Meat consumption and incident type 2 diabetes: an individual-participant federated meta-analysis of 1·97 million adults with 100 000 incident cases from 31 cohorts in 20 countries

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Summary

Background Meat consumption could increase the risk of type 2 diabetes. However, evidence is largely based on studies of European and North American populations, with heterogeneous analysis strategies and a greater focus on red meat than on poultry. We aimed to investigate the associations of unprocessed red meat, processed meat, and poultry consumption with type 2 diabetes using data from worldwide cohorts and harmonised analytical approaches.

Methods This individual-participant federated meta-analysis involved data from 31 cohorts participating in the InterConnect project. Cohorts were from the region of the Americas (n=12) and the Eastern Mediterranean (n=2), European (n=9), South-East Asia (n=1), and Western Pacific (n=7) regions. Access to individual-participant data was provided by each cohort; participants were eligible for inclusion if they were aged 18 years or older and had available data on dietary consumption and incident type 2 diabetes and were excluded if they had a diagnosis of any type of diabetes at baseline or missing data. Cohort-specific hazard ratios (HRs) and 95% CIs were estimated for each meat type, adjusted for potential confounders (including BMI), and pooled using a random-effects meta-analysis, with meta-regression to investigate potential sources of heterogeneity.

Findings Among 1 966 444 adults eligible for participation, 107 271 incident cases of type 2 diabetes were identified during a median follow-up of 10 (IQR 7–15) years. Median meat consumption across cohorts was 0–110 g/day for unprocessed red meat, 0–49 g/day for processed meat, and 0–72 g/day for poultry. Greater consumption of each of the three types of meat was associated with increased incidence of type 2 diabetes, with HRs of 1·10 (95% CI 1·06–1·15) per 100 g/day of unprocessed red meat (I^2=61%), 1·15 (1·11–1·20) per 50 g/day of processed meat (I^2=59%), and 1·08 (1·02–1·14) per 100 g/day of poultry (I^2=68%). Positive associations between meat consumption and type 2 diabetes were observed in North America and in the European and Western Pacific regions; the CIs were wide in other regions. We found no evidence that the heterogeneity was explained by age, sex, or BMI. The findings for poultry consumption were weaker under alternative modelling assumptions. Replacing processed meat with unprocessed red meat or poultry was associated with a lower incidence of type 2 diabetes.

Interpretation The consumption of meat, particularly processed meat and unprocessed red meat, is a risk factor for developing type 2 diabetes across populations. These findings highlight the importance of reducing meat consumption for public health and should inform dietary guidelines.

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Introduction

Global meat production has increased rapidly over the past 50 years. Dietary meat consumption surpasses optimal dietary guidelines in many regions,[1] and is correlated with an elevated burden of non-communicable diseases, including type 2 diabetes.[2–4] Type 2 diabetes affects more

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Research in context

Evidence before this study

We searched PubMed for articles published between Jan 1, 1970, and Dec 1, 2023, using the terms "meat" OR "poultry" OR "chicken" AND "diabetes", with no language restrictions; this search returned 2583 results. 21 individual cohort studies and nine meta-analysis studies that evaluated associations between meat consumption and type 2 diabetes in populations were considered. The reference lists of these studies were also screened to identify other relevant publications. All the existing meta-analyses were conducted on the basis of published summary data and the included studies were primarily from high-income countries, mainly within Europe and North America. Limitations of these meta-analyses included publication bias and large heterogeneity. Additionally, previous studies focused primarily on the consumption of unprocessed red meat and processed meat, with little evidence for poultry, and had conflicting conclusions. A few reviews indicated that consuming red meat might be associated with a slightly higher risk of incident type 2 diabetes, and some critiqued the current evidence as being insufficient to guide dietary recommendations or intervention.

Added value of this study

Our prospective study of almost 1·97 million participants—with more than 100 000 incident cases during follow-up—examined associations of the consumption of unprocessed red meat, processed meat, and poultry with incident type 2 diabetes across global populations, in a federated meta-analysis of individual-participant data. This study included 31 cohorts from 20 countries, which—to our knowledge—exceeds the scale of any previous research on this topic. Notably, our study included previously under-represented populations from the Eastern Mediterranean and Western Pacific regions and from South America and south Asia, and we used harmonised data and unified analytical methods. We found that higher meat consumption, particularly of unprocessed red meat and processed meat, was associated with higher incidence of type 2 diabetes across populations. Positive associations were observed in the region of the Americas and in the European and Western Pacific regions; the CIs were broader in the Eastern Mediterranean region and in south Asia. The positive association between poultry consumption and type 2 diabetes was smaller and more heterogeneous across cohorts than that for red meat consumption. Moreover, our findings indicated that replacing processed meat with either unprocessed red meat or poultry was associated with a lower risk of type 2 diabetes.

Implications of all the available evidence

Our federated meta-analysis supports dietary recommendations to limit the consumption of processed meat and unprocessed red meat to reduce the risk of type 2 diabetes. Evidence regarding the effect of poultry consumption is less consistent, highlighting the need for further research. The consumption of unprocessed red meat and poultry had a lower risk association with type 2 diabetes than the consumption of processed meat, and further comparison between these types of meat is warranted. This study is, to our knowledge, the most comprehensive evidence base to date on the consumption of different types of meat and the risk of developing type 2 diabetes and, together with previous evidence, provides support for public health initiatives to reduce the consumption of meat to improve human health and planetary sustainability.

than 500 million people worldwide and is estimated to affect 1 billion people by 2050.[4] Evidence from several meta-analyses of published prospective studies shows a positive association between intakes of unprocessed red meat and processed meat and the risk of type 2 diabetes.[5–11] However, some reviews have drawn contradictory conclusions on the certainty of evidence in this field.[12–15] Specifically, some studies concluded that the current evidence is weak and of low certainty for guiding dietary recommendations to limit meat consumption. These conclusions were derived from similar published data and results to other meta-analyses, but the data were interpreted differently (eg, without considering biological mechanisms) and through different evidence-grading approaches (such as the burden of proof approach or the GRADE approach, which are potentially influenced by epidemiological biases[16]), and potential conflicts of interest cannot be ruled out.[13–15] Poultry has often been considered a potentially healthier alternative to red and processed meat;[17–19] however, the association between poultry consumption and type 2 diabetes risk has been characterised in only a few studies, with inconclusive results.[6,20–22] Moreover, published associations between meat consumption and the incidence of type 2 diabetes have been heterogeneous, probably because of variations in research methods (such as the extent of adjustment for potential confounders and baseline-only *vs* repeated dietary assessment) and variations in population-specific characteristics (such as cooking methods).[5,6,13,14]

Besides the heterogeneity in published findings, the existing evidence shows a geographical imbalance. The majority of studies are from populations in the USA and Europe with few from Asia and other areas, underscoring the need for evaluation in diverse populations.[5,6] An analysis of geographically diverse data is crucial for characterising the association between meat consumption and incident type 2 diabetes and understanding the potential sources of the heterogeneity.

To our knowledge, no study to date has conducted a meta-analysis of individual-participant data to investigate the association between meat consumption and incident type 2 diabetes. In this study, we hypothesised that intakes of unprocessed red meat and processed meat are associated with higher incidence of type 2 diabetes

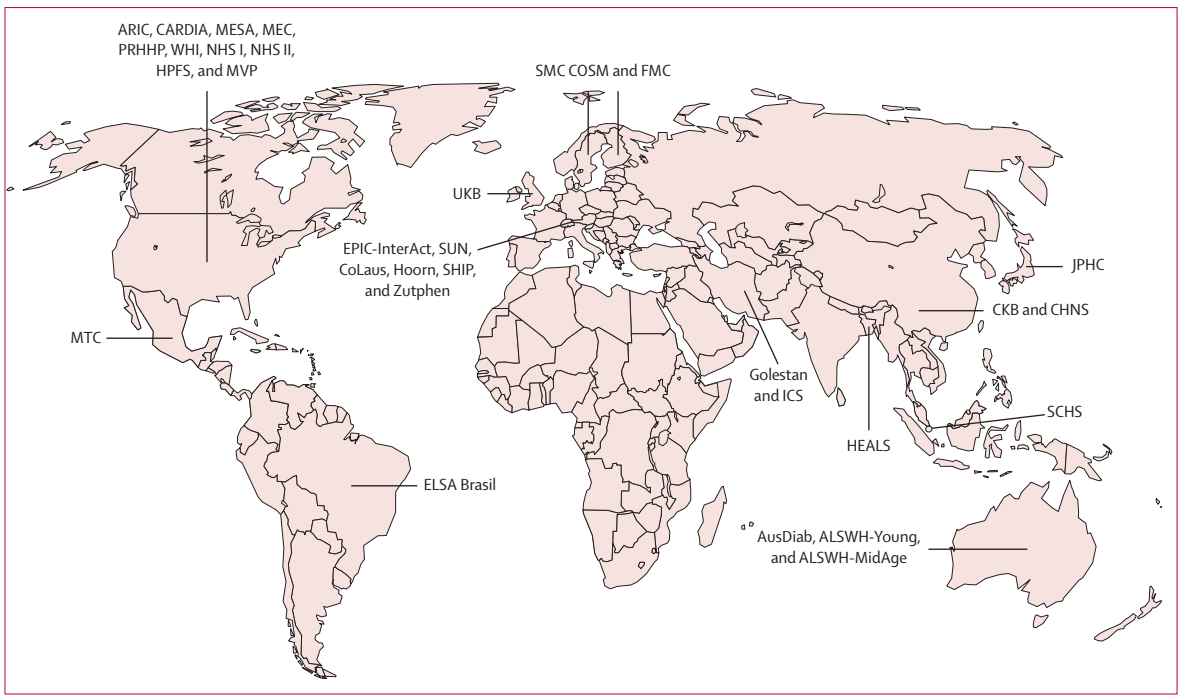

Figure 1: **The geographical distribution of the 31 cohorts**
ALSWH=Australian Longitudinal Study on Women's Health. ARIC=Atherosclerosis Young Adults Study. AusDiab=Australian Diabetes, Obesity and Lifestyle Study. CARDIA=Coronary Artery Risk Development in Young Adults. CHNS=China Health and Nutrition Survey. CKB=China Kadoorie Biobank. CoLaus=Cohorte Lausannoise Study. COSM=Cohort of 50 000 Swedish Men. ELSA-Brasil=Brasilian Longitudinal Study of Adult Health. EPIC=European Prospective Investigation into Cancer. FMC=Finnish Mobile Clinic Health Examination Survey. HEALS=Health Effects of Arsenic Longitudinal Study. Golestan=The Golestan Cohort Study. Hoorn=Hoorn Study. HPFS=Health Professionals Follow-up Study. ICS=Isfahan Cohort Study. JPHC=Japan Public Health Center-based Prospective Study. MEC=Multiethnic Cohort Study. MESA=Multi-Ethnic Study of Atherosclerosis. MTC=The Mexican Teachers' Cohort. MVP=Million Veteran Program. NHS=Nurses' Health Study. PRHHP=Puerto Rico Heart Health Program. SCHS=Singapore Chinese Health Study. SHIP=Study of Health in Pomerania. SMC=Swedish Mammography Cohort. SUN=Seguimiento Universidad de Navarra cohort study. UKB=UK Biobank. WHI=Women's Health Initiative Study. Zutphen=Zutphen Elderly Study.

and that poultry consumption is not associated with risk of type 2 diabetes, and could therefore be a healthier alternative to unprocessed red meat and processed meat. We aimed to address these hypotheses by estimating associations between meat consumption and type 2 diabetes using a federated meta-analysis of harmonised individual-participant data from diverse populations within the global InterConnect project.

Methods

Study design and participants

This federated meta-analysis used data from cohorts participating in the InterConnect project. This international research project aims to optimise the use of individual-participant data by enabling cross-cohort analyses without pooling data at a central location. The InterConnect registry was compiled using systematic searches of the literature alongside surveys of other online study registries, investigation of websites relating to consortia of studies, and searches of the grey literature to identify unpublished data. This registry included more than 200 independent cohorts and has established several consortia for conducting federated meta-analyses and addressing specific research questions.[23–26] Cohorts eligible for the current study contained participants aged 18 years or older with available data for dietary consumption and incident type 2 diabetes. For each cohort, we excluded participants with a diagnosis of prevalent diabetes of any type at analytical baseline, those with implausible energy intakes (<500 kcal/day or >3500 kcal/day for women and <800 kcal/day or >4200 kcal/day for men), or those with missing values for any of the exposures, outcomes, or potential confounders. We attempted to contact 115 eligible cohorts, of which 31 from 20 countries agreed to participate in this study (figure 1, appendix pp 2–7). We were unable to establish contact with 60 cohorts, 11 lacked the capacity or resources to contribute, nine lapsed communications during the process, and four did not have sufficient data on exposure, outcome, or covariates. We classified regions according to the WHO, and the 31 cohorts included 12 from the region of the Americas (Brazil, Mexico, Puerto Rico, and the USA), nine from the European region (Denmark, Finland, France, Germany, Spain, Sweden, Switzerland, The Netherlands, and the UK), seven from the Western Pacific region (Australia, China, Japan, and Singapore), two from the Eastern Mediterranean region (Iran), and one from the South-East Asia region (Bangladesh). A third of participants were from the Western Pacific

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See Online for appendix

For the **US Department of Agriculture databases** see https://www.nal.usda.gov/human-nutrition-and-food-safety/food-composition

region. Four different methods were used in the meta-analysis of individual participant data. Of the 31 participating cohorts, ten followed the procedure for the federated meta-analysis (appendix p 17); ten uploaded their data to a central server in Cambridge, UK, following the approval of data-sharing requests; eight provided summarised statistics following a standardised analysis protocol; and three granted data access through a trusted research environment (appendix p 5). All cohorts obtained ethical review board approval at the host institution and written or oral informed consent from participants.

Consumption of meat and other food groups

Dietary information in the participating cohorts was collected by self-reported approaches: 26 cohorts used food frequency questionnaires, three used dietary history, and two used dietary records (appendix p 2). Most cohorts provided exposure data in units of g/day. The consumption data in other formats were transformed to g/day on the basis of variable-specific standard portion sizes sourced from the databases from the US Department of Agriculture Three primary exposure variables were determined by calculating total consumption levels of unprocessed red meat (eg, beef, pork, lamb, and veal), processed meat (eg, bacon, ham, sausage, and hot dog), and poultry (eg, chicken, turkey, duck, and goose). Consumption levels of other food groups were considered as covariates. Dietary information was collected once in most cohorts, except for in the Health Professionals Follow-up Study (HPFS), the Nurses' Health Study (NHS) I, and NHS II, which assessed participants' diets every 2–4 years from baseline (1986 for HPFS, 1980 for NHS I, and 1991 for NHS II; appendix p 2).[27] Total energy intake was calculated using cohort-specific or region-specific serving-size estimates and food composition information.

Ascertainment of incident type 2 diabetes

We used two different definitions of type 2 diabetes,[24,25] one as the primary outcome and one as the secondary outcome. For the primary definition, a case of incident type 2 diabetes was confirmed if one or more of the following criteria were fulfilled: (1) diagnosis ascertained by linkage to a registry or medical record; (2) confirmed use of antidiabetic medication; or (3) self-report of diagnosis by physician or use of antidiabetic medication, verified by any of the following: at least one additional source from (1) and (2); biochemical measurement (glucose concentration or HbA_{1c}); or a validation study in which subjective information was verified by a within-cohort validation substudy with high concordance. For the secondary definition, which was more inclusive, a case of incident type 2 diabetes was confirmed if any of the following criteria were fulfilled: diagnosis ascertained by linkage to a registry or medical record; confirmed use of antidiabetic medication; self-report of diagnosis by physician or use of antidiabetic medication; or biochemical measurement (glucose concentration or HbA_{1c}).

Covariates

We considered the following covariates as potential confounding factors (for cohort-specific details, see appendix p 8) according to published literature and biological plausibility: sociodemographic characteristics (age, sex, ethnicity, and education level), health and lifestyle behaviours (smoking, drinking alcohol, and physical activity), dietary information (consumption of fruits, vegetables, fish, dairy, legumes, soy, nuts and seeds, eggs, cereal products, whole grains, potatoes, fibre, sugar-sweetened beverages, coffee, tea, and cooking fat and total energy intake), BMI, comorbidities at baseline (hypertension, dyslipidaemia, myocardial infarction, stroke, or cancer), and family history of any type of diabetes. The three types of meat were mutually adjusted for each other.

Statistical analysis

For the ten cohorts setting up a server for federated analysis, cohort-specific analyses were conducted using DataSHIELD (dsBase version 6.3.0, dsSurvival v2.1.0; appendix p 17).[28,29] In the JPHC study, Poisson regression was used to estimate risk ratios, but for all other studies hazard ratios (HRs) and 95% CIs for the association of each meat type with the hazard of type 2 diabetes were estimated using Cox regression models fit to the data in each cohort. In the EPIC-InterAct case-cohort study, Prentice-weighted Cox regression was used.[30] For unprocessed red meat and poultry, a serving was considered to be 100 g, whereas a serving of processed meat was considered to be 50 g. As commonly consumed, 100 g/day red meat equates to a daily consumption of a small steak or a medium-sized hamburger patty; 50 g/day processed meat equates to two or three slices of bacon or a medium-sized sausage. Thus, HRs were estimated for 100 g/day of unprocessed red meat, 50 g/day of processed meat, and 100 g/day of poultry, equivalent to a standard portion size for each type of meat. Multiple models were fitted: model 1 adjusted for age and sex; model 2 further adjusted for education, smoking, physical activity, alcohol intake, squared alcohol intake, total energy intake, BMI, squared BMI, and dietary information (see Covariates). Models not adjusting for BMI were also fitted to examine the effect of BMI adjustment on the association between meat consumption and type 2 diabetes. Some potential confounders (eg, waist circumference, cooking method, family history of any type of diabetes, and comorbidity) were not available for many studies and were examined only in additional analyses.

We pooled estimated effects across all cohorts and by global region using a random-effects meta-analysis. Heterogeneity was quantified using I^2 statistics. To investigate potential sources of heterogeneity, we

	Number of participants (N=1 966 444)	Proportion of women, men (%)	Age (years)	Meat consumption (g/day)			Primary outcome		Secondary outcome	
				Unprocessed red meat	Processed meat	Poultry	Number of events (N=107 271)	Median follow-up period (years)	Number of events (N=112 110)	Median follow-up period (years)
Region of the Americas										
ARIC	11 893	55·6%, 44·4%	54 (49–59)	66 (40–120)	16 (8–36)	32 (16–49)	804	9·1	2339	9·0
CARDIA	3923	58·7%, 41·3%	25 (22–28)	110 (47–190)	17 (7–33)	63 (29–120)	198	25·0	396	25·0
ELSA-Brasil	10 972	57·3%, 42·7%	50 (45–57)	49 (32–93)	15 (6–28)	72 (24–100)	1695	8·0	1695	8·0
HPFS	45 302	0·0%, 100·0%	53 (49–65)	61 (0–985)	11 (0–314)	49 (0–1680)	4385	23·5	4385	23·5
MEC	143 811	43·1%, 56·9%	59 (51–67)	30 (16–49)	13 (6–23)	32 (19–54)	7856	17·0	7856	17·0
MESA	4923	54·0%, 46·0%	61 (53–70)	32 (16–56)	4 (0–11)	34 (18–59)	228	9·0	692	9·0
MTC	46 650	100·0%, 0·0%	42 (35–46)	23 (13–42)	22 (12–35)	34 (11–34)	2012	6·6	2132	6·6
MVP	225 667	100·0%, 0·0%	65(53–78)	45 (24–93)	10 (5–24)	60 (30–110)	9874	5·6	9874	5·6
NHS I	69 698	100·0%, 0·0%	46 (39–52)	63 (0–1676)	8 (0–682)	43 (0–1176)	5644	21·3	5644	21·3
NHS II	90 746	100·0%, 0·0%	36 (33–41)	58 (0–1359)	8 (0–633)	52 (0–1260)	7411	25·4	7411	25·4
PRHHP	6977	0·0%, 100·0%	52 (47–57)	28 (0–85)	0 (0–28)	0 (0–57)	213	5·0	825	5·0
WHI	83 491	100·0%, 0·0%	64 (58–69)	25 (11–48)	7 (2–16)	25 (12–48)	7404	7·9	7721	7·9
Eastern Mediterranean region										
Golestan	10 145	51·7%, 48·3%	50 (45–56)	9 (4–17)	0 (0–2)	48 (26–77)	686	4·2	1191	4·1
ICS	3125	49·1%, 50·9%	46 (41–56)	48 (32–113)	0 (0–8)	16 (16–48)	417	7·0	417	7·0
European region										
CoLaus	3208	57·6%, 42·4%	57 (47–67)	27 (12–48)	17 (7–33)	17 (9–25)	80	9·0	80	9·0
FMC	9057	48·6%, 51·4%	38 (25–51)	60 (38–92)	40 (20–70)	0 (0–3)	481	24·0	481	24·0
Hoorn	2800	54·2%, 45·8%	57 (52–62)	32 (18–47)	40 (24–63)	8 (4–18)	21	7·0	295	7·0
EPIC-InterAct	25 952	57·3%, 42·7%	55 (50–61)	42 (20–66)	27 (15–43)	17 (6–29)	11 089	11·0	11 089	11·0
SHIP	2841	53·2%, 46·8%	47 (35–59)	53 (30–56)	49 (20–58)	12 (12–17)	93	13·0	294	14·0
SMC COSM	49 461	45·9%, 54·1%	58 (52–66)	44 (26–63)	32 (19–45)	8 (8–10)	4831	18·0	4910	18·0
SUN	18 446	60·1%, 39·9%	35 (27–46)	74 (43–100)	47 (28–69)	64 (43–130)	224	11·0	576	11·0
UKB	456 708	55·2%, 44·8%	58 (38–73)	75 (0–130)	3 (0–80)	36 (0–57)	16 592	7·2	16 592	7·2
Zutphen	485	0·0%, 100·0%	70 (67–74)	69 (52–89)	25 (12–40)	7 (0–19)	11	10·0	62	10·0
South Asia										
HEALS	11 871	57·7%, 42·3%	36 (30–45)	0 (0–24)	NA	0 (0–0)	166	4·0	166	4·0
Western Pacific region and east Asia										
ALSWH-MidAge	8617	100·0%, 0·0%	52 (51–54)	55 (31–90)	12 (5–23)	22 (12–37)	869	15·0	869	15·0
ALSWH-Young	6939	100·0%, 0·0%	28 (26–29)	48 (24–82)	15 (6–28)	26 (13–43)	118	15·0	118	15·0
AusDiab	6199	55·3%, 44·7%	50 (41–59)	61 (35–98)	18 (8–32)	26 (13–40)	197	12·0	390	12·0
CHNS	7962	52·7%, 47·3%	49 (39–60)	18 (0–60)	0 (0–3)	8 (4–20)	21	6·0	311	6·0
CKB	482 423	58·9%, 41·1%	51 (42–59)	29 (29–100)	NA	12 (7–18)	9601	7·2	9601	7·2
JPHC	70 386	55·0%, 45·0%	56 (49–63)	42 (22–65)	5 (0–10)	8 (3–14)	1322	5·0	1322	5·0
SCHS	45 235	57·5%, 42·5%	54 (49–61)	21 (12–34)	1 (0–3)	16 (8–28)	5185	12·0	5185	12·0

Data are n or median (IQR) unless otherwise stated. In the AusDiab cohort, incident type 2 diabetes was defined using HbA_{1c}. ALSWH=Australian Longitudinal Study on Women's Health. ARIC=Atherosclerosis Young Adults Study. AusDiab=Australian Diabetes, Obesity and Lifestyle Study. CARDIA=Coronary Artery Risk Development in Young Adults. CHNS=China Health and Nutrition Survey. CKB=China Kadoorie Biobank. CoLaus=Cohorte Lausannoise Study. COSM=Cohort of 50 000 Swedish Men. ELSA-Brasil=Brasilian Longitudinal Study of Adult Health. EPIC=European Prospective Investigation into Cancer. FMC=Finnish Mobile Clinic Health Examination Survey. HEALS=Health Effects of Arsenic Longitudinal Study. Golestan=The Golestan Cohort Study. Hoorn=Hoorn Study. HPFS=Health Professionals Follow-up Study. ICS=Isfahan Cohort Study. JPHC=Japan Public Health Center-based Prospective Study. MEC=Multiethnic Cohort Study. MESA=Multi-Ethnic Study of Atherosclerosis. MTC=The Mexican Teachers' Cohort. MVP=Million Veteran Program. NHS=Nurses' Health Study. PRHHP=Puerto Rico Heart Health Program. SCHS=Singapore Chinese Health Study. SHIP=Study of Health in Pomerania. SMC=Swedish Mammography Cohort. SUN=Seguimiento Universidad de Navarra cohort study. UKB=UK Biobank. WHI=Women's Health Initiative Study. Zutphen=Zutphen Elderly Study.

Table: **Characteristics of the included cohorts from the InterConnect project**

conducted meta-regression analyses using the following study-level characteristics: median intake of meat, mean age, sex, mean BMI, number of incident cases, dietary assessment approach, geographical area, and duration of follow-up.

We conducted various secondary analyses in each cohort and pooled the results using a random-effects meta-analysis. We used a fixed-effect meta-analysis as an alternative approach to combine estimates across cohorts. Effect modification was examined by age

(age <60 years or ≥60 years), sex, and BMI (<25 kg/m² or ≥25 kg/m²) by conducting subgroup analyses for each of these variables. To explore non-linearity in the associations of interest, the exposure was modelled as categorical or using restricted cubic splines. The main analyses were repeated with the secondary definition of type 2 diabetes as the outcome variable. Behavioural characteristics might be different between participants with comorbidities and those without, or between meat consumers and non-consumers. To reduce potential confounding by these characteristics, we repeated the analysis after excluding participants with any comorbidity (dyslipidaemia, hypertension, myocardial infarction, stroke, or cancer) at baseline and after excluding non-consumers of each meat type. We also repeated analyses after excluding individuals who developed type 2 diabetes during the first 2 years of follow-up to reduce the possibility of reverse causality. For the primary findings, the certainty of the meta-evidence was evaluated by two authors (CL and FI) using the NutriGrade scoring system (possible score 0–10 points), accounting for precision, heterogeneity, directness, and various sources of bias.[31]

We conducted food substitution analyses to test whether one meat type could be a healthier alternative to the other for reducing the risk of type 2 diabetes.[32] We computed a logged difference between the estimated coefficients,[17,32] eg, $\ln(\beta_{poultry} - \beta_{processed\ meat})$, from the most adjusted Cox model to estimate the hypothetical effect of substituting 100 g/day of poultry for 50 g/day of processed meat. In other words, this example would test the modelled effect of replacing 50 g/day of processed meat with 100 g/day of poultry.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

This federated meta-analysis included data from 1966 444 individuals from 31 cohorts participating in the InterConnect project (table, figure 1, appendix pp 2–4). Among these cohorts, 18 had not previously published findings on this research topic. Six cohorts (the Australian Longitudinal Study on Women's Health [ALSWH]-MidAge, ALSWH-Young, the Mexican Teachers' Cohort [MTC], NHS I, NHS II, and the Women's Health Initiative Study [WHI]) comprised entirely women and three cohorts (HPFS, the Puerto Rico Heart Health Program [PRHHP], and the Zutphen Elderly Study [Zutphen]) consisted of men only. 21 cohorts recruited participants with median ages between 40 years and 60 years, six cohorts recruited participants younger than 40 years, and in four cohorts participants were 60 years or older.

Meat consumption varied by population (table, appendix p 9). The median consumption of unprocessed red meat ranged from 0 (IQR 0–24) g/day in the Health Effects of Arsenic Longitudinal Study (HEALS) cohort in Bangladesh to 110 (47–190) g/day in the Coronary Artery Risk Development in Young Adults (CARDIA) cohort in the USA. For processed meat, consumption ranged from 0 g/day (0 [0–2] g/day in the Golestan Cohort Study [Golestan; Iran], 0 [0–8] g/day in the Isfahan Cohort Study [ICS; Iran], and 0 [0–28] g/day in the PRHHP cohort [Puerto Rico]) to 49 (20–58) g/day in the Study of Health in Pomerania (SHIP) cohort in Germany. Poultry consumption ranged from 0 g/day (0 [0–0] g/day in the HEALS cohort and 0 [0–57] g/day in the PRHHP cohort) to 72 (24–100) g/day in the Brasilian Longitudinal Study of Adult Health (ELSA Brasil) cohort from Brazil. Cohorts in the European region reported higher consumption of processed meat than those in other regions, whereas cohorts in the region of the Americas reported higher poultry consumption than those in other regions.

Over a median follow-up of 10 (IQR 7–15) years, 107 271 incident cases of type 2 diabetes were identified according to the primary definition (table). The consumption of unprocessed red meat was positively associated with incident type 2 diabetes in the most adjusted model, with an HR per 100 g/day intake of 1·10 (95% CI 1·06–1·15; I^2=61%; figure 2). Associations were also seen for processed meat consumption, with an HR per 50 g/day intake of 1·15 (1·11–1·20; I^2=59%), and poultry consumption, with an HR per 100 g/day of 1·08 (1·02–1·14; I^2=68%). The positive associations of unprocessed red meat and processed meat with incident type 2 diabetes were significant in the region of the Americas (HRs 1·13 [1·06–1·20] for unprocessed red meat and 1·17 [1·10–1·24] for processed meat), in the European region (HRs 1·06 [1·04–1·09] for unprocessed red meat and 1·13 [1·07–1·19] for processed meat), and in the Western Pacific region and east Asia (HRs 1·17 [1·01–1·36] for unprocessed red meat and 1·15 [1·01–1·32] for processed meat). These associations were not evident in the Eastern Mediterranean region (two studies) and in South Asia (one study). The positive association between poultry consumption and incidence of type 2 diabetes was significant in the European region (1·10 [1·01–1·21]), whereas it was not significant in other regions.

Heterogeneity between cohorts was found for all the observed associations between meat and type 2 diabetes (figure 2). There was no evidence that the heterogeneity was explained by age, sex, or BMI (appendix p 10). The association of unprocessed red meat with type 2 diabetes was weaker in European cohorts than in American cohorts by 8% (95% CI 1–15; p=0·022; HRs 1·06 *vs* 1·13; appendix p 11). There was also a suggestion that the associations were stronger in cohorts with larger numbers of type 2 diabetes cases.

Results from the primary analyses were substantiated in our secondary analyses using fixed-effect models for the pooled meta-analysis, evaluating the secondary definition

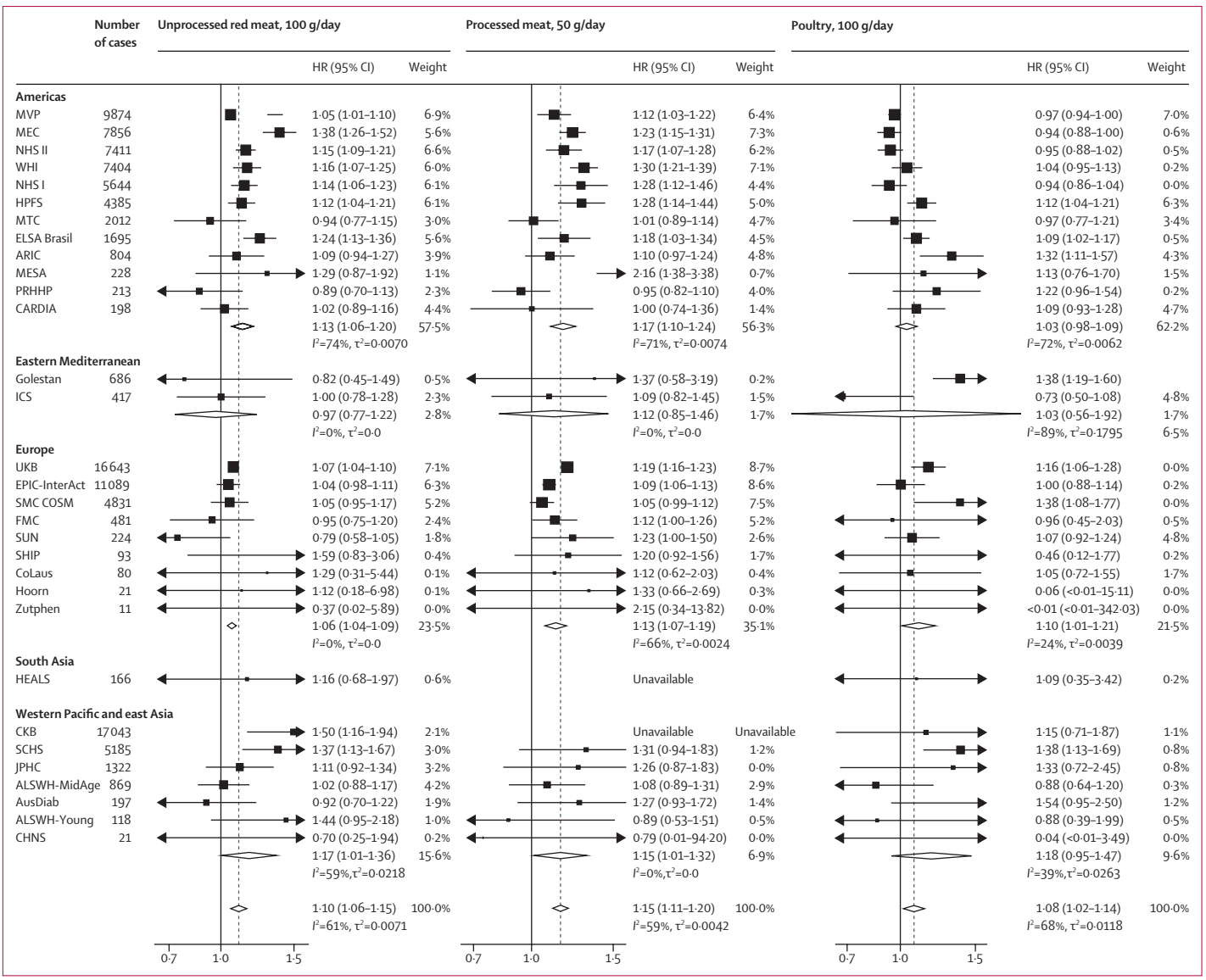

Figure 2: **Associations of meat consumption with incident type 2 diabetes in cohorts from the InterConnect project**

HRs with 95% CIs were estimated for each meat type and adjusted for age, sex, education level, smoking status, physical activity, alcohol intake, total energy intake, BMI, and other food intakes (fruit, vegetables, fish, dairy, legumes, soy, nuts and seeds, eggs, cereal products, whole grains, potatoes, fibre, sugar-sweetened beverages, coffee, tea, and, mutually, the other meat types). For full names of the cohorts, see appendix pp 2–4. For each region, the sum of the percentages might not equal the total stated owing to rounding. ALSWH=Australian Longitudinal Study on Women's Health. ARIC=Atherosclerosis Young Adults Study. AusDiab=Australian Diabetes, Obesity and Lifestyle Study. CARDIA=Coronary Artery Risk Development in Young Adults. CHNS=China Health and Nutrition Survey. CKB=China Kadoorie Biobank. CoLaus=Cohorte Lausannoise Study. COSM=Cohort of 50 000 Swedish Men. ELSA-Brasil=Brasilian Longitudinal Study of Adult Health. EPIC=European Prospective Investigation into Cancer. FMC=Finnish Mobile Clinic Health Examination Survey. HEALS=Health Effects of Arsenic Longitudinal Study. Golestan=The Golestan Cohort Study. Hoorn=Hoorn Study. HPFS=Health Professionals Follow-up Study. HR=hazard ratio. ICS=Isfahan Cohort Study. JPHC=Japan Public Health Center-based Prospective Study. MEC=Multiethnic Cohort Study. MESA=Multi-Ethnic Study of Atherosclerosis. MTC=The Mexican Teachers' Cohort. MVP=Million Veteran Program. NHS=Nurses' Health Study. PRHHP=Puerto Rico Heart Health Program. SCHS=Singapore Chinese Health Study. SHIP=Study of Health in Pomerania. SMC=Swedish Mammography Cohort. SUN=Seguimiento Universidad de Navarra cohort study. UKB=UK Biobank. WHI=Women's Health Initiative Study. Zutphen=Zutphen Elderly Study.

of type 2 diabetes, adding each of the additional exclusion criteria sequentially (ie, meat non-consumers, individuals with comorbidity, cases of early-onset type 2 diabetes in the first 2 years of follow-up), or altering covariates (appendix pp 12–14). Illustrative models without BMI adjustment showed HRs of 1·18 (95% CI 1·07–1·29) for unprocessed red meat, 1·23 (1·14–1·34) for processed meat, and 1·21 (1·12–1·31) for poultry; for models with BMI adjustment, HRs were reduced to 1·10 (1·06–1·15) for unprocessed red meat, 1·15 (1·11–1·20) for processed meat, and 1·08 (1·02–1·14) for poultry (appendix p 12). Additionally, the association between poultry consumption and the incidence of type 2 diabetes was weaker when using a fixed-effect meta-analysis (HR [95% CI] per 100 g/day of poultry 1·02 [1·00–1·04]), adjusting for cooking methods (1·05 [0·98–1·12]), or excluding meat

non-consumers (1·06 [0·99–1·13]; appendix pp 12–14). The certainty of evidence was rated as high (≥8 points) for unprocessed red meat and processed meat and moderate (7 points) for poultry. The analyses exploring potential dose–response relationships found log-linear associations for each meat type, without any obvious threshold or ceiling effect (appendix p 15).

In the most adjusted model including BMI, replacing 50 g/day of processed meat with 100 g/day of unprocessed red meat was estimated to reduce the hazard of type 2 diabetes by 7% on average (HR 0·93 [95% CI 0·90–0·97]; appendix p 16). A similar estimate was obtained when replacing 50 g/day of processed meat with 100 g/day of poultry (0·90 [0·82–0·97]). We found no evidence that replacing unprocessed red meat with poultry was associated with a reduction in incident type 2 diabetes (0·98 [0·90–1·97]).

Discussion

The InterConnect project enabled an extensive evaluation of associations between meat consumption and type 2 diabetes using an individual-participant federated meta-analysis, including more than 100 000 cases of incident type 2 diabetes arising from 31 cohorts in 20 countries. Our findings show that the consumption of unprocessed red meat, processed meat, and poultry were each associated with an increased risk of type 2 diabetes. The associations varied across cohorts, but we found no specific factor (ie, age, sex, BMI, number of incident cases, follow-up duration, levels of meat consumption, dietary assessment approach, or geographical location) that could meaningfully account for this heterogeneity. The association between poultry consumption and type 2 diabetes was weaker than that for unprocessed red meat and processed meat consumption, but still suggested a slightly higher rate of type 2 diabetes. Moreover, when replacing processed meat consumption, both unprocessed red meat and poultry consumption were associated with a lower risk of developing type 2 diabetes in modelled food substitution analyses.

To our knowledge, we provide the most comprehensive evidence to date on the associations of unprocessed red meat and processed meat with type 2 diabetes, and our findings partly align with previous evidence.[5–11,33] Compared with the previous publication-based meta-analysis by Shi and colleagues[5] and others,[6–11] our study showed weaker positive associations based on estimates from 31 cohorts, 18 of which had not previously published data on the associations between meat consumption and type 2 diabetes. The stronger associations summarised from previously published meta-analyses could reflect publication bias in the previous summary evidence[20] and highlights the crucial role of a prospective pooling project in evidence synthesis.[24,25,34] Additionally, the smaller magnitude of the associations we found could reflect regression dilution due to the use of single baseline measurements of dietary habits. The magnitude of the association observed in our study was smaller than that in a 2023 pooled analysis of three US cohorts by Gu and colleagues[19] that incorporated repeated measures of meat consumption and time-varying covariates. However, the estimates by Gu and colleagues[19] and our summary estimates were similar before and after adjustment for BMI; eg, Gu and colleagues[19] reported HRs per 100 g/day of unprocessed red meat of 1·28 before BMI adjustment and 1·12 after BMI adjustment, whereas we reported 1·18 before BMI adjustment and 1·10 after BMI adjustment. The difference in the estimates before adjustment for BMI could reflect a population-specific confounding effect, including health consciousness and dietary misreporting due to BMI and long-term behavioural characteristics that cumulatively determined BMI. Notably, adjusting for baseline BMI provided interpretation under the energy-balanced condition, but could cause over-adjustment; BMI might be on the causal pathway and therefore be a mediator of the association between meat consumption and type 2 diabetes because of an association between meat intake and weight gain.[35,36] Our approach, showing results with and without adjustment for BMI, covers the possibility of BMI functioning as a potential confounder or a potential mediator.

Additionally, our research provides more comprehensive evidence further to previous inconclusive findings on the association between poultry intake and incident type 2 diabetes.[6,20,22] Although earlier studies mostly reported no relationship, the quality of included studies was evaluated as relatively low.[20,37] A 2020 meta-analysis indicated a weak positive association between poultry consumption and incident type 2 diabetes.[6] That meta-analysis involved published estimates from seven cohorts, five of which were included in our current federated meta-analysis. Our study improved upon previous evidence for poultry and type 2 diabetes by including nearly four times the number of incident cases and populations across diverse geographical regions; we also used harmonised analysis methods and reduced publication bias by including previously unpublished studies. However, the evidence for the positive association between poultry consumption and incidence of type 2 diabetes is still uncertain, because the association was heterogeneous by population and its strength was sensitive to modelling approaches, such as meta-analysis models. A random-effects model tends to assign disproportionate weight to small studies, resulting in broader CIs of pooled results.[38,39] Following Cochrane guidelines, we reported primary results using a random-effects meta-analysis owing to observed heterogeneity between cohorts.[40] Moreover, we additionally conducted a fixed-effect meta-analysis. In our study, the risk of type 2 diabetes associated with the consumption of unprocessed red meat and processed meat remained consistent between random-effects and fixed-effect approaches, but the strength of the association differed

by approach for poultry consumption. This result reinforces the robustness of our findings for red meat but suggests a potential heterogeneous association between poultry consumption and type 2 diabetes risk across populations. Despite the lower certainty in the association with poultry, we can conclude that consuming poultry might be associated with lower incidence of type 2 diabetes than consuming processed meat, as supported by the current food substitution analyses.

The underlying mechanisms that link meat intake with the development of type 2 diabetes are not fully established. Randomised controlled trials have investigated a mechanistic link between meat consumption intervention and risk markers for type 2 diabetes, such as HbA_{1c}, postprandial insulin concentration, and insulin resistance; however, no definitive effects have been reported.[41] Notably, the trials were only able to assess short-term effects of meat consumption on glycaemic traits rather than long-term effects on disease risk. Technologies such as metabolomics have emerged as complementary tools in nutritional epidemiology and the identification of metabolomic signatures for meat consumption is helping to enhance the mechanistic understanding of the association between meat consumption and disease risk, adding biological plausibility to the findings from observational studies.[42]

Meat consumption could affect type 2 diabetes risk through different causal mechanisms that worsen insulin sensitivity, pancreatic β-cell function, or both.[33] For example, red meat is rich in saturated fatty acids but low in polyunsaturated fatty acids, and switching from a diet rich in saturated fatty acids to one rich in polyunsaturated fatty acids was found to be associated with improved insulin resistance in a meta-analysis of short-term trials.[43] Additionally, meat is characterised by its high protein content, and some research has indicated a potential association between a high intake of animal proteins and increased risk of type 2 diabetes.[44–46] Another potential mechanism could be via trimethylamine *N*-oxide, a gut microbiota-dependent metabolite generated during the digestion of choline and L-carnitine, which are abundant in red meat, although the exact mechanism is yet to be established.[47] Nitrate or nitrite additives and the formation of *N*-nitroso compounds during meat processing are associated with a higher risk of type 2 diabetes.[48] Small-scale trials have indicated that advanced glycation end products—compounds generated when cooking meat products at high temperatures, such as frying or grilling—could contribute to oxidative stress, pro-inflammatory response, and subsequently insulin resistance.[49–51] Meat can be a major source of iron in many populations, but long-term iron intake has been implicated in an increased risk of type 2 diabetes in observational studies[52] and in Mendelian randomisation analysis.[53]

A strength of this study is that, to our knowledge, it is the largest meta-analysis on the topic to date, evaluating individual-level data across diverse populations. However, whether these findings can be generalised to Africa and the Middle East, for example, remains unknown. The prevalence of type 2 diabetes in the Middle East and north Africa is the highest globally at 16·2% and is estimated to increase to 19·3% by 2045, according to the International Diabetes Federation's Diabetes Atlas. Pursuing additional studies in these and other regions, such as south Asia, is essential to better understand the association between meat consumption and the development of type 2 diabetes. The potentially unique characteristics of meat consumption, the overall diet, and the cooking methods in such regions could aid local prevention strategies and advance our understanding of the mechanisms linking meat consumption to type 2 diabetes risk. This study accounted for a comprehensive range of potential confounding factors and used a federated approach that facilitated the harmonisation of data and the standardisation of analysis methods, thereby decreasing heterogeneity related to different analytical approaches. This study design resulted in smaller heterogeneities in the observed associations (59–68%) than those from previously published meta-analyses (76–93%).[5,6] Nevertheless, a moderate degree of heterogeneity in the observed associations persisted and could reflect differences in study design, the validity of meat intake assessment, and the ascertainment of diabetes, as well as true variation in the effects of consuming meat due to different subtypes of meat products, cooking methods, or physiological responses across populations in different regions. For example, cooking methods affect the nutrient composition of meats, including poultry. In the USA, fried chicken is a prevalent fast food and high levels of consumption could indicate a pattern of fast-food dietary habits in some participants. Therefore, further studies investigating the effects of lowering meat consumption remain crucial to optimise the application of the current evidence to the improvement of public health.

For the **Diabetes Atlas** see https://diabetesatlas.org/

This study has several limitations. We attempted to harmonise the analytical variables and analysis methods, but we were unable to use consistent tool development procedures and data collection methods for dietary consumption, potential confounders, and the type 2 diabetes outcomes. The lack of such harmonisation could have contributed to the observed heterogeneity. Our findings indicate a small association between meat consumption and incident type 2 diabetes, but the true magnitude of the association could have been underestimated owing to the use of baseline-only dietary exposure data in most cohorts, as well as our inability to conduct any correction for potentially varying degrees of measurement error in dietary assessment across cohorts. Such attenuation was illustrated in the US-based Harvard cohort analyses, published in 2023, in which an HR of 1·28 for type 2 diabetes was calculated per serving of total red meat using cumulative average dietary data, but this was reduced to 1·13 when using baseline-only dietary

data.[19] Similarly, after using regression calibration to account for measurement error, stronger associations between meat intake and type 2 diabetes risk were observed than when such a correction was not made in the Harvard cohorts.[19] Nonetheless, the smaller association identified in our federated meta-analysis is noteworthy, as it shows a consistent association across various populations. The observational nature of this research raises the possibility that residual confounding might exist, due to unmeasured or unaccounted factors as well as covariate measurement error. For example, meat consumption can be diverse, with varying preparation methods and properties, contributing to heterogeneity and residual confounding. Specifically, different fatty acid isomers or potentially harmful chemicals—such as advanced glycation end products—that can arise from different cooking methods and use of cooking fats were not accounted for in this or any other published research that we are aware of. Moreover, potential confounding from varying sociocultural factors could not be fully considered. Meat is a source of energy intake. Imprecise adjustment for energy homoeostasis could occur if energy intake and BMI were inaccurately measured. If energy balance is not a mediator, the observed associations could therefore reflect the bias away from the null owing to positive energy balance from meat consumption as well as relatively unhealthy lifestyles associated with meat consumption. Of 115 potentially eligible cohorts, only 31 were included in the current analysis for reasons beyond our control. Nonetheless, among the included cohorts, 18 had not previously published on this topic, with their inclusion reducing publication bias. Although we considerably increased the geographical diversity of study locations compared with previous analyses, overall there is still limited availability of studies from Africa, the Middle East, south Asia, and central and South America, reflecting an important research gap and highlighting the need for prospective epidemiological research in these locations.

In conclusion, higher meat consumption was associated with higher type 2 diabetes incidence in a global individual-participant-based federated meta-analysis. The current findings support the notion that lowering the consumption of unprocessed red meat and processed meat could benefit public health by reducing the incidence of type 2 diabetes. Uncertainty remains regarding the positive association between poultry consumption and the incidence of type 2 diabetes, and this association should be further investigated. Beyond research on type 2 diabetes, our integrative work stimulates further investigation on sustainable dietary patterns to reduce meat consumption and its effect on other non-communicable diseases, multimorbidity, and planetary health.

Contributors

NJW, NGF, FI, and CL designed the research. CL, TRPB, and FI conducted the federated meta-analyses. CL wrote the first draft of the manuscript with supervision from NJW, FI, SJS, and NGF. All authors interpreted the results and critically revised the article for important intellectual content, and read and approved the final version. CL and TRPB verified the data. NJW, NGF, FI, CL, and TRPB had access to raw data for the federated meta-analyses. All authors had final responsibility for the decision to submit for publication.

Declaration of interests

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Data sharing

The project was undertaken using a federated approach in which analyses are conducted centrally while data remain within the governance structure of the original studies. Data are held peripherally across multiple research institutions rather than being transferred and stored at a central location. Researchers seeking the analysis dataset for this work should submit requests to the individual studies detailed in the appendix (pp 2–3). Data from studies funded by the US National Institutes of Health were downloaded from the BioLINCC repository (https://biolincc.nhlbi.nih.gov/home/, accessed March 15, 2021). Summary estimates for these analyses were provided from the CKB cohort by MGK, from the CoLaus cohort by PM-V, from the JPHC cohort by FI, from the HPFS, NHS I, and NHS II cohorts by J-PD-C, and from the MVP cohort by YL.

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