaturated fatty acids than animal oils. Canola oil and corn oil may ameliorate blood lipid profile and protect against CVD risk factors [5, 6], whereas butter raises total and LDL cholesterol levels [7]. Canola oil- or olive oil-enriched diet could improve glycemic control in patients with type 2 diabetes [6, 8]. However, only a few studies have provided weak evidence of cooking oil/fat consumption in relation to all-cause and cardiometabolic mortality [9–11]. The associations of lard, canola oil, and corn oil consumption with cardiometabolic mortality remain lacking.

To fill these gaps, we assessed the long-term associations of 6 typical cooking oils/fats, including butter, margarine, lard, corn oil, canola oil, and olive oil, with all-cause, cardiometabolic, and other major cause-specific mortality in the National Institutes of Health-American Association of Retired Persons (NIH-AARP) Diet and Health Study.

Methods
Study population
The NIH-AARP Diet and Health Study is a large prospective cohort consisting of 617,119 US men and women aged 50–71 years. At baseline in 1995–1996, validated questionnaires were mailed to 3.5 million AARP members from 6 US states (California, Florida, Louisiana, New Jersey, North Carolina, and Pennsylvania) and 2 metropolitan areas (Atlanta, Georgia, and Detroit, Michigan) to collect data on demographics, lifestyle, and dietary characteristics. All participants provided written informed consent. Among 567,169 participants who completed the questionnaires, we excluded participants who were proxy responders, had duplicate records, decided to withdraw, moved or died before entry, and had null person-years of follow-up or extreme total energy intake (<800 or >4200 kcal/day for men and <600 or >3500 kcal/day for women [12]). Finally, 521,120 persons were selected (Additional file 1: Fig. S1), which was approved by the Institutional Review Board of the National Cancer Institute.

Assessment of diet and cooking oils/fats
Dietary intake was assessed at baseline using a 124-item self-administered food frequency questionnaire (FFQ) developed as the diet history questionnaire (DHQ) and validated by National Cancer Institute [13]. The frequency and portion sizes of food consumption were recorded during the past year. Some questions were asked to collect the frequency of oils/fats used in cooking and added after cooking, such as “How often was oil, butter, or margarine used to fry or saute the vegetables, eggs, or meat you ate?” followed by options from “never” to “4 or more times per day” and “When you ate each of the foods listed in this table, how often was butter or margarine added after cooking or at table?” followed by options from “almost never or never” to “more than half the time.” Participants were also asked to select the types of oils/fats they regularly used, including butter, margarine, lard, corn oil, canola oil, and olive oil. Portion sizes for individual oils/fats were estimated based on the 1994–1996 USDA Continuing Survey of Food Intakes by Individuals (CSFII) [14] and intakes of cooking oils/fats were then calculated by multiplying the frequency of consumption with the corresponding portion size derived from CSFII. Cooking oils/fats included in foods were also accounted for by asking questions such as the frequency of consuming butter or margarine on bread or rolls. Three typical solid fats (butter, margarine, and lard) and 3 commonly consumed vegetable oils (olive
the functions of energy density (g 2000 kcal)
Intakes of individual cooking oils/fats were expressed as
Statistical analysis
exceeds 99% in this cohort study. The complete follow-up rate for mortality
curred earlier. The complete follow-up rate for mortality
of the baseline questionnaire to the time of death or the
end of follow-up (31 December 2011), whichever oc-
curred earlier. The complete follow-up rate for mortality
exceeds 99% in this cohort study.

Mortality
All the participants were followed for address changes
via the US Postal Service National Change of Address
database, responses to study-related mailings, and direct
notifications from cohort members. Deaths were identi-
ﬁed by annual linkage to the Social Security Administra-
Death Master File and conﬁrmed by follow-up
searches of the National Death Index Plus. The Inter-
national Classiﬁcation of Diseases 9th and 10th Revision
codes were used to classify death causes (Additional ﬁle 1:
Table S1). Follow-up was calculated from the return date
date of the baseline questionnaire to the time of death or the
end of follow-up (31 December 2011), whichever oc-
curred earlier. The complete follow-up rate for mortality
exceeds 99% in this cohort study.

Statistical analysis
Intakes of individual cooking oils/fats were expressed as
the functions of energy density (g 2000 kcal⁻¹ day⁻¹)
using the nutrient density method [16]. We used Cox
proportional hazards regression models to estimate haz-
ard ratios (HRs) and 95% conﬁdence intervals (CIs) for
mortality. Model 1 was adjusted for age and sex at base-
line. Model 2 was further adjusted for race, marital sta-
tus, education, household income, body mass index
(BMI), alcohol, smoking, vigorous physical activity, usual
activity at work, perceived health condition, and history
of cancer, heart disease, stroke, and diabetes. Our ﬁnal
multivariate model 3 was additionally adjusted for HEI-
2015 (with no fat components), total energy intake, and
consumption of remaining oils where appropriate. Tests
for linear trend were performed by assigning median
values to corresponding categories of intake and model-
ing the values as continuous variables. We also esti-
imated the associations of hypothetical substitution of 1
tablespoon/day olive oil, canola oil, or corn oil for the
equivalent amounts of butter and margarine with mor-
tality by simultaneously including individual cooking oils
as continuous variables and total cooking oil intake in
the same multivariable model (substitution model), which also contained total energy intake, HEI, and other
non-dietary covariates. Total oil/fat intake was held con-
stant in this model. By leaving butter or margarine out
of this model, regression coefﬁcients of the remaining
oils bear the interpretations as the theoretical effects of
substituting one of these oils for the equivalent amounts
of butter or margarine while holding other oils un-
changed. A ﬁxed 1-tablespoon/day increase corresponds
to an increment of approximately 14 g/day butter/mar-
garine or 8 g/day vegetable oils [9, 17].

We further separately analyzed the associations for
stick margarine and tub/soft margarine, respectively.
Subgroup analyses were also conducted according to
important potential effect modiﬁers and P values for
interactions were tested by the likelihood-ratio test.
Sensitivity analyses were performed by excluding par-
ticipants who had extreme BMI (< 18.5 or > 40 kg/m²);
using the propensity-score adjustment [18] to further
control for potential residual confounding from mea-
sured variables; further adjusting for history of hyper-
tension and hypercholesteremia and the use of aspirin
and multivitamins; excluding the initial 4years of
follow-up; excluding those who had CVD, cancer, or
diabetes at baseline; or ending up the follow-up at
the year 2004 (midpoint, 8 years of follow-up). We
also tested whether the associations were affected by
the use of cholesterol-lowering medications among
persons who provided this information in the resurvey
(n = 293,918).

Statistical analyses were performed with SAS version
9.4 (SAS Institute, Cary, NC, USA). Tests were two-
sided and the signiﬁcance was deﬁned as P < 0.05.

Results
Population characteristics and cooking oil/fat
consumption
During an average of 16 years of follow-up (7,307,097
person-years), 129,328 individuals died, including 85,037
men and 44,291 women. At baseline, participants with
higher butter consumption were less likely to be mar-
rried, have prevalent heart disease, and use aspirin, and
they had lower protein intake and lower HEI scores. Par-
ticipants with higher margarine consumption were more
likely to have a higher BMI, use aspirin, and have heart
disease, stroke, and diabetes, and they had lower
household income and lower alcohol intake. The median
intakes in the highest tertile among con-
sumers were 13.7 g 2000 kcal⁻¹ day⁻¹ for butter and
20.6 g 2000 kcal⁻¹ day⁻¹ for margarine, respectively
(Table 1). Participant characteristics according to
corn oil, canola oil, and olive oil consumption are
shown in Additional ﬁle 1: Table S2. The Spearman corre-
lations between individual cooking oil/fat consumption
are presented in Additional ﬁle 1: Table S3.
Butter and margarine consumption was strongly associated with higher all-cause mortality in all multivariable-adjusted models. In contrast, intakes of canola oil and olive oil were both inversely associated with all-cause mortality. Corn oil consumption was related to higher all-cause mortality after adjusting for age and sex, but the association became non-significant after adjusting further covariates (Table 2). Compared to non-consumers, the multivariable HRs of all-cause mortality in the highest categories were 1.09 (95% CI, 1.07–1.11) for butter (P-trend < 0.001), 1.07 (95% CI, 1.05–1.10) for margarine (P-trend < 0.001), 0.97 (95% CI, 0.95–0.99) for canola oil (P-trend < 0.001), and 0.96 (95% CI, 0.95–0.98) for olive oil (P-trend < 0.001) (Table 2). Every 1-tablespoon/day increment of butter or margarine consumption was related to 7% and 4% higher all-cause mortality, respectively.

### Table 1: Baseline characteristics of participants from the NIH-AARP Diet and Health Study according to butter and margarine consumption

| Characteristics | Butter consumption | Margarine consumption |
|-----------------|--------------------|-----------------------|
|                 | Non-consumers | T1 | T2 | T3 | Non-consumers | T1 | T2 | T3 |
| Range (g 2000 kcal⁻¹ d⁻¹) | 0 | ≤ 3.1 | 3.2–8.5 | ≥ 8.6 | 0 | ≤ 5.7 | 5.8–13.7 | ≥13.8 |
| n | 303,987 | 72,377 | 72,378 | 72,378 | 134,374 | 128,915 | 128,916 | 128,915 |
| Age (y) | 63.0 | 62.2 | 62.5 | 63.1 | 62.5 | 62.3 | 62.8 | 63.6 |
| Male (%) | 58.4 | 65.1 | 61.2 | 51.7 | 56.3 | 64.3 | 62.7 | 52.0 |
| BMI (kg/m²) | 26.4 | 26.1 | 26.5 | 26.4 | 26.1 | 26.2 | 26.6 | 26.5 |
| Race (%) | | | | | | | | |
| White | 92.3 | 89.4 | 91.3 | 92.6 | 91.7 | 89.9 | 92.5 | 93.0 |
| Black | 3.8 | 3.1 | 3.6 | 3.4 | 3.6 | 3.4 | 3.5 | 4.0 |
| Hispanic | 1.6 | 3.0 | 2.1 | 1.3 | 1.7 | 2.7 | 1.7 | 1.1 |
| Asian | 0.9 | 2.6 | 1.4 | 0.9 | 1.2 | 2.1 | 0.8 | 0.5 |
| Married (%) | 69.9 | 68.1 | 67.9 | 63.0 | 65.5 | 69.7 | 71.0 | 67.6 |
| Annual household income (USD)ᵃ | 47,243 | 51,690 | 50,330 | 49,925 | 50,282 | 50,557 | 48,047 | 46,077 |
| College graduate or postgraduate (%) | 37.3 | 47.5 | 39.8 | 36.8 | 40.1 | 44.6 | 38.2 | 33.2 |
| Current smoker (%) | 10.8 | 9.1 | 13.2 | 16.1 | 12.9 | 9.6 | 12.0 | 12.1 |
| Physical activity, ≥ 5 times/wk (%) | 19.4 | 22.1 | 17.6 | 16.3 | 19.8 | 21.6 | 18.0 | 17.1 |
| Heart disease (%) | 15.7 | 12.9 | 11.5 | 10.5 | 12.2 | 13.8 | 14.3 | 15.7 |
| Stroke (%) | 2.2 | 1.8 | 1.9 | 2.1 | 1.9 | 2.0 | 2.1 | 2.5 |
| Cancer (%) | 9.1 | 8.4 | 8.6 | 9.7 | 9.0 | 8.4 | 8.9 | 9.7 |
| Diabetes (%) | 9.6 | 7.4 | 8.3 | 9.2 | 7.8 | 9.7 | 9.3 | 11.6 |
| Fair or poor health (%) | 13.5 | 10.7 | 12.0 | 13.5 | 12.0 | 11.2 | 12.9 | 15.4 |
| Currently using multivitamins (%) | 55.8 | 56.6 | 55.2 | 54.8 | 56.1 | 56.4 | 55.0 | 55.2 |
| Daily use of aspirin (%) | 16.2 | 14.4 | 13.0 | 11.9 | 13.5 | 15.2 | 15.2 | 15.8 |
| Daily dietary intake | | | | | | | | |
| Total energy (kcal/d) | 1666.6 | 1651.6 | 1759.3 | 1749.3 | 1711.1 | 1649.3 | 1733.4 | 1661.4 |
| Alcohol from alcoholic drinks (g/d) | 1.5 | 2.5 | 2.7 | 2.0 | 2.2 | 2.1 | 2.0 | 1.2 |
| Total protein (% of energy) | 15.5 | 15.6 | 15.2 | 14.6 | 15.0 | 15.7 | 15.5 | 15.2 |
| Total fat (% of energy) | 29.8 | 26.6 | 31.1 | 35.0 | 31.1 | 26.6 | 30.4 | 32.8 |
| Butter | 0.0 | 1.0 | 5.5 | 13.7 | 4.0 | 0.3 | 0.0 | 0.0 |
| Margarine | 10.4 | 1.1 | 4.3 | 0.0 | 0.0 | 2.4 | 9.3 | 20.6 |
| Corn oil | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Canola oil | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Olive oil | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Healthy Eating Index score | 70.5 | 70.4 | 66.4 | 61.6 | 65.8 | 70.1 | 68.6 | 70.2 |

Data are medians or percentages. BMI body mass index, T tertile
ᵃHousehold income in 1999

#### All-cause mortality

Butter and margarine consumption was strongly associated with higher all-cause mortality in all multivariable-adjusted models. In contrast, intakes of canola oil and olive oil were both inversely associated with all-cause mortality. Corn oil consumption was related to higher all-cause mortality after adjusting for age and sex, but the association became non-significant after adjusting further covariates (Table 2). Compared to non-consumers, the multivariable HRs of all-cause mortality in the highest categories were 1.09 (95% CI, 1.07–1.11) for butter (P-trend < 0.001), 1.07 (95% CI, 1.05–1.10) for margarine (P-trend < 0.001), 0.97 (95% CI, 0.95–0.99) for canola oil (P-trend < 0.001), and 0.96 (95% CI, 0.95–0.98) for olive oil (P-trend < 0.001) (Table 2). Every 1-tablespoon/day increment of butter or margarine consumption was related to 7% and 4% higher all-cause mortality, respectively. In contrast, each 1-tablespoon/day increment of canola or olive oil consumption was related to lower all-cause mortality.
Table 2 HRs (95% CIs) of all-cause mortality according to cooking oil/fat consumption

| Categories of individual cooking oil/fat consumption | Non-consumers | T1 | T2 | T3 | P trend |
|------------------------------------------------------|--------------|----|----|----|---------|
| **Butter**                                           |              |    |    |    |         |
| Median intake (IQR)                                  | 0            | 1.0 (0.4–2.0) | 5.5 (4.2–6.9) | 13.7 (10.7–18.8) |         |
| Death cases/n                                        | 75,826/303,987 | 15,792/72,377 | 17,915/72,378 | 19,795/72,378 |         |
| Person-years                                         | 4,262,749    | 1,030,708 | 1,014,202 | 999,439 |         |
| Model 1\(^a\)                                        | 1.00         | 0.88 (0.86–0.89) | 1.02 (1.00–1.03) | 1.14 (1.13–1.16) | < 0.001 |
| Model 2\(^b\)                                        | 1.00         | 0.96 (0.94–0.97) | 1.04 (1.02–1.06) | 1.12 (1.10–1.14) | < 0.001 |
| Model 3\(^c\)                                        | 1.00         | 0.98 (0.96–1.00) | 1.05 (1.03–1.06) | 1.09 (1.07–1.11) | < 0.001 |
| **Margarine**                                        |              |    |    |    |         |
| Median intake (IQR)                                  | 0            | 2.4 (0.9–4.0) | 9.3 (7.4–11.4) | 20.6 (16.7–26.6) |         |
| Death cases/n                                        | 32,633/134,374 | 29,070/128,915 | 32,583/128,916 | 35,042/128,915 |         |
| Person-years                                         | 1,888,086    | 1,829,523 | 1,804,411 | 1,785,077 |         |
| Model 1\(^a\)                                        | 1.00         | 0.90 (0.89–0.92) | 1.01 (0.99–1.02) | 1.08 (1.06–1.09) | < 0.001 |
| Model 2\(^b\)                                        | 1.00         | 0.94 (0.92–0.95) | 0.99 (0.97–1.00) | 1.00 (0.99–1.02) | < 0.001 |
| Model 3\(^c\)                                        | 1.00         | 0.99 (0.97–1.01) | 1.03 (1.01–1.05) | 1.07 (1.05–1.09) | < 0.001 |
| **Corn oil**                                         |              |    |    |    |         |
| Median intake (IQR)                                  | 0            | 0.4 (0.2–0.5) | 1.1 (0.8–1.4) | 3.4 (2.4–5.5) |         |
| Death cases/n                                        | 98,499/399,360 | 9400/40,586 | 10,240/40,587 | 11,189/40,587 |         |
| Person-years                                         | 5,605,569    | 574,055 | 567,538 | 559,935 |         |
| Model 1\(^a\)                                        | 1.00         | 0.95 (0.93–0.97) | 1.03 (1.01–1.05) | 1.12 (1.10–1.14) | < 0.001 |
| Model 2\(^b\)                                        | 1.00         | 0.96 (0.94–0.98) | 0.99 (0.97–1.01) | 1.02 (1.00–1.04) | 0.21    |
| Model 3\(^c\)                                        | 1.00         | 0.97 (0.94–0.99) | 0.98 (0.96–1.00) | 0.99 (0.97–1.01) | 0.092   |
| **Canola oil**                                       |              |    |    |    |         |
| Median intake (IQR)                                  | 0            | 0.4 (0.2–0.5) | 1.0 (0.8–1.3) | 3.2 (2.3–5.3) |         |
| Death cases/n                                        | 95,507/376,913 | 10,571/48,069 | 11,129/48,069 | 12,121/48,069 |         |
| Person-years                                         | 5,269,352    | 684,537 | 680,475 | 672,733 |         |
| Model 1\(^a\)                                        | 1.00         | 0.88 (0.86–0.89) | 0.91 (0.89–0.92) | 0.98 (0.96–0.99) | < 0.001 |
| Model 2\(^b\)                                        | 1.00         | 0.94 (0.93–0.96) | 0.96 (0.94–0.97) | 0.97 (0.95–0.99) | < 0.001 |
| Model 3\(^c\)                                        | 1.00         | 0.98 (0.95–1.00) | 0.97 (0.95–0.99) | 0.97 (0.95–0.99) | < 0.001 |
| **Olive oil**                                        |              |    |    |    |         |
| Median intake (IQR)                                  | 0            | 0.4 (0.3–0.5) | 1.2 (0.9–1.5) | 3.8 (2.6–6.2) |         |
| Death cases/n                                        | 91,948/353,766 | 11,878/55,784 | 12,386/55,785 | 13,116/55,785 |         |
| Person-years                                         | 4,930,793    | 796,402 | 793,033 | 786,869 |         |
| Model 1\(^a\)                                        | 1.00         | 0.85 (0.84–0.87) | 0.87 (0.86–0.89) | 0.91 (0.89–0.93) | < 0.001 |
| Model 2\(^b\)                                        | 1.00         | 0.94 (0.92–0.96) | 0.96 (0.94–0.98) | 0.97 (0.95–0.99) | < 0.001 |
| Model 3\(^c\)                                        | 1.00         | 0.96 (0.94–0.99) | 0.97 (0.95–0.98) | 0.96 (0.95–0.98) | < 0.001 |

HRs (95% CIs) were estimated using Cox proportional hazards models. CI confidence interval, HR hazard ratio, T tertile
\(^a\)Adjusted for age and sex
\(^b\)Adjusted for BMI (in kg/m\(^2\); < 18.5, 18.5 to 25, 25 to 30, 30 to 35, ≥ 35, or missing), race (white, black, Hispanic/Asian/Pacific Islander/American Indian/Alaskan native, or unknown/missing), education (less than high school, high school graduate, some college, college graduate, or unknown/missing), marital status (married/living as married or widowed/divorced/separated/never married/unknown), household income (quintiles), smoking (never smoked; quit, ≤ 20 cigarettes a day; quit, > 20 cigarettes a day; currently smoking, ≤ 20 cigarettes a day; currently smoking, > 20 cigarettes a day; or unknown), alcohol (0, 0.1–4.9, 5.0–29.9, or ≥ 30 g/day), vigorous physical activity (never/rarely, 1–3 times/month, 1–2 times/week, 3–4 times/week, ≥ 5 times/week, or unknown), usual activity at work (sit all day, sit much of the day/walk sometimes, stand/walk often/no lifting, lift/carry light loads, and carry heavy loads), perceived health condition (excellent, very good, good, fair or poor), and history of heart disease (yes or no), stroke (yes or no), diabetes (yes or no), and cancer (yes or no) at baseline
\(^c\)Additionally adjusted for Healthy Eating Index-2015, total energy intake, and consumption of remaining oils where appropriate (butter, margarine, lard, corn oil, canola oil, olive oil, and other vegetable oils)
day increment of canola oil or olive oil consumption was associated with 2% and 3% of reductions in all-cause mortality, respectively (Fig. 1a).

Cardiometabolic mortality

The consumption of butter and margarine was positively associated with CVD mortality after multivariate adjustment, whereas olive oil intake was inversely associated with CVD mortality (Table 3). Compared with non-consumers, participants in the highest tertile of olive oil consumption had 5% (HR = 0.95, 95% CI 0.92–0.99; P-trend = 0.001) lower CVD mortality, but those in the highest tertiles of butter and margarine consumption had 8% (HR = 1.08, 95% CI 1.05–1.12; P-trend < 0.001) and 10% (HR = 1.10, 95% CI 1.06–1.14; P-trend < 0.001) higher CVD mortality, respectively. Canola oil consumption was marginally associated with lower CVD mortality (P-trend = 0.052), while corn oil intake was not related to CVD mortality. Similar associations were also observed for heart disease mortality (Additional file 1: Table S4). Besides, borderline trends toward lower and higher stroke mortality were observed for corn oil (P-trend = 0.061) and butter (P-trend = 0.059) consumption, respectively. For diabetes mortality, we detected positive associations for butter and margarine consumption. Compared with non-consumers, participants in the highest tertiles of butter and margarine consumption had 18% (HR = 1.18, 95% CI 1.06–1.32; P-trend = 0.0041) and 12% (HR = 1.12, 95% CI 1.00–1.26; P-trend = 0.047) higher diabetes mortality, respectively. In contrast, olive oil consumption was inversely related to diabetes mortality (HR comparing the highest tertile with non-consumers = 0.87, 95% CI 0.77–0.99; P-trend = 0.019). Overall, each 1-tablespoon/day increment of butter or margarine consumption was associated with 8% and 6% higher cardiometabolic mortality, respectively, while every 1-tablespoon/day increment of olive oil consumption was related to 4% decreased cardiometabolic mortality (Fig. 1b). Restricted-cubic-spline regression yielded similar results (Fig. 2a–e).

Other non-cardiometabolic mortality

For other cause-specific mortality, butter consumption was associated with higher mortality from cancer, respiratory disease (RD), kidney disease, and chronic liver

---

**Fig. 1** Multivariable-adjusted hazard ratios of total and cardiometabolic mortality for 1-tablespoon/day increment in cooking oil/fat consumption. Forest plots show the multivariable HRs of total (a) and cardiometabolic (b) mortality associated with 1-tablespoon/day increment in butter, margarine, corn oil, canola oil, and olive oil consumption. HRs were adjusted for age, sex, BMI, race, education, marital status, household income, smoking, alcohol, vigorous physical activity, usual activity at work, perceived health condition, history of heart disease, stroke, diabetes, and cancer at baseline, Healthy Eating Index-2015, total energy intake, and consumption of remaining oils where appropriate (butter, margarine, lard, corn oil, canola oil, olive oil, and other vegetable oils). Horizontal lines represent 95% CIs.
| Categories of individual cooking oil/fat consumption | Non-consumers | T1          | T2          | T3          | P trend |
|----------------------------------------------------|--------------|-------------|-------------|-------------|---------|
| **Cardiovascular disease mortality**                |              |             |             |             |         |
| Butter                                             |              |             |             |             |         |
| Death cases/n                                      | 23,406/303,987 | 4623/72,377 | 5213/72,378 | 5505/72,378 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.83 (0.80–0.86) | 0.96 (0.93–0.99) | 1.04 (1.01–1.07) | < 0.001 |
| Model 2<sup>b</sup>                                | 1.00         | 0.93 (0.90–0.96) | 1.02 (0.99–1.05) | 1.07 (1.04–1.11) | < 0.001 |
| Model 3<sup>c</sup>                                | 1.00         | 0.96 (0.93–1.00) | 1.04 (1.01–1.08) | 1.08 (1.05–1.12) | < 0.001 |
| Margarine                                          |              |             |             |             |         |
| Death cases/n                                      | 9305/134,374 | 8630/128,915 | 9901/128,916 | 10,911/128,915 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.93 (0.90–0.96) | 1.06 (1.03–1.09) | 1.17 (1.14–1.21) | < 0.001 |
| Model 2<sup>b</sup>                                | 1.00         | 0.95 (0.92–0.98) | 1.02 (0.99–1.05) | 1.04 (1.01–1.07) | < 0.001 |
| Model 3<sup>c</sup>                                | 1.00         | 1.01 (0.97–1.04) | 1.06 (1.02–1.09) | 1.10 (1.06–1.14) | < 0.001 |
| Corn oil                                           |              |             |             |             |         |
| Death cases/n                                      | 29,443/399,360 | 2830/40,586 | 3068/40,587 | 3406/40,587 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.97 (0.93–1.01) | 1.03 (0.99–1.07) | 1.14 (1.10–1.18) | < 0.001 |
| Model 2<sup>b</sup>                                | 1.00         | 0.99 (0.96–1.03) | 1.00 (0.97–1.04) | 1.02 (0.99–1.06) | 0.22    |
| Model 3<sup>c</sup>                                | 1.00         | 1.01 (0.96–1.05) | 0.99 (0.95–1.03) | 1.00 (0.96–1.03) | 0.78    |
| Canola oil                                         |              |             |             |             |         |
| Death cases/n                                      | 28,520/376,913 | 3149/48,069 | 3362/48,069 | 3716/48,069 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.89 (0.85–0.92) | 0.93 (0.89–0.96) | 1.01 (0.97–1.04) | 0.70    |
| Model 2<sup>b</sup>                                | 1.00         | 0.96 (0.92–1.00) | 0.97 (0.94–1.01) | 0.97 (0.94–1.01) | 0.080   |
| Model 3<sup>c</sup>                                | 1.00         | 0.99 (0.95–1.04) | 0.98 (0.94–1.02) | 0.97 (0.94–1.00) | 0.052   |
| Olive oil                                          |              |             |             |             |         |
| Death cases/n                                      | 27,962/353,766 | 3377/55,784 | 3578/55,785 | 3830/55,785 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.81 (0.78–0.84) | 0.84 (0.81–0.87) | 0.88 (0.85–0.91) | < 0.001 |
| Model 2<sup>b</sup>                                | 1.00         | 0.92 (0.89–0.96) | 0.95 (0.92–0.98) | 0.95 (0.92–0.98) | 0.002   |
| Model 3<sup>c</sup>                                | 1.00         | 0.93 (0.89–0.97) | 0.95 (0.92–0.99) | 0.95 (0.92–0.99) | 0.001   |
| **Diabetes mortality**                             |              |             |             |             |         |
| Butter                                             |              |             |             |             |         |
| Death cases/n                                      | 389/72,377   | 427/72,378  | 537/72,378  | 3512/72,378 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.75 (0.67–0.83) | 0.84 (0.76–0.94) | 1.10 (1.00–1.21) | 0.062   |
| Model 2<sup>b</sup>                                | 1.00         | 0.93 (0.84–1.04) | 0.96 (0.86–1.06) | 1.11 (1.01–1.22) | 0.037   |
| Model 3<sup>c</sup>                                | 1.00         | 0.97 (0.86–1.09) | 0.99 (0.89–1.11) | 1.18 (1.06–1.32) | 0.004   |
| Margarine                                          |              |             |             |             |         |
| Death cases/n                                      | 782/134,374  | 732/128,915 | 896/128,916 | 1102/128,915 |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.94 (0.85–1.04) | 1.16 (1.05–1.27) | 1.44 (1.32–1.58) | < 0.001 |
| Model 2<sup>b</sup>                                | 1.00         | 0.97 (0.88–1.07) | 1.03 (0.93–1.13) | 1.06 (0.96–1.16) | 0.091   |
| Model 3<sup>c</sup>                                | 1.00         | 1.05 (0.93–1.18) | 1.08 (0.97–1.21) | 1.12 (1.00–1.26) | 0.047   |
| Corn oil                                           |              |             |             |             |         |
| Death cases/n                                      | 2670/399,360 | 235/40,586  | 296/40,587  | 311/40,587  |         |
| Model 1<sup>a</sup>                                | 1.00         | 0.88 (0.77–1.00) | 1.09 (0.97–1.23) | 1.15 (1.03–1.30) | 0.009   |
| Model 2<sup>b</sup>                                | 1.00         | 0.94 (0.82–1.08) | 1.06 (0.94–1.19) | 0.95 (0.85–1.07) | 0.56    |
| Model 3<sup>c</sup>                                | 1.00         | 0.96 (0.83–1.12) | 1.02 (0.90–1.16) | 0.95 (0.84–1.07) | 0.41    |
Table 3 HRs (95% CIs) of CVD and diabetes mortality according to cooking oil/fat consumption (Continued)

| Categories of individual cooking oil/fat consumption | Non-consumers | T1 | T2 | T3 | P trend |
|------------------------------------------------------|---------------|----|----|----|---------|
| **Canola oil**                                        |               |    |    |    |         |
| Death cases/n                                        | 2560/376,913  | 270/48,069 | 325/48,069 | 357/48,069 |         |
| Model 1<sup>a</sup>                                  | 1.00          | 0.84 (0.74–0.95) | 1.00 (0.89–1.12) | 1.09 (0.97–1.21) | 0.14    |
| Model 2<sup>b</sup>                                  | 1.00          | 0.99 (0.87–1.12) | 1.10 (0.98–1.23) | 0.99 (0.88–1.10) | 0.95    |
| Model 3<sup>c</sup>                                  | 1.00          | 1.07 (0.92–1.24) | 1.08 (0.96–1.22) | 0.99 (0.88–1.11) | 0.96    |
| **Olive oil**                                         |               |    |    |    |         |
| Death cases/n                                        | 2635/353,766  | 257/55,784  | 309/55,785  | 311/55,785  |         |
| Model 1<sup>a</sup>                                  | 1.00          | 0.64 (0.56–0.73) | 0.76 (0.67–0.85) | 0.75 (0.67–0.84) | <0.001  |
| Model 2<sup>b</sup>                                  | 1.00          | 0.85 (0.75–0.97) | 0.97 (0.86–1.09) | 0.87 (0.77–0.98) | 0.022   |
| Model 3<sup>c</sup>                                  | 1.00          | 0.84 (0.72–0.98) | 0.94 (0.83–1.06) | 0.87 (0.77–0.99) | 0.019   |

HRs (95% CIs) were estimated using Cox proportional hazards models. CI confidence interval, HR hazard ratio, T tertile
<sup>a</sup>Adjusted for age and sex
<sup>b</sup>Additionally adjusted for BMI (in kg/m<sup>2</sup>; < 18.5, 18.5 to 25, 25 to 30, 30 to 35, ≥ 35, or missing), race (white, black, Hispanic/Asian/Pacific Islander/American Indian/Alaskan native, or unknown/missing), education (less than high school, high school graduate, some college, college graduate, or unknown/missing), marital status (married/living as married/divorced/separated/never married/unknown), household income (quintiles), smoking (never smoked; quit, > 20 cigarettes a day; or unknown), alcohol (0, 0.1–2.9, 3.0–4.9, 5.0–29.9, 30.0–49.9, or ≥ 50.0 g/day), vigorous physical activity (never/rarely, 1 time per month, 1–2 times/month, 1–2 times/week, 3–4 times/week, ≥5 times/week, or unknown/missing), marriage (married/living as married/divorced/separated/never married/unknown), household income (quintiles), smoking (never smoked; quit, > 20 cigarettes a day; or unknown), alcohol (0, 0.1–2.9, 3.0–4.9, 5.0–29.9, 30.0–49.9, or ≥ 50.0 g/day), vigorous physical activity (never/rarely, 1 time per month, 1–2 times/month, 1–2 times/week, 3–4 times/week, ≥5 times/week, or unknown/missing), usual activity at work (sit all day, sit much of the day/walk sometimes, stand/walk often/no lifting, lift/carry light loads, and carry heavy loads), perceived health condition (excellent, very good, good, fair, or poor), and history of heart disease (yes or no), stroke (yes or no), diabetes (yes or no), and cancer (yes or no) at baseline
<sup>c</sup>Additional adjustment for Healthy Eating Index-2015, total energy intake, and consumption of remaining oils where appropriate (butter, margarine, lard, corn oil, canola oil, olive oil, and other vegetable oils)

Substitution for butter and margarine
Substituting 1 tablespoon/day (8 g/day) corn oil, canola oil, or olive oil for equivalent amounts of butter was associated with 5%, 6%, and 7% lower all-cause mortality, respectively. Likewise, substituting 1 tablespoon/day corn oil, canola oil, or olive oil for equivalent amounts of butter was associated with 5%, 6%, and 8% lower cardiometabolic mortality, respectively. For the cause-specific mortality by the replacement of butter, each 1-tablespoon/day increment of canola oil was associated with 7%, 5%, and 11% of reductions in CVD, cancer, and RD mortality, respectively, and each 1-tablespoon/day increment of olive oil was related to 7%, 16%, 21%, and 15% lower mortality from CVD, RD, AD, and diabetes, respectively. Besides, we detected 5% lower cancer mortality when replacing 1 tablespoon/day butter with corn oil (Fig. 3 and Additional file 1: Table S7).

When replacing margarine, each 1-tablespoon/day increment of corn oil, canola oil, or olive oil was associated with 3%, 5%, and 5% lower all-cause mortality, respectively. Similarly, each 1-tablespoon/day increment of corn oil, canola oil, or olive oil was associated with 4%, 6%, and 7% lower cardiometabolic mortality, respectively. Regarding the cause-specific mortality, replacing with 1 tablespoon/day canola oil was associated with lower CVD mortality (6%) and RD mortality (9%), respectively, and replacing with olive oil was related to lower mortality from CVD (6%), RD (14%), AD (25%), and diabetes (13%), respectively. Each 1-tablespoon/day increment of corn oil was related to 24% lower AD mortality (Fig. 3 and Additional file 1: Table S7).

Subgroup analyses
In secondary analyses for stick and tub/soft margarine consumption, most of the associations were similar except a significant association of stick but not tub/soft margarine consumption with higher AD mortality (Additional file 1: Table S8). Subgroup analyses showed significant modifications for the associations with all-cause mortality stratified by sex, baseline BMI, smoking status, alcohol drinking, income level, and HEI score (Additional file 1: Table S9). Although positive associations of butter and margarine consumption with all-cause mortality persisted in all the subgroups, the associations for butter consumption were stronger among men than women (P-interaction = 0.022) and among non-obese participants than obese participants (P-interaction< 0.001), while the
Fig. 2 Cubic spline curves for the association between individual cooking oil intakes and cardiometabolic mortality. Hazard ratios are based on Cox proportional hazards models adjusted for age, sex, BMI, race, education, marital status, household income, smoking, alcohol, vigorous physical activity, usual activity at work, perceived health condition, history of heart disease, stroke, diabetes, and cancer at baseline, Healthy Eating Index-2015, total energy intake, and consumption of remaining oils where appropriate (butter, margarine, lard, corn oil, canola oil, olive oil, and other vegetable oils).
associations for margarine consumption were more pronounced among non-smokers or former smokers ($P$-interaction = 0.004) and those with higher income level ($P$-interaction < 0.001) and higher HEI score ($P$-interaction = 0.001). Notably, the inverse association of olive oil consumption with all-cause mortality was restricted to alcohol drinkers ($P$-interaction = 0.003).

**Sensitivity analyses**
Both significant and non-significant associations did not change materially after exclusion of participants with extreme BMIs, or further adjustment for a propensity score, history of hypertension and hypercholesteremia, or the use of multivitamins and aspirin (Additional file 1: Tables S10-S13). We also detected largely similar associations when we further adjusted for the use of cholesterol-lowering medications, excluded those with CVD, cancer, or diabetes at baseline and those with the first 4 years of follow-up; or censored participants at 8-year follow-up (Additional file 1: Tables S14-S17).

**Discussion**
In this large prospective cohort, intakes of butter and margarine were associated with higher all-cause, cardiometabolic, and other major cause-specific mortality, whereas intakes of canola oil and olive oil were related to lower mortality. Substituting corn oil, canola oil, or olive oil for butter and margarine was associated with lower all-cause, cardiometabolic, cancer, RD, and AD mortality.

Current dietary recommendations on butter consumption largely depend on the assumed negative effect of high SFA content (> 65%) [19] in relation to higher all-cause mortality and CVD incidence [20, 21] regardless of beneficial ingredients such as vitamins, PUFAs, MUFAs, and ruminant trans-fat. However, a previous...
multi-center nationwide study reported no significant association of butter consumption with all-cause mortality and CVD incidence [22]. Nonetheless, evidence from intervention trials indicated that the butter-enriched diet elevated total and LDL cholesterol compared with the diet rich in vegetable oils or coconut oil [5, 6]. In the current US prospective study, we observed strong associations with higher total and CVD mortality. These data emphasize the reductions in butter consumption among the US population for the management of cardiovascular health. Interestingly, a previous meta-analysis of 11 studies revealed a weak inverse relationship of butter with health. Asthma onset was contributed by the intake of margarine [30], supporting our finding of elevated RD mortality. We observed overall neutral associations of corn oil consumption with mortality only except a marginal inverse association with stroke mortality. Corn oil could ameliorate plasma atherogenic lipids among participants with elevated cholesterol [33]. However, substituting vegetable oils rich in linoleic acid for SFAs [34] was not associated with lower all-cause or CVD mortality [35]. Unlike corn oil, canola oil as a cardioprotective contributor is rich in MUFAs and α-linolenic acid [36]. Canola oil supplementation could ameliorate overall blood lipid profiles and improve glycemic control and inflammatory effects of MUFAs [37].

The cardioprotective association of olive oil has been supported by the Spanish European Prospective into Cancer and Nutrition study [38], the Nurses’ Health Study and the Health Professionals Follow-up Study [39], and the PREvención con Dieta MEDiterránea study of patients at high CVD incidence [40]. Consistent with our finding, a previous US women study also showed a lower risk of diabetes with higher olive oil intake [17]. Mediterranean diet supplemented with olive oil seemed to be effective in reducing the risk of developing diabetes among participants at high cardiovascular risk [41]. A recent meta-analysis also demonstrated that olive oil supplementation could lower HbA1c and fasting plasma glucose levels among diabetic patients [8]. Besides, the association with lower AD mortality might be due to the neuroprotective phenols and oleocanthal in olive oil. Collectively, these data underscored the health benefits of olive oil and provided evidence on habitual olive oil consumption as a key contributor to the healthy Mediterranean diet [40]. Increasing the consumption of olive oil may confer health benefits on cardiometabolic health and reduce mortality.

Subgroup analyses demonstrated stronger associations of butter consumption with higher mortality among men than women, which could be due to sex-dependent fatty acid metabolism [42], and higher CVD mortality rates and lower life expectancy in men than women. The interaction between olive oil and alcohol drinking status on mortality might be due to the correlation between olive oil consumption and the Mediterranean pattern which included wine. Future research is warranted to elucidate the observed interactions between smoking, alcohol drinking, BMI, and HEI score and cooking oils/fats.

Strengths of the current study include the large population size, long-term duration with a high follow-up rate (>99%), and a large number of deaths from various causes. We excluded participants with chronic diseases.
at baseline or initial 4 years of follow-up to further reduce the possibility of reverse causality and found similar results, indicating the robustness of our findings. The limitations should also be noted. First, the observed associations might be partly due to residual confounding despite comprehensive adjustment for well-known risk factors. Second, although validated, our FFQ might still produce measurement errors. Given the prospective study design, any mismeasurement in cooking oil/fat consumption would likely be random for mortality, resulting in conservative associations. Third, the overall intake level of individual vegetable oils was low in this population with a relatively narrow intake range. Nonetheless, we still detected significant protective associations of these vegetable oils, especially when substituting for solid fats. Fourth, due to the lack of measurement data, we could not further analyze the associations between fats/oils with different cooking methods and mortality, which could make our results more informative. In addition, dietary intakes were only assessed at baseline, and potential dietary changes could occur during the long-term follow-up. Nonetheless, this might not appreciably change our results because we also observed similar associations when censoring participants at a shorter duration (8 years) of follow-up. Moreover, the potential changes in the constituents of specific oils could not be captured. Typically, margarines contain high amount of trans-fat in 1990s. However, trans-fat was phased out in the last decade. In recent years, soft margarines have contained no trans-fat and only hard and tub may still contain. This probably would have weakened the observed positive associations of margarine consumption. Finally, a causal relationship may not be established due to the observational nature.

Conclusion

In summary, consumption of butter and margarine was associated with higher all-cause and cardiometabolic mortality. Intakes of canola oil and olive oil were associated with lower total mortality and corn oil had a neutral association with mortality. From the standpoint of public health, intakes of butter and margarine may be limited while olive oil consumption may be recommended to lower deaths from cardiometabolic diseases. Replacing butter and margarine with corn oil, canola oil, or olive oil may confer health benefits on cardiometabolic health and reduce mortality. Taken together, current dietary recommendations should continue to highlight shifting the intake from solid fats, including butter and margarine, to non-hydrogenated vegetable oils, such as corn oil, canola oil, and olive oil, for the prevention of cardiometabolic diseases and premature deaths.

Abbreviations

AARP: Formerly known as the American Association for Retired Persons; AD: Alzheimer’s disease; BMI: Body mass index; CI: Confidence interval; CVD: Cardiovascular disease; FFQ: Food frequency questionnaire; HEI: Healthy Eating Index; HR: Hazard ratio; MUFAs: Monounsaturated fatty acid; PUFAs: Polyunsaturated fatty acid; RD: Respiratory disease; SFA: Saturated fatty acid

Supplementary Information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12916-021-01961-2.

Additional file 1: Figure S1. Flow of participants in current NIH-AARP prospective cohort. Table S1. Categories for causes of death. Table S2. Baseline characteristics of participants according to corn oil, canola oil and olive oil consumption. Table S3. Spearman correlations between individual cooking oils. Table S4. Multivariable-adjusted HRs (95% CIs) of heart disease and stroke mortality according to individual oil consumption. Table S5. Multivariable-adjusted HRs (95% CIs) of mortality from non-cardiometabolic causes according to individual oil consumption. Table S6. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality according to subgroup analyses. Table S7. Data source of Fig. 3. Multivariable-adjusted HRs (95% CIs) for substituting tablespoon/day canola oil, corn oil, or olive oil for equivalent amounts of butter and margarine. Table S8. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality associated with consumption of stick margarine and other margarine. Table S9. Multivariable-adjusted HRs (95% CIs) of all-cause mortality from subgroup analyses. Table S10. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that excluded those with extreme BMIs. Table S11. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that further adjusting for a propensity score. Table S12. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that further adjusted for history of hypertension and hypercholesteremia. Table S13. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that further adjusted for aspirin and multivitamins use. Table S14. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that further adjusted for the use of cholesterol-lowering medications (n=293,918). Table S15. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that excluded those with cardiovascular disease, cancer, or diabetes at baseline. Table S16. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that excluding the first 4 years of follow-up. Table S17. Multivariable-adjusted HRs (95% CIs) of all-cause and cause-specific mortality from the sensitivity analysis that followed up for 8 years.

Acknowledgements

We are indebted to the participants in the NIH-AARP Diet and Health Study for their outstanding cooperation. We also thank Sigurd Hermansen and Kerry Grace Morrisey from Westat for study outcome ascertainment and management and Leslie Carroll at Information Management Services for data support and analysis. Cancer incidence data from the Atlanta metropolitan area were collected by the Georgia Center for Cancer Statistics, Department of Epidemiology, Rollins School of Public Health, Emory University, Atlanta, Georgia. Cancer incidence data from California were collected by the California Cancer Registry, California Department of Public Health’s Cancer Surveillance and Research Branch, Sacramento, California. Cancer incidence data from the Detroit metropolitan area were collected by the Michigan Cancer Surveillance Program, Community Health Administration, Lansing, Michigan. The Florida cancer incidence data used in this report were collected by the Florida Cancer Data System (Miami, Florida) under contract with the Florida Department of Health, Tallahassee, Florida. The views expressed herein are solely those of the authors and do not necessarily reflect those of the FDCC or FDOH. Cancer incidence data from Louisiana were collected by the Louisiana Tumor Registry, Louisiana State University Health Sciences Center School of Public Health, New Orleans, Louisiana. Cancer incidence data from New
Jersey were collected by the New Jersey State Cancer Registry, The Rutgers Cancer Institute of New Jersey, New Brunswick, New Jersey. Cancer incidence data from North Carolina were collected by the North Carolina Central Cancer Registry, Raleigh, North Carolina. Cancer incidence data from Pennsylvania were supplied by the Division of Health Statistics and Research, Pennsylvania Department of Health, Harrisburg, Pennsylvania. The Pennsylvania Department of Health specifically disclaims responsibility for any analyses, interpretations, or conclusions. Cancer incidence data from Arizona were collected by the Arizona Cancer Registry, Division of Public Health Services, Arizona Department of Health Services, Phoenix, Arizona. Cancer incidence data from Texas were collected by the Texas Cancer Registry, Cancer Epidemiology and Surveillance Branch, Texas Department of State Health Services, Austin, Texas. Cancer incidence data from Nevada were collected by the Nevada Central Cancer Registry, Division of Public and Behavioral Health, State of Nevada Department of Health and Human Services, Carson City, Nevada.

Authors’ contributions
YZ and JI designed and supervised the conduct of the whole study and obtained funding. PZ, LM, and FW were responsible for the data analysis of the exposures. WH provided statistical assistance. YZ and PZ wrote the first draft of the paper. All authors participated in the study design, generation of hypotheses, interpretation of data, and critical review of the report. The author(s) read and approved the final manuscript.

Funding
This research was supported by the Zhejiang Provincial Natural Science Foundation of China (grant number LR18C200001), the National Natural Science Foundation of China (grant no. 81773419), and the Intramural Research Program of the NIH National Cancer Institute.

Availability of data and materials
Because of the sensitive nature of the data collected for this study, requests to access the dataset from qualified researchers trained in human subject confidentiality protocols may be sent to the National Cancer Institute Division of Cancer Epidemiology & Genomics to Linda M. Liao (e-mail: liaolm@mail.nih.gov).

Declarations
Ethics approval and consent to participate
Written informed consent was obtained from all men and women who participated in the study, which was approved by the Institutional Review Board of the National Cancer Institute (Proposal #201807-0012).

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
1Department of Food Science and Nutrition, Zhejiang Key Laboratory for Agro-Food Processing, Full Institute of Food Science, College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou 310058, Zhejiang, China. 2Department of Nutrition, School of Public Health, and Department of Nutrition of Affiliated Second Hospital, Zhejiang University School of Medicine, 866 Yuhangtang Road, Hangzhou 310058, Zhejiang, China. 3Department of Medical Epidemiology and Biostatistics, Karolinska Institutet, Huddinge, SE-171 77 Stockholm, Sweden.

Received: 27 November 2020 Accepted: 17 March 2021
Published online: 15 April 2021

References
1. Consumption of vegetable oils worldwide from 2013/14 to 2018/2019, by oil type (in million metric tons), https://www.statista.com/statistics/269337/vegetable-oils-global-consumption/. Accessed 1 Sept 2020.
2. Forouhi NG, Krauss RM, Taubes G, Willett W. Dietary fat and cardiometabolic health: evidence, controversies, and consensus for guidance. BMJ. 2018;361:k2139.
3. Dietary Guidelines Advisory Committee. Scientific Report of the 2015 Dietary Guidelines Advisory Committee (Advisory Report). In: U.S. Department of Health and Human Services (HHS) and the U.S. 3 Department of Agriculture (USDA), editor. 2015.
4. Mozaffarian D, Ludwig DS. Dietary guidelines in the 21st century—a time for food. JAMA. 2010;304(6):681–2. https://doi.org/10.1001/jama.2010.1116.
5. Schwinghackl L, Bogensberger B, Benčič A, Knüppel S, Boeijing H, Hoffmann G. Effects of oils and solid fats on blood lipids: a systematic review and network meta-analysis. J Lipid Res. 2018;59(9):1771–82. https://doi.org/10.1194/jlr.P085522.
6. Jenkins DJA, Kendall CWC, Vasan V, Faulkner D, Augustin LSA, Mitchell S, Ireland C, Srichaikal K, Mirahimi A, Chiavaroli L, Bianco Meija S, Nishi S, Sahye-Pudaruth S, Patel D, Bashyam B, Viden G, de Souza RJ, Sievenpiper JL, Coveny J, Josse RG, Leiter LA. Effect of lowering the glycemic load with canola oil on glycemic control and cardiovascular risk factors: a randomized controlled trial. Diabetes Care. 2014;37(7):1806–14. https://doi.org/10.2337/dc13-2990.
7. Engel S, Tholstrup T. Butter increased total and LDL cholesterol compared with olive oil but resulted in higher HDL cholesterol compared with a habitual diet. Am J Clin Nutr. 2015;102(2):305–15. https://doi.org/10.3945/ajcn.115.112227.
8. Schwinghackl L, Lampousi AM, Portillo MP, Ramaguera D, Hoffmann G, Boeijing H. Olive oil in the prevention and management of type 2 diabetes mellitus: a systematic review and meta-analysis of cohort studies and intervention trials. Nutr Diab. 2017;7(4):e262. https://doi.org/10.1038/nutd.2017.012.12.
9. Pimpin L, Wu JHY, Haskelberg H, Del Gobbo L, Mozaffarian D. Is butter back? A systematic review and meta-analysis of butter consumption and risk of cardiovascular disease, diabetes, and total mortality. Plos One. 2016; 11(6):e0158118. https://doi.org/10.1371/journal.pone.0158118.
10. Guasch-Ferré M, Hu FB, Martínez-González MA, Fito M, Bulló M, Estruch R, Ros E, Corella D, Recondo J, Gómez-Gracia E, Fiol M, Lapetra J, Serra-Majem L, Muñoz MA, Pintó X, Lamuela-Raventós RM, Basora J, Buil-Cosiales P, Soro JV, Ruiz-Gutiérrez V, Martínez JA, Salas-Salvadó J. Olive oil intake and risk of cardiovascular disease and mortality in the PREDIMED Study. BMC Med. 2014;12(1):78. https://doi.org/10.1186/1741-7015-12-78.
11. Guasch-Ferré M, Zong G, Willett Walter C, Zock P, Wanders Anne J, Hu Frank B, et al. Associations of monounsaturated fatty acids from plant and animal sources with total and cause-specific mortality in two US prospective cohort studies. Circ Res. 2019;124(8):1266–75. https://doi.org/10.1161/CIRCRESAHA.118.313996.
12. CW.C. Nutritional epidemiology. New York: Oxford University Press; 1998.
13. Midthune D, Schatzkin A, Subar AF, Thompson FE, Freedman LS, Carroll RJ, Shumakovitch MA, Kipnis V. Validating an FFQ for intake of episodically consumed foods: application to the National Institutes of Health–AARP Diet and Health Study. Public Health Nutr. 2011;14(7):1212–21. https://doi.org/10.1017/S136894621000632.
14. Subar AF, Midthune D, Kullendorf M, Brown CC, Thompson FE, Kipnis V. Schatzkin A. Evaluation of alternative approaches to assign nutrient values to food groups in frequency questionnaires. Am J Epidemiol. 2000; 152(3):279–86. https://doi.org/10.1093/aje/152.3.279.
15. Krebs-Smith SM, Panuuci TE, Subar AF, Kirkpatrick SJ, Lerman JA, Tozzo JA, et al. Update of the healthy eating index: HEI-2015. J Acad Nutr Diet. 2018;118(9):1591–602. https://doi.org/10.1016/j.jand.2018.05.021.
16. Willett WC. Chapter 5: food frequency methods; chapter 6: reproducibility and validity of food-frequency questionnaires; 2012.
17. Guasch-Ferré M, Hu FB, Martínez-González MA, Sun Q, Willett WC, Hu FB. Olive oil consumption and risk of type 2 diabetes in US women. Am J Clin Nutr. 2015;102(2):479–86. https://doi.org/10.3945/ajcn.114.111209.
18. D’Agostino RB. Propensity score methods for bias reduction in the comparison of a treatment to a non-randomized control group. Stat Med. 1998;17(19):2265–81. https://doi.org/10.1002/(SICI)1097-028X(19981015)17:1 9<2265::AID-SIM918>3.0.CO;2-B.
19. 2013–2020 Dietary Guidelines for Americans, 8th Edition. U.S. Department of Health and Human Services and U.S. Department of Agriculture December. 2015.
20. Wang DD, Li Y, Chiuve SE, Stampfer MJ, Manson JE, Rimm EB, et al. Association of specific dietary fats with total and cause-specific mortality. JAMA Intern Med. 2016;176(8):1134–45. https://doi.org/10.1001/jama. internmed.2016.2417.
