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Associations of different definitions of prediabetes and diabetes with all-cause and cause-specific mortality: a nationally representative cohort study

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Abstract

Background: Different glycemic indicators and diagnostic criteria for prediabetes and diabetes identify overlapping but distinct populations. However, the extent to which these definitions lead to differences in estimated prevalence and associated health outcomes remains unclear. This study aimed to compare the prevalence of prediabetes and newly diagnosed diabetes across different glycemic indicators and diagnostic criteria, and to examine their associations with mortality and life expectancy.

Methods: We analyzed data from 141,945 adults from a nationally representative cohort study (the 2013 cycle of China Chronic Disease and Risk Factors Surveillance) in China, with follow-up through December 2021. Using fasting plasma glucose (FPG), 2-hour postload glucose (2hPG), and hemoglobin A1c (HbA1c) levels, prediabetes was defined according to the American Diabetes Association (ADA), World Health Organization (WHO), or International Expert Committee (IEC) criteria, and newly diagnosed diabetes was defined according to the ADA criteria. Cox proportional hazards regression models were used to estimate hazard ratios (*HRs*) of all-cause and cause-specific mortality associated with different definitions, with adjustment for demographic characteristics, socioeconomic status, lifestyle factors, dietary factors, and baseline comorbidities. Life expectancy was estimated using sex- and age-specific abridged life tables by integrating population mortality rates with exposure-specific *HRs* and prevalence.

Results: Prediabetes prevalence varied widely across glycemic indicators, with the highest estimate of 26.2% (95% CI 24.0–28.4) based on ADA FPG criteria and the lowest estimate of 3.0% (95% CI 2.8–3.2) based on IEC HbA1c criteria, while the prevalence of newly diagnosed diabetes was 4.4% (95% CI 4.1–4.8) based on ADA FPG, 2.6% (95% CI 2.4–2.8) based on ADA HbA1c, and 3.6% (95% CI 3.3–3.8) based on ADA 2hPG. Over a median follow-up of 9.0 years, a total of 6924 deaths were documented. Compared with people with normoglycemia, prediabetes defined by FPG (either ADA or WHO criteria) was not significantly associated with increased risks of all-cause or cardiovascular disease (CVD) mortality (all *P*-values >0.05). In contrast, prediabetes defined by 2hPG or HbA1c (either ADA or IEC criteria), was associated with higher risks of all-cause mortality (*HRs* ranged from 1.13 to 1.23; all *P*-values <0.001) and CVD mortality (*HRs* ranged from 1.12 to 1.25; all *P*-values <0.001). Prediabetes defined by 2hPG or HbA1c, but not FPG, was associated with 1.1–2.3 years reduction in life expectancy, with the largest loss observed for IEC HbA1c. In addition, diabetes defined by FPG, 2hPG or HbA1c was each significantly associated with a higher risk of all-cause and CVD mortality (*HRs* ranged from 1.25 to 1.51; all *P*-values <0.001), and a reduction in life expectancy (2.0–3.7 years). Furthermore, the 2hPG-based definition of prediabetes and diabetes was associated with mortality risk, independent of FPG and HbA1c levels.

Conclusions: These findings suggest that reliance on FPG alone may fail to identify certain individuals at elevated mortality risk. In contrast, 2hPG and HbA1c provide additional prognostic information beyond FPG.

Key words Diabetes; Prediabetes; Mortality; Life expectancy; Prospective study

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Background

Type 2 diabetes (T2D) represents a persistent global health challenge, with China experiencing the largest burden of prediabetes and diabetes worldwide [1]. In 2024, about 148.0 million adults in China were living with diabetes, constituting approximately 25% of the global diabetes burden [2]. Concurrently, prediabetes remains highly prevalent among the Chinese adult population, defining a substantially large high-risk cohort for future progression to diabetes [3]. Both conditions, as disorders of glucose metabolism, are associated with a significant reduction in life expectancy and an increased risk of cardiovascular and cancer mortality [4-6]. Specifically, individuals with prediabetes exhibit a 13%–30% elevated risk of cardiovascular events compared to normoglycemic individuals [7], while those with T2D face a substantially greater cardiovascular burden, with relative risks typically increased 2- to 4-fold [8]. Given the considerable and growing burden of dysglycemia in China [3], proactive screening and early intervention in this population are crucial to mitigate future disease complications and reduce the associated public health impact.

In contemporary guidelines, prediabetes and diabetes can be identified using any fasting plasma glucose (FPG), 2-hour postload glucose (2hPG), and hemoglobin A1c (HbA1c), or a combination of these measures [5,6,9]. FPG has emerged as the most widely adopted test in clinical settings, largely due to its practicality and lower cost [10,11]. Although all three glycemic indicators offer clinical utility, the estimated prevalence of prediabetes and diabetes varies substantially depending on which criterion is applied. Furthermore, their associations with long-term mortality differ across indicators [12-17]. Previous studies investigating these associations have reported inconsistent results, often limited by the assessment of only one or two glycemic measures, modest sample sizes, and restricted generalizability [12-17]. Comprehensive evidence, particularly in East Asian populations, remains scarce [9,18]. Additionally, while diabetes is uniformly defined according to the established American Diabetes Association (ADA) thresholds, there is no international consensus on the optimal definition of prediabetes; five distinct sets of diagnostic cutoffs are currently recommended by major guideline bodies [5,6,9]. A clearer delineation of how these diagnostic criteria and corresponding biomarkers relate to mortality and life expectancy is essential to refine screening approaches, inform early intervention, and ultimately mitigate the disease burden attributable to dysglycemia.

To address these gaps, the present study uses data from a large nationally representative Chinese cohort to systematically evaluate the prevalence of multiple diagnostic definitions of prediabetes based on FPG, 2hPG, and HbA1c according to recommendations from major international guidelines, as well as their associations with all-cause and cause-specific mortality and life expectancy. In addition, we evaluated the prevalence and mortality risk of newly diagnosed diabetes defined by these glycemic indicators. By directly comparing different diagnostic criteria and biomarkers within the same population, this study aims to inform more effective screening strategies and preventive interventions for dysglycemia in China.

Methods

Study design and participants

This study used data from the 2013 China Chronic Disease and Risk Factors Surveillance (CCDRFS), a nationally representative cross-sectional survey of noninstitutionalized adults aged ≥18 years who had resided at their current residence for at least 6 months in the preceding year. The CCDRFS is established by the National Center for Chronic and Noncommunicable Disease Control and Prevention (NCNCD) of the Chinese Center for Disease Control and Prevention (China CDC) and is designed to monitor trends in the prevalence of noncommunicable diseases and related risk factors across mainland China [1,3,19]. The survey employs a multistage stratified random sampling strategy to ensure national representativeness, covering 31 provinces, autonomous regions, and municipalities. Detailed information on data collection and covariates is summarized in Additional file 1: Methods. The 2013 CCDRFS and this study were approved by the ethical review committee of the NCNCD (201307). All participants signed the written informed consent. The 2013 CCDRFS included 156,063 participants with valid identification numbers. After excluding 14,118 individuals with missing data on blood glycemic indicators or self-reported diabetes status, 141,945 participants were included in the association analyses. For the prevalence analysis, individuals with missing glycemic data (12,969 participants) were excluded, yielding a final analytical sample of 143,094 participants.

Assessment of prediabetes and newly diagnosed diabetes

Fasting blood samples were obtained after at least 10 h of overnight fasting. FPG and 2hPG following a standardized 75-g oral glucose tolerance test (OGTT) were measured in accordance with a national protocol [1,3]. Plasma glucose concentrations were determined using either the glucose oxidase or the hexokinase method, with all participating laboratories following a centralized standardization and

quality-control program to ensure inter-laboratory comparability [20]. HbA1c was measured from venous blood stored at −80 °C and analyzed within 1 month at a central certified laboratory. Detailed information on the assay method and quality control is provided in the Additional file 1: Methods.

Diagnostic criteria for prediabetes differ slightly among major organizations, including the ADA, the World Health Organization (WHO), and the International Expert Committee (IEC) [5,6,9]. The ADA defines prediabetes as an FPG level of 5.6–6.9 mmol/L, a 2hPG level of 7.8–11.0 mmol/L, or a HbA1c level of 5.7%–6.4%. The WHO uses a slightly higher FPG cutoff (6.1–6.9 mmol/L) and the same 2hPG range as the ADA, but does not include HbA1c, whereas the IEC defines prediabetes solely based on HbA1c levels of 6.0%–6.4%, without corresponding FPG or 2hPG criteria. For this epidemiological analysis, newly diagnosed diabetes was defined as having no prior diagnosis of diabetes and meeting at least one of the following glycemic criteria at baseline: an FPG level ≥7.0 mmol/L, a 2hPG level ≥11.1 mmol/L after a 75-g OGTT, or an HbA1c level ≥6.5% [21]. Although this classification aligns broadly with clinical diagnostic standards, it differs from routine clinical practice, which typically involves confirmatory testing and stepwise diagnostic algorithms.

Ascertainment of death

Mortality outcomes for all cohort participants were ascertained through automated linkage with the National Mortality Surveillance system, with follow-up extending through 31 December 2021. Death records were annually verified and coded in accordance with standardized quality control procedures [22]. The underlying causes of death were classified using the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10). Cardiovascular disease (CVD) mortality included codes I00–I99, and cancer mortality included codes C00–C97.

Statistical analysis

Primary analysis: prevalence estimation and associations with mortality

Weighted estimates of the prevalence of prediabetes and newly diagnosed diabetes by different definitions were calculated. The statistical weights consisted of two components: sampling weights, derived from the inverse of each participant's selection probability to account for the complex survey design, and post-stratification weights, calibrated to align the sample demographics with the age- and sex-specific structure of the 2010 Chinese national census population. Sample characteristics were reported as mean±standard deviations (SD) for continuous variables, and percentages for categorical variables. Differences in baseline characteristics across glycemic exposure groups were evaluated using the Kruskal-Wallis test for continuous variables and the chi-square test for categorical variables. Cox proportional hazard models were used to estimate adjusted hazard ratios (*HRs*) of all-cause and cause-specific mortality associated with the different definitions, with normoglycemia as the reference group. Person-years were calculated from baseline to the date of death or censoring date. Schoenfeld residuals were used to test the proportional hazards assumption, and no violation was observed. *HRs* and 95% confidence intervals (CIs) were adjusted for residence area, age, sex, education level, household income, smoking, alcohol consumption, physical activity, body mass index, red meat intakes, vegetable and fruit intakes, hypertension, dyslipidemia, and self-reported CVD and cancer. All covariates had less than 5% missing values. For categorical variables, missing values were treated as a separate indicator category; for continuous variables, missing values were imputed using the median.

Primary analysis: life expectancy estimation

To quantify the reduction in life expectancy associated with different definitions of prediabetes and newly diagnosed diabetes, we used life tables. In the primary analyses, we built the life table starting at age 40 years and ending at age 100 years with the following three estimates to calculate the cumulative survival from 40 years onward: 1) sex- and age-specific all-cause mortality rates from the Global Burden of Disease 2019; 2) constant *HRs* for mortality associated with each glycemic exposure group estimated from the CCDRFS; and 3) sex- and age-specific population prevalences of the exposure groups. These life expectancy estimates reflect population-level, model-based summaries rather than individual-level predictions. Details of the methods used to estimate life expectancy are provided in the Additional file 1: Methods. By applying Arriaga's decomposition method, we estimated the cause-specific contributions to the life expectancy difference between people with (pre)diabetes and people with normoglycemia to identify the key contributors to the overall reduction in life expectancy due to cause-specific mortality differences [23].

Secondary analysis: mutually adjusted models of glycemic indicators and dose-response relationships

To compare the relative strength of associations between different glycemic indicators and mortality outcomes, we constructed pairwise mutually adjusted Cox proportional hazards models including baseline FPG, HbA1c, and 2hPG levels as continuous variables. Before mutual adjustment,

collinearity diagnostics were assessed. Variance inflation factors (VIFs) for FPG, HbA1c, and 2hPG were 1.89, 1.69, and 1.81, respectively, and below commonly used thresholds for problematic multicollinearity (i.e., VIF >5).

Additionally, we explored potential nonlinear relationships between glycemic levels and mortality risk using restricted cubic spline models.

Sensitivity analyses

To evaluate the robustness of the associations between glycemic definitions and mortality estimated in the main Cox regression analyses, a series of sensitivity analyses were performed, including Fine-Gray competing-risks models for CVD and cancer mortality, and survey-weighted Cox proportional hazard models accounting for the complex survey design. To account for potential regression dilution bias arising from single baseline glycemic measurements, we conducted sensitivity analyses using previously published reliability estimates as proxies for the regression dilution ratio, including an intraclass correlation coefficient (ICC) of 0.70 for FPG, an ICC of 0.75 for HbA1c, and a repeated-measure correlation coefficient of 0.89 for 2hPG, derived from prior studies with repeat glycemic measurements [24-26]. Specifically, log-transformed *HRs* were divided by the corresponding reliability estimates to obtain corrected estimates. Further details are provided in the Additional file 1: Methods. In addition, to assess the robustness of the life expectancy estimates, we conducted sensitivity analyses by constructing the life table from age 40 to 90 years and applying competing-risk models for cause-specific mortality.

Stratified analyses

To examine potential heterogeneity in the associations between glycemic definitions and all-cause mortality, stratified analyses were conducted by age (<65, ≥65 years), sex (males, females), residence area (urban, rural), and hypertension (yes, no). Potential effect modifications were examined by testing the corresponding multiplicative interaction terms.

All statistical analyses were conducted using SAS version 9.4 (SAS Institute Inc) and R software version 4.2.1 (R Foundation for Statistical Computing). All statistical tests were two-sided, and $P<0.05$ was considered statistically significant.

Results

Baseline characteristics and prevalence across glycemic definitions

In the CCDRFS cohort, the study enrolled 141,945 participants aged ≥18 years, with 42.9% being male. The median age was 50.9 years [interquartile range (IQR): 41.8–61.1]. Different definitions of prediabetes and diabetes yield varying prevalence estimates. The prevalence of prediabetes was 36.2% (95% CI 34.3–38.0) using ADA criteria, 16.4% (95% CI 15.3–17.4) using WHO criteria, and 3.0% (95% CI 2.8–3.2) using IEC criteria. Moreover, the prevalence varied by glycemic indicator, being highest with ADA FPG criteria [26.2% (95% CI 24.0–28.4)] and lowest with IEC HbA1c [3.0% (95% CI 2.8–3.2)] (Fig. 1a). These comparisons are descriptive summaries of weighted prevalence estimates across definitions and do not represent formal statistical comparisons. For newly diagnosed diabetes, the total prevalence was 6.8% (95% CI 6.4–7.2), with 4.4% (95% CI 4.1–4.8) defined by FPG, 2.6% (95% CI 2.4–2.8) by HbA1c, and 3.6% (95% CI 3.3–3.8) by 2hPG (Fig. 1a). Similar patterns across glycemic indicators were observed in both males and females (Additional file 1: Fig. S1). Across all diagnostic definitions, the prevalence of prediabetes increased progressively with age (Additional file 1: Fig. S1).

Different definitions identify distinct prediabetes populations, with limited overlap. Based on ADA definition, FPG defined the largest proportion of prediabetes (70.8%), and only 5.9% were identified by all three definitions (Fig. 1b). The overlap between WHO FPG-defined prediabetes and WHO 2hPG-defined prediabetes was 16.8% (Fig. 1c). Compared with prediabetes identified by FPG, 2hPG or HbA1c-defined prediabetes were more likely to be older and female, with lower education and household income (all *P*-values <0.001) (Additional file 1: Table S1). IEC HbA1c-defined prediabetes had the highest prevalence of overweight/obesity, hypertension, and dyslipidemia, and the lowest prevalence of excessive alcohol drinkers (all *P*-values <0.001) (Additional file 1: Table S1). Among newly diagnosed diabetes cases, the largest proportion was identified by FPG (64.7%), and only 18.2% met all three criteria (Fig. 1d). Diabetes identified by HbA1c was more likely to be female and had the highest prevalence of overweight/obesity and dyslipidemia (all *P*-values <0.001) (Additional file 1: Table S2). 2hPG-defined diabetes was the oldest and had the highest prevalence of hypertension (all *P*-values <0.001) (Additional file 1: Table S2).

Mortality risk according to different glycemic definitions

During 1,252,893 person-years of follow-up [median (IQR): 9.0 (8.8–9.3) years], there were 6924 deaths recorded, including 2327 CVD deaths and 1673 cancer deaths. In multivariable-adjusted Cox proportional hazard models, prediabetes defined by 2hPG or HbA1c was associated with

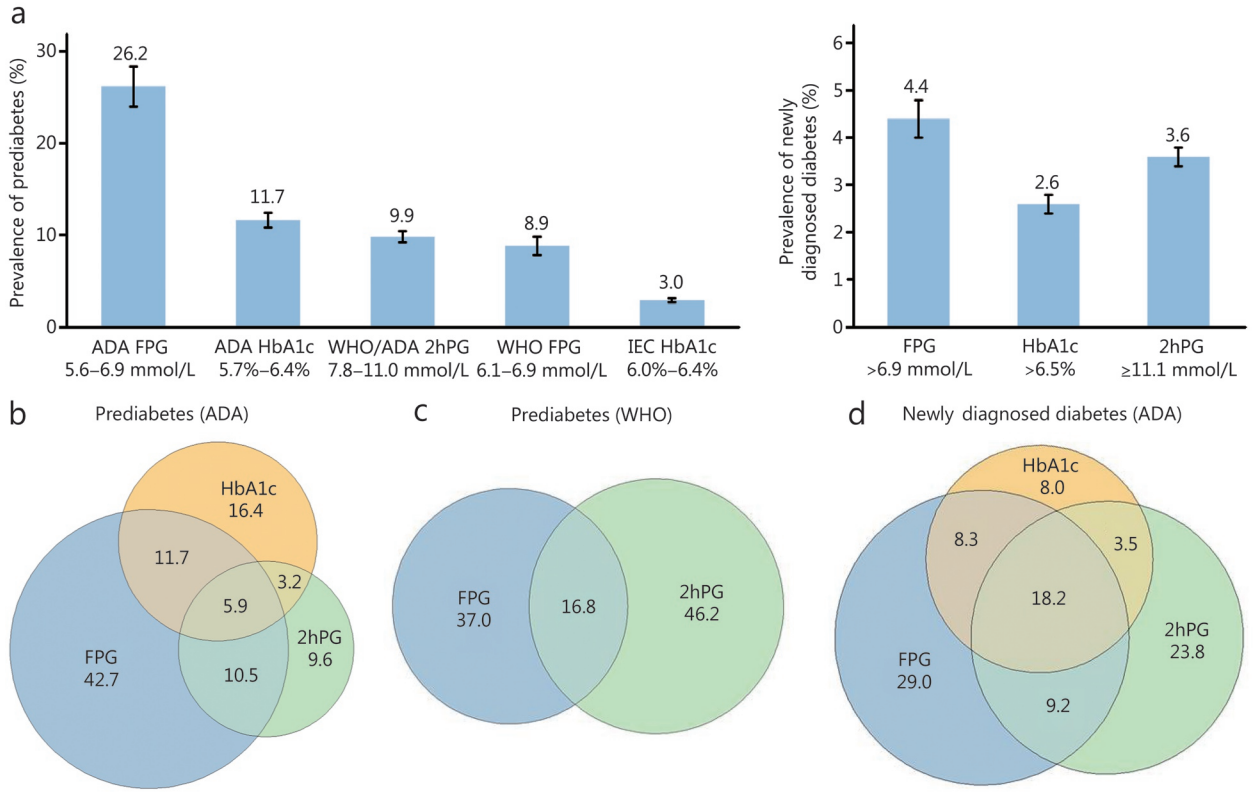

Fig. 1 Prevalence of prediabetes and newly diagnosed diabetes in the Chinese population aged ≥18 years by different definitions in 2013.

a Prevalence of prediabetes and diabetes by different definitions. **b** The percentage of prediabetes by different glycemic indicators (ADA criteria). **c** The percentage of prediabetes by different glycemic indicators (WHO criteria). **d** The percentage of newly diagnosed diabetes by different glycemic indicators (ADA criteria). Bars represent survey-weighted prevalence estimates, and error bars indicate 95% confidence intervals accounting for the complex survey design. ADA. American Diabetes Association; FPG. Fasting plasma glucose; WHO. World Health Organization; HbA1c. Hemoglobin A1c; IEC. International Expert Committee; 2hPG. 2-hour postload glucose

higher risks of all-cause mortality (*HRs* ranged from 1.13 to 1.23; all *P*-values <0.001), with IEC HbA1c definition showing the largest *HR* (*HR*=1.23, 95% CI 1.13–1.33; *P*-value <0.001), compared with normoglycemic individuals (Fig. 2). Notably, prediabetes diagnosed by FPG, of either ADA or WHO criteria, was not associated with the risk of all-cause mortality (all *P*-values >0.05) (Fig. 2). Similar patterns were observed for CVD mortality (Additional file 1: Table S3), while none of the prediabetes definitions were significantly associated with cancer mortality (Additional file 1: Table S4). Additionally, all diabetes definitions, including FPG, HbA1c, or 2hPG, were associated with the increased risk of all-cause mortality (*HRs* ranged from 1.25 to 1.51; all *P*-values <0.001) and CVD mortality (*HRs* ranged from 1.25 to 1.44; all *P*-values <0.001) in individuals with newly diagnosed diabetes (Fig. 2; Additional file 1: Table S3). Newly diagnosed diabetes, defined by 2hPG and HbA1c (*HR* ranged from 1.33 to 1.49; all *P*-values <0.05), but not by FPG, was associated with cancer mortality (Additional file 1: Table S4).

Life expectancy according to different glycemic definitions

Compared with normoglycemic individuals, 2hPG- and HbA1c-defined prediabetes were associated with a significant reduction in life expectancy (*P*-values <0.001). Among them, IEC HbA1c-defined prediabetes displayed the largest reduction [2.3 years (95% CI 1.6–3.0) for males and 2.2 years (95% CI 1.6–2.9) for females, *P*-values <0.001], followed by those defined by WHO/ADA 2hPG [1.1 years (95% CI 0.6–1.6) for both males and females, *P*-values <0.001] (Fig. 3). In contrast, FPG-defined prediabetes was not associated with life expectancy loss (*P*-values >0.05) (Fig. 3). All definitions of newly diagnosed diabetes were associated with the reduction in life expectancy, with the most pronounced reduction observed under the WHO/ADA 2hPG definition [3.7 years (95% CI 3.0–4.3), *P*-values <0.001], whereas the smallest reduction was observed under the ADA FPG definition [2.0

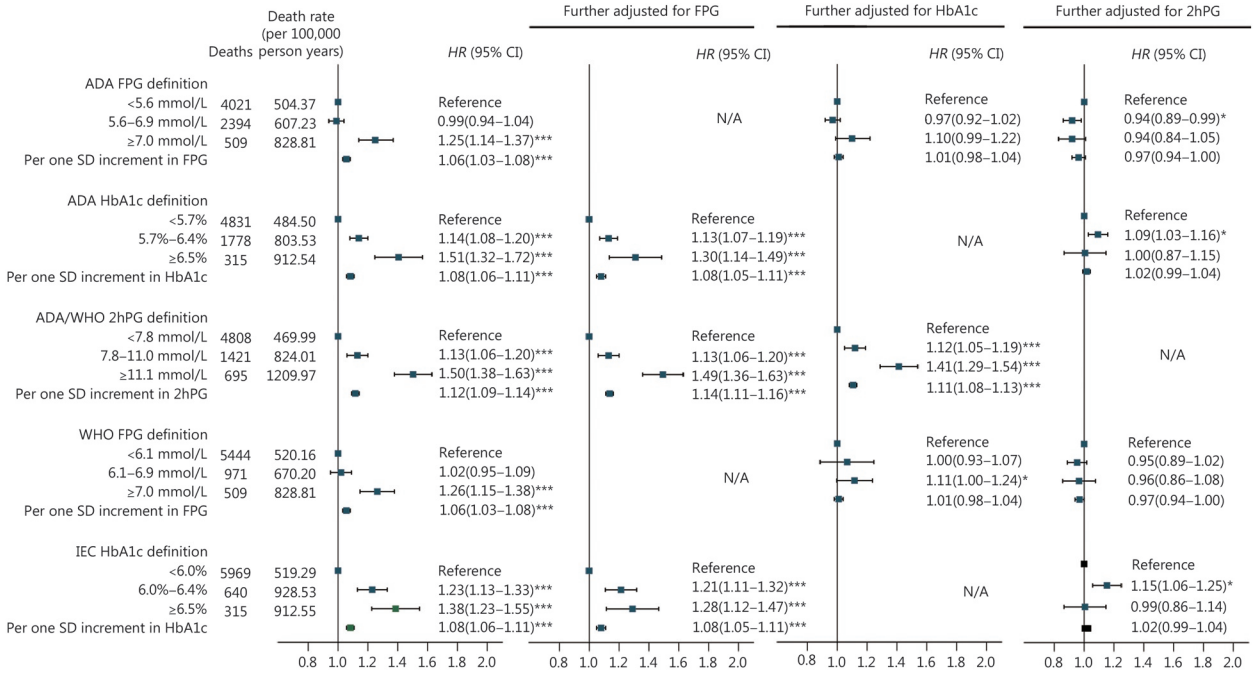

Fig. 2 Number of deaths, all-cause mortality rates, and adjusted hazard ratios (*HRs*) by different definitions of prediabetes and newly diagnosed diabetes.

The *HRs* were adjusted for age (five-year group), sex (male, or female), residence (urban, or rural), education (junior high school and below, high school, or college and above), household income (<¥20,000/year, ≥¥20,000/year, or not answer/don't know), smoking (never smoked, past smoker, or active smoker), alcohol consumption (excessive, or rare/nondrinker), physical activity (<150 min/week, or ≥150 min/week), red meat intakes (<100 g/d, or ≥100 g/d), vegetable and fruit intakes (<400 g/d, or ≥400 g/d), body mass index (<18.5, 18.5–23.9, 24–27.9, or ≥28 kg/m^2), hypertension (yes, or no), dyslipidemia (yes, or no), self-reported CVD (yes, or no), and self-cancer (yes, or no). *P*-values correspond to the Wald test for the *HRs* comparing each glycemic exposure group with the normoglycemic reference group. *P<0.05, ***P<0.001 compared with the reference group. ADA. American Diabetes Association; CI. Confidence interval; FPG. Fasting plasma glucose; WHO. World Health Organization; HbA1c. Hemoglobin A1c; IEC. International Expert Committee; N/A. Not available; SD. Standard deviation; 2hPG. 2-hour postload glucose

years (95% CI 1.3–2.7), *P*-values <0.001]. (Additional file 1: Fig. S2). Notably, CVD and other non-cancer deaths were the leading contributors to life-expectancy loss associated with prediabetes, with contributions varying by definition (35%–46% for CVD deaths and 19%–65% for other non-cancer causes). CVD deaths accounted for the largest proportion of life-expectancy loss associated with diabetes (35%–47%).

Mortality risk after mutual adjustment of glycemic indicators

To compare the relative strength of the associations between different glycemic indicators and mortality risk, we included baseline FPG, HbA1c, and 2hPG in the models and performed pairwise mutually adjusted analyses. The associations of HbA1c-defined prediabetes and diabetes with all-cause mortality were markedly attenuated after further adjustment for 2hPG (Fig. 2). Specifically, the *HR* for all-cause mortality comparing ADA HbA1c-defined diabetes with HbA1c <5.7% decreased from 1.51 (95% CI 1.32–1.72) to 1.00 (95% CI 0.87–1.15) after adjustment for 2hPG (Fig. 2). Similar attenuation was observed for HbA1c-defined prediabetes, with the *HR* changed from 1.14 (95% CI 1.08–1.20) to 1.09 (95% CI 1.03–1.16). Consistent patterns were observed for CVD and cancer mortality (Additional file 1: Tables S3-S4). Notably, only 2hPG-defined prediabetes remained significantly associated with an increased risk for all-cause mortality after adjustment for FPG or HbA1c levels (Fig. 2; Additional file 1: Tables S3-S4). Compared with individuals with 2hPG <7.8 mmol/L, those with 2hPG-defined prediabetes had an *HR* of 1.13 (95% CI 1.06–1.20) after adjustment for FPG and 1.12 (95% CI 1.05–1.19) after adjustment for HbA1c for all-cause mortality (Fig. 2). Consistent patterns were observed for CVD mortality (Additional file 1: Tables S3). Independent associations were also observed for 2hPG-defined newly diagnosed diabetes, which remained associated with all-cause, CVD, and cancer mortality after accounting for the other glycemic measures (Fig. 2; Additional file 1: Tables S3-S4). For example, compared with individuals with 2hPG <7.8 mmol/L, 2hPG-defined newly diagnosed diabetes had an *HR* of 1.49

(95% CI 1.36–1.63) for all-cause mortality after adjustment for FPG and 1.41 (95% CI 1.29–1.54) after adjustment for HbA1c (Fig. 2).

Mortality risk according to combined glycemic definitions

Figure 4 presents the mortality risk associated with prediabetes and newly diagnosed diabetes based on combined criteria using FPG, HbA1c, and 2hPG, as defined by the ADA, WHO,

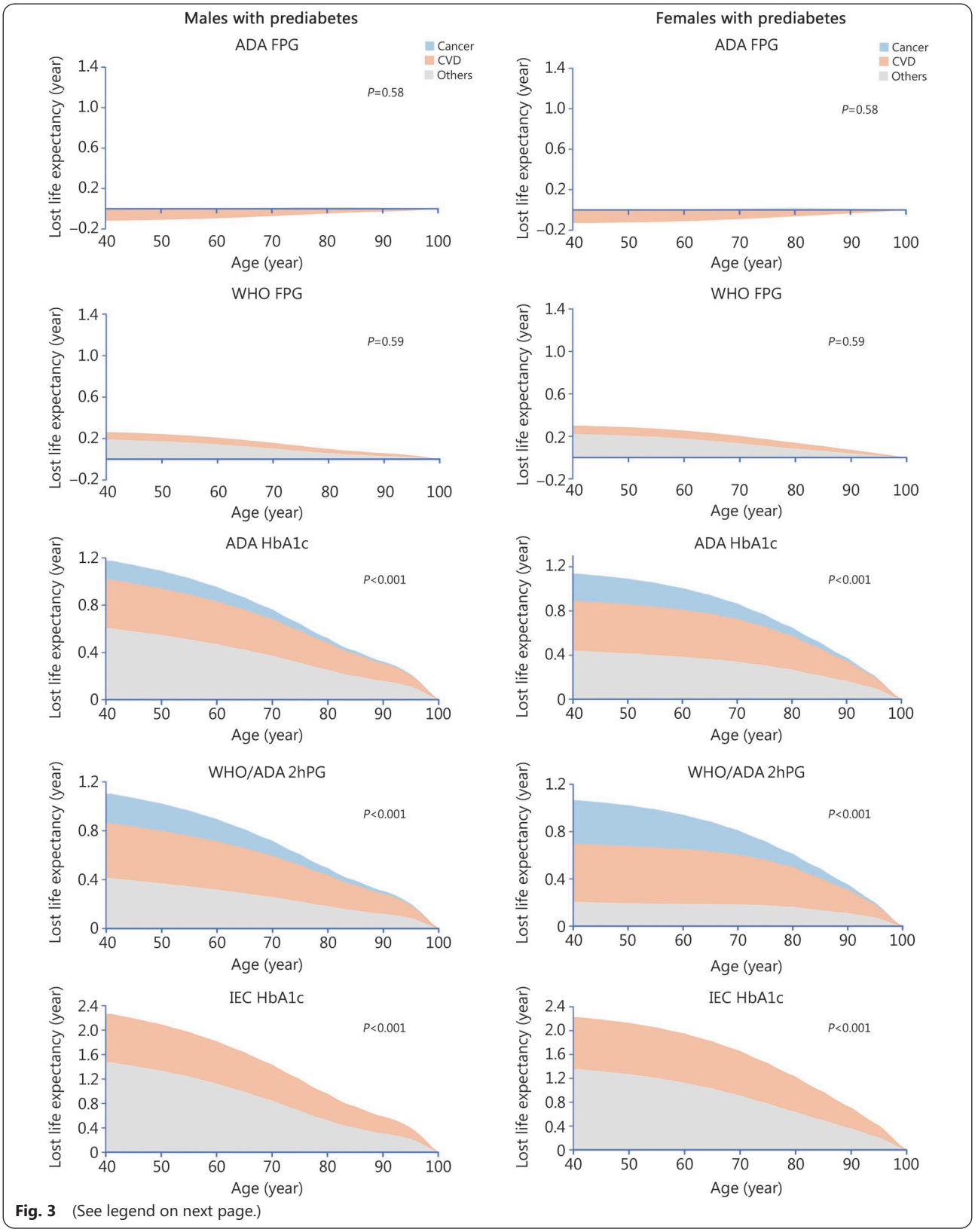

Fig. 3 (See legend on next page.)

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Fig. 3 Estimated years of life lost attributable to increased deaths from CVD, cancer, and other causes in people with prediabetes by different definitions.

The *HRs* applied to estimate life expectancy were adjusted for age (five-year group), sex (male, or female), residence (urban, or rural), education (junior high school and below, high school, or college and above), household income (<¥20,000/year, ≥¥20,000/year, or not answer/don't know), smoking (never smoked, past smoker, or active smoker), alcohol consumption (excessive, or rare/nondrinker), physical activity (<150 min/week, or ≥150 min/week), red meat intakes (<100 g/d, or ≥100 g/d), vegetable and fruit intakes (<400 g/d, or ≥400 g/d), body mass index (<18.5, 18.5–23.9, 24–27.9, or ≥28 kg/m^2), hypertension (yes, or no), dyslipidemia (yes, or no), self-reported CVD (yes, or no), and self-cancer (yes, or no). *P*-values were derived from Cox proportional hazards models for all-cause mortality comparing each glycemic exposure group with the normoglycemic reference group. ADA. American Diabetes Association; CVD. Cardiovascular disease; FPG. Fasting plasma glucose; *HR*. Hazard ratio. WHO. World Health Organization; HbA1c. Hemoglobin A1c; IEC. International Expert Committee; 2hPG. 2-hour postload glucose

and IEC. No significant increase in all-cause mortality risk was observed in individuals with prediabetes who met the FPG definition but did not meet the HbA1c definition (*HRs* ranged from 1.01 to 1.04; all *P*-values >0.05) or 2hPG definition (*HRs* ranged from 0.96 to 0.97; all *P*-values >0.05) (Fig. 4a, b). Additionally, individuals with prediabetes who met 2hPG definition had a significantly increased risk of all-cause mortality, regardless of whether they also met the HbA1c definition (*HRs* ranged from 1.10 to 1.26; all *P*-values <0.05) (Fig. 4a, b). The same results were observed among people with newly diagnosed diabetes defined by 2hPG (*HRs* ranged from 1.45 to 1.59; all *P*-values <0.05) (Fig. 4c). The results for CVD mortality were generally similar in direction. However, several subgroup estimates (e.g., the combined abnormal categories) did not reach statistical significance, probably due to the relatively small number of CVD deaths.

Dose-response relationships between glycemic indicators and mortality

Multivariable-adjusted restricted cubic spline analyses showed that only 2hPG was positively associated with all-cause, CVD, and cancer mortality in a linear dose-response relationship ($P_{nonlinear}$>0.05), while both FPG and HbA1c displayed J-shaped associations with all-cause and CVD mortality, respectively ($P_{nonlinear}$<0.05) (Additional file 1: Fig. S3).

Sensitivity analyses

The main results remained materially unchanged across all sensitivity analyses, including Fine-Gray competing-risks analyses for CVD and cancer mortality (Additional file 1: Table S5), survey-weighted Cox proportional hazard models accounting for the complex survey design (Additional file 1: Table S6), and sensitivity analyses addressing potential regression dilution (Additional file 1: Table S7). In addition, the sensitivity analyses using a life table constructed from age 40 to 90 years and competing-risk models yielded results similar to the primary analyses (Additional file 1: Figs. S4, S5). The J-shaped associations of FPG and HbA1c with all-cause and CVD mortality were largely preserved after excluding participants who died within the first three years of follow-up or those with a history of CVD or cancer at baseline (Additional file 1: Fig. S6).

Stratified analyses

In age-stratified analyses, ADA/WHO 2hPG-defined prediabetes was associated with a higher relative risk of all-cause mortality among participants younger than 65 years, whereas the association was attenuated and not statistically significant among those aged 65 years or older (*P* for interaction=0.03). Similar results were also observed in 2hPG-defined diabetes (*HR*=1.75, 95% CI 1.53–2.00 vs. *HR*=1.37, 95% CI 1.23–1.52; *P* for interaction=0.02) (Additional file 1: Table S8). No significant interaction was observed between different definitions and sex, residence area, or hypertension history (Additional file 1: Tables S9-S11).

Discussion

Based on a nationally representative cohort, we comprehensively compared definitions of prediabetes and diabetes across three glycemic indicators (FPG, 2hPG, and HbA1c) and among international organization criteria to provide an integrated evaluation of their impact on prevalence estimates and risk stratification. The results revealed that different definitions for prediabetes and diabetes can yield varying estimates of their prevalence and identify distinct subsets of individuals at risk. Notably, 2hPG- or HbA1c-defined prediabetes was associated with higher all-cause and CVD mortality and shorter life expectancy, whereas FPG-defined prediabetes showed no significant association. These findings could inform more targeted approaches, such as incorporating 2hPG or HbA1c testing among individuals with normal fasting glucose but elevated cardiometabolic risk to better identify

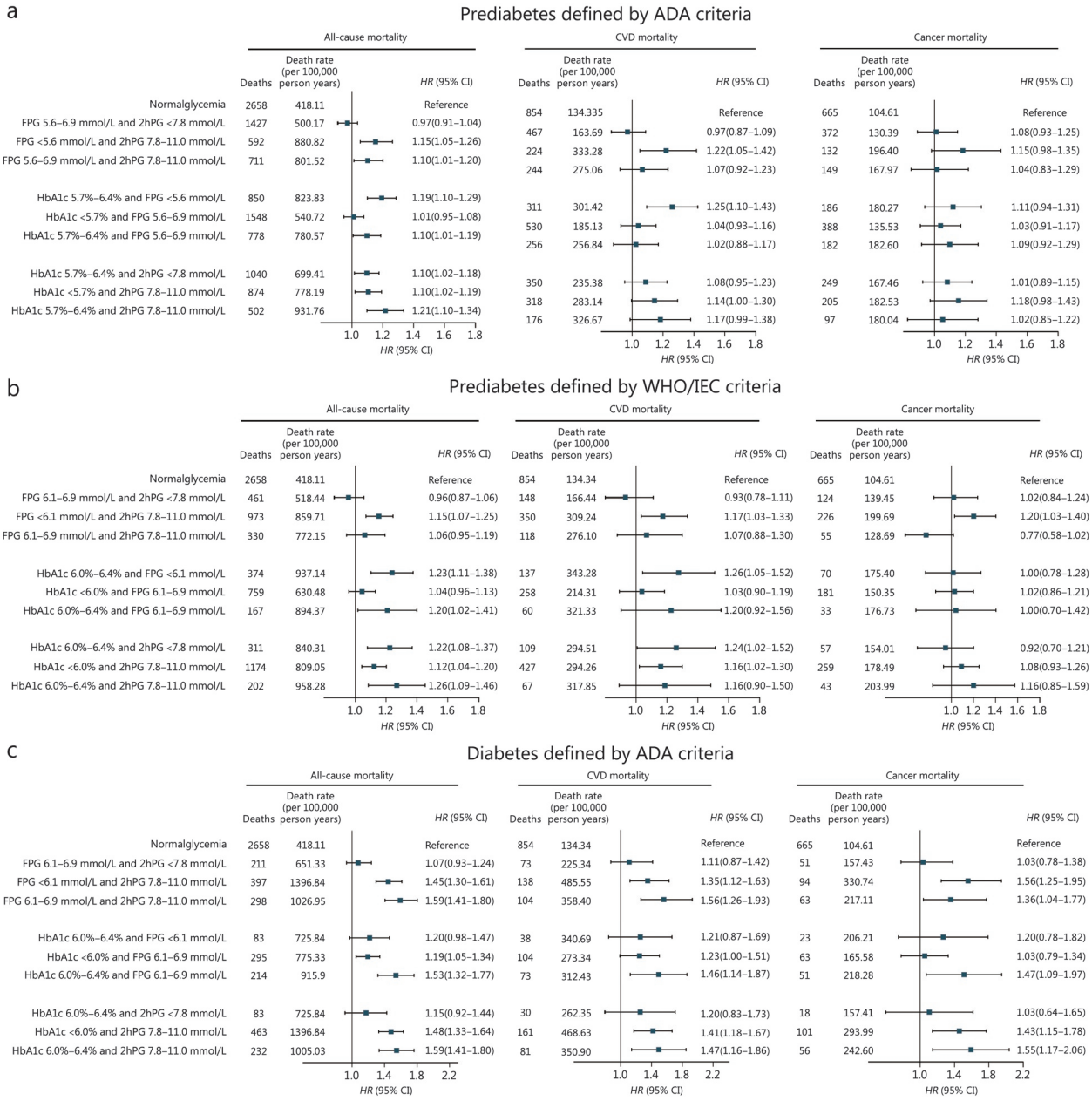

Fig. 4 Number of deaths, all-cause and cause-specific mortality rates, and adjusted hazard ratios (*HRs*) by different definitions of prediabetes and newly diagnosed diabetes.

a Prediabetes defined by ADA criteria. **b** Prediabetes defined by WHO/IEC criteria. **c** Diabetes is defined by the ADA criteria. The *HRs* were adjusted for age (five-year group), sex (male, or female), residence (urban, or rural), education (junior high school and below, high school, or college and above), household income (<¥20,000/year, ≥¥20,000/year, or not answer/don't know), smoking (never smoked, past smoker, or active smoker), alcohol consumption (excessive, or rare/nondrinker), physical activity (<150 min/week, or ≥150 min/week), red meat intakes (<100 g/d, or ≥100 g/d), vegetable and fruit intakes (<400 g/d, or ≥400 g/d), body mass index (<18.5, 18.5–23.9, 24–27.9, or ≥28 kg/m^2), hypertension (yes, or no), dyslipidemia (yes, or no), self-reported CVD (yes, or no), and self-cancer (yes, or no). Given the limited sample size, mutually exclusive phenotype analyses were conducted pairwise, focusing on two glycemic indicators at a time. ADA. American Diabetes Association; CI. Confidence interval; CVD. Cardiovascular disease; FPG. Fasting plasma glucose; WHO. World Health Organization; HbA1c. Hemoglobin A1c; IEC. International Expert Committee; 2hPG. 2-hour postload glucose

high-risk populations and reduce hyperglycemia-related mortality.

In China, the prevalence of prediabetes varied substantially depending on the diagnostic threshold applied. Prediabetes, defined by ADA FPG (26.2%) or ADA HbA1c (11.7%), was almost two or three times higher than that defined by WHO

FPG (8.9%) or IEC HbA1c (3.0%). Similar patterns were also observed in US data, including both FPG (ADA 26.2% vs. WHO 7.0%) and HbA1c (ADA 19.6% vs. IEC 6.2%) [27,28]. Moreover, although the ADA FPG definition identifies the majority of people with prediabetes, more than one-third of HbA1c or 2hPG-defined prediabetes were classified as normoglycemia based on the FPG definition in this study.

To date, the association between different glycemic indicators and mortality risk remains inconclusive. While several studies reported an increased risk of all-cause or CVD mortality among individuals with impaired fasting glucose, others did not find significant associations [7,29,30]. Some evidence suggested that 2hPG-defined (pre)diabetes was more strongly associated with mortality than FPG- or HbA1c-defined (pre)diabetes [31-33]. In contrast, a UK study reported that 2hPG-defined diabetes only predicted cardiovascular risk when HbA1c was also elevated, raising questions about the added value of 2hPG in risk prediction [12]. More recently, a European study reported that sustained prediabetes, defined using repeated measurements, irrespective of the glycemic marker, was associated with increased cardiovascular and mortality risk even without progression to diabetes [34]. Differences across studies may reflect variations in population characteristics, follow-up duration, covariate adjustment, and whether prediabetes was defined longitudinally or at a single baseline assessment. Notably, most existing evidence was derived from Western populations and primarily focused on comparisons between only two glycemic indicators at a time. Given these limitations and the uncertain generalizability of prior findings to East Asian populations, we provide important complementary evidence by examining all possible combinations of FPG, 2hPG, and HbA1c using data from a large, nationally representative Chinese cohort.

In the present study, we did not observe a significant association of FPG-defined prediabetes (of either ADA or WHO criteria) with increased risk of all-cause, CVD and cancer mortality in China. In contrast to FPG, 2hPG, and HbA1c definition (of either ADA or IEC criteria) were associated with increased risk of all-cause and CVD mortality compared with normoglycemic individuals, respectively. These findings illustrate that relying solely on the FPG definition can overlook the mortality risk of individuals with increased 2hPG or HbA1c but normal FPG levels. These implications are significant, especially in clinical settings where FPG is the primary method used for hyperglycemia screening [10].

European Diabetes Epidemiology Group recommends reassessing the current FPG cutoff for defining non-diabetic hyperglycemia, expressing concerns that a lower threshold could result in overdiagnosis and unnecessary treatment for individuals who may not be at significant risk [35]. The results of this study also support this recommendation. Furthermore, considering that the cutoff for defining prediabetes is mainly based on the studies conducted in Western countries, especially Europe and North America, while Asians typically have higher FPG levels than Europeans due to differences in genetic background, diet, and lifestyle [36,37], the FPG cutoff for prediabetes in Asians needs to be carefully explored in the future.

This study provides support for the potential added value of incorporating 2hPG and HbA1c measurements in risk stratification. Similarly, evidence from several large population-based studies has shown that dysglycemia defined by elevated 2hPG, but not FPG alone, is strongly associated with mortality risk [14]. Other studies further demonstrated that 2hPG provides risk information independent of fasting glucose and HbA1c [38,39]. In parallel, HbA1c has been shown to identify a broader subgroup of individuals with elevated cardiometabolic risk and to be more strongly associated with CVD risk and mortality than FPG [40,41].

As guidelines increasingly prioritize cardiometabolic screening, HbA1c is likely to become the primary test for diagnosing prediabetes and diabetes, replacing OGTT [21]. This alteration raises the concern of whether this shift in diagnostic criteria could lead to missing individuals at high risk for mortality. Consistent with this, the results of this study illustrate that the excess mortality risk of HbA1c-defined hyperglycemia may be partly attributable to postprandial hyperglycemia. This issue may be particularly relevant in Asian populations, where isolated impaired glucose tolerance is common [42-44], reflecting a pathophysiological profile characterized by relatively preserved hepatic insulin sensitivity, moderate to severe insulin resistance in skeletal muscle, and a pronounced defect in late-phase insulin secretion [45]. Additionally, recent evidence indicates that genetically determined hemoglobin variants prevalent among individuals of Asian ancestry can systematically lower HbA1c, potentially delaying the identification of dysglycemia [46]. Together, these findings emphasize the importance of the 2h OGTT in identifying high-risk individuals who may be missed by HbA1c-based screening strategies, particularly in Asian populations.

Although the findings of this study indicate that 2hPG provides prognostic information beyond FPG and HbA1c, the feasibility of widespread OGTT remains limited in population-

based and routine clinical settings because of time, cost, and participant burden. Universal OGTT screening is therefore unlikely to be practical. Rather than replacing FPG-based strategies, selective use of 2hPG or HbA1c among individuals with normal fasting glucose but elevated cardiometabolic risk may represent a pragmatic compromise.

In this study, prediabetes was not significantly associated with cancer mortality, a finding consistent with several prior cohort studies reporting weak or null associations for prediabetes [47-49], in contrast to the more consistently observed associations for overt diabetes [50,51]. The absence of a clear association may reflect the relatively mild and heterogeneous nature of dysglycemia at the prediabetes stage, as well as potential exposure misclassification due to a single baseline measurement, limited numbers of cancer deaths, and heterogeneity across cancer types. Further studies with repeated glycemic measurements, longer follow-up, and cancer subtype-specific analyses are needed to clarify the relationship between prediabetes and cancer mortality.

The strength of this study includes the use of a large, nationally representative sample of the general population in China. The study adheres to rigorous protocols for assessing glycemia and related risk factors, employing standardized procedures and trained personnel. Additionally, the inclusion of all three key glycemic indicators is a significant advantage, as few studies have data on all three markers simultaneously. Several limitations of this study should be acknowledged. First, glycemic status was assessed only at baseline, and changes during follow-up were not captured, which may have introduced non-differential misclassification and attenuated associations toward the null. Future studies incorporating repeated glycemic measurements are warranted to evaluate mortality risks associated with persistent prediabetes and distinct glycemic trajectories, such as progression to diabetes or reversion to normoglycemia. Second, the lack of fasting insulin measurements limited the ability to directly assess insulin resistance, which may underline differences across glycemic markers. Future studies with insulin-related biomarkers are needed. Third, diabetes type could not be distinguished; however, given that incident cases occurred in adults from a population-based cohort, most cases are likely to be T2D, and any potential misclassification would not materially affect the main findings. Fourth, although the results of this study, consistent with previous studies [52,53], suggested that prediabetes and diabetes were associated with higher mortality among younger participants than older participants, the age-stratified interaction analyses were exploratory and involved multiple subgroup comparisons, and further studies are needed for confirmation. Fifth, despite extensive adjustment for some demographic and clinical factors, we could not fully rule out the role of residual and unmeasured confounding by factors, such as medication use during follow-up, healthcare utilization patterns, and conditions affecting HbA1c validity (e.g., chronic kidney disease or anemia), etc, in this study. These factors are more common among individuals with higher baseline health risk and greater clinical contact, and may be associated with either improved or worsened prognosis depending on the specific context. As a result, residual confounding related to these factors could bias effect estimates in either direction.

Conclusions

In a nationally representative cohort study, we found that prediabetes, defined by 2hPG and HbA1c, but not FPG, was associated with increased risks of all-cause and CVD mortality in Chinese individuals. These findings suggest that reliance on FPG alone may fail to identify certain individuals at elevated mortality risk. In contrast, 2hPG and HbA1c provide additional prognostic information beyond FPG. From a clinical and public health perspective, targeted use of OGTT and HbA1c, particularly among high-risk individuals, may improve risk stratification and support earlier, more effective preventive interventions.

Abbreviations

ADA: American Diabetes Association
CCDRFS: China Chronic Disease and Risk Factors Surveillance
CDC: Center for Disease Control and Prevention
CVD: Cardiovascular disease
FPG: Fasting plasma glucose
HbA1c: Hemoglobin A1c
HR: Hazard ratio
IEC: International Expert Committee
IFG: Impaired fasting glucose
NCNCD: National Center for Chronic and Noncommunicable Disease Control and Prevention
OGTT: Oral glucose tolerance test
T2D: Type 2 diabetes
VIF: Variance inflation factor
WHO: World Health Organization
2hPG: 2-hour postload glucose

Supplementary information

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Additional file 1: Methods. Table S1 Baseline characteristics of prediabetes by different definitions. **Table S2** Baseline characteristics of newly diagnosed diabetes by different definitions. **Table S3** Number of deaths, cardiovascular mortality rates, and adjusted hazard ratios by different definitions of prediabetes and newly diagnosed diabetes. **Table S4** Number of deaths, cancer mortality rates, adjusted hazard ratio by different definitions of

prediabetes and newly diagnosed diabetes. **Table S5** Associations of different definitions of prediabetes and diabetes with cause-specific mortality: Fine-Gray competing-risks analyses. **Table S6** Association between different definitions of prediabetes and diabetes with all-cause and cause-specific mortality accounted for the complex survey design. **Table S7** Sensitivity analysis of associations after correction for regression dilution bias. **Table S8** Adjusted *HR* (95% CI) for all-cause mortality by different definitions of prediabetes and newly diagnosed diabetes and age. **Table S9** Adjusted *HR* (95% CI) for all-cause mortality by different clinical categories of prediabetes and newly diagnosed diabetes and sex. **Table S10** Adjusted *HR* (95% CI) for all-cause mortality by different definitions of prediabetes and newly diagnosed diabetes and residence. **Table S11** Adjusted *HR* (95% CI) for all-cause mortality by different definitions of prediabetes and newly diagnosed diabetes and hypertension. **Fig. S1** Prevalence of prediabetes (a) and newly diagnosed diabetes (b) in the Chinese population aged ≥18 years by different definitions and gender/age in 2013. **Fig. S2** Estimated years of life lost attributable to increased deaths from cardiovascular disease, cancer, and other causes in people with newly diagnosed diabetes by different definitions. **Fig. S3** Dose-response relationship between different glycemic indicators and all-cause and cause-specific mortality. **Fig. S4** Sensitivity analysis of years of life lost in people with prediabetes due to cause-specific mortality using age-restricted life tables and competing-risk models. **Fig. S5** Sensitivity analysis of years of life lost in people with newly diagnosed diabetes due to cause-specific mortality using age-restricted life tables and competing-risk models. **Fig. S6** Dose-response relationship between different glycemic indicators and all-cause and cause-specific mortality, excluding deaths occurring within the first three years of follow-up and participants with major comorbidities at baseline.

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Authors' contributions

MZ, ZXQ, YW, XZ, and SYZ contributed equally to this study. GL, KH, LMW, and MGZ conceived and designed the study and took responsibility for the integrity of the data and the accuracy of the data analysis. ZXQ, YW, KH, GL, and MZ drafted the manuscript. ZXQ, YW, SYZ, and MZ did the analysis. MZ, XZ, and SYZ completed the follow-up work. XZ, SHX, and SYZ accessed and verified the underlying data. AP, LMW, CL, and ZPZ give administrative, technical, or material support. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All the authors read and approved the final manuscript.

Availability of data and materials

As subsequent follow-up investigations are still in progress, data collected for the study, including individual participant data, will not be made available to others. When all follow-up investigations are finished, data might be made available on request via email from the corresponding authors.

Declarations

Ethics approval and consent to participate

The CCDRFS study was approved by the ethical review committee of the National Center for Chronic and Noncommunicable Disease Control and Prevention, China CDC (201307). Written informed consent was obtained from all participants prior to data collection.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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