

Four-year changes in metabolic burden and transitions to cardiovascular disease and death: a longitudinal CHARLS study

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Abstract

Background

Metabolic abnormalities evolve over time, yet their associations may differ between cardiovascular disease (CVD) onset and death before or after CVD. We examined whether four-year change in metabolic burden was associated with transitions among CVD-free, CVD, and death states in Chinese middle-aged and older adults.

Methods

This longitudinal cohort study used the China Health and Retirement Longitudinal Study. Five metabolic components were assessed in 2011 and 2015, and subsequent transitions were observed during 2015–2018 and 2018–2020. Change in the component count was modelled continuously and as improvement, stability, or deterioration. Transition-specific discrete-time logistic models estimated odds ratios (ORs) for CVD-free to CVD, CVD-free to all-cause death, and CVD to all-cause death, with participant-clustered robust standard errors.

Results

Among 4,716 participants, 1,855 (39.3%) improved, 1,730 (36.7%) remained stable, and 1,131 (24.0%) deteriorated. The 8,732 interval records included 939 CVD-free-to-CVD, 220 CVD-free-to-death, and 103 CVD-to-death transitions. Each one-component increase in metabolic burden was associated with higher odds of CVD onset (OR 1.14, 95% confidence interval [CI] 1.06–1.21). Improvement versus stability was associated with lower odds of CVD onset (OR 0.79, 95% CI 0.66–0.94). Continuous metabolic change was not associated with direct death from the CVD-free state (OR 1.08, 95% CI 0.93–1.25) or death after CVD (OR 0.91, 95% CI 0.74–1.12). The CVD-onset estimate was similar after sampling and attrition weighting, exclusion of baseline diabetes, and restriction to the later follow-up interval.

Conclusions

Four-year worsening of metabolic burden was associated with subsequent CVD onset, while metabolic improvement was associated with lower odds of moving from a CVD-free state to CVD. Associations with mortality transitions were imprecise. Repeated metabolic assessment may provide information about CVD development that is not captured by a single baseline measurement.

Background

Cardiovascular risk in later life reflects the joint and changing influence of adiposity, blood pressure, glucose regulation, and lipid metabolism. Chinese cohort data show substantial burdens of hypertension

and other vascular risk factors, together with marked differences in awareness and control [1–3]. Because these abnormalities may accumulate or resolve over time, a single baseline measurement provides only a partial account of the metabolic environment in which cardiovascular disease develops.

Previous CHARLS studies have examined several predictors of cardiovascular outcomes, including depressive symptoms [4], sarcopenia [5], and changes in frailty [6]. Other reports have focused on TyG-based measures of insulin resistance [7–9] or a combined metabolic-inflammatory index [10]. Most evaluated incident CVD, stroke, or death as separate or composite endpoints. They did not distinguish CVD onset among survivors from death before a recognized CVD diagnosis or death after CVD. A transition analysis allows these stages to be considered separately.

The triglyceride-glucose (TyG) index was validated against direct measures of insulin sensitivity [11, 12]. In CHARLS, TyG-BMI has been associated with incident CVD [7, 8], and longitudinal change in TyG-BMI has been studied in relation to stroke [9]. Joint TyG and BMI patterns have also been examined for stroke risk [10]. Other studies compared modified TyG measures [13], combined TyG with inflammatory markers [14, 15], or evaluated estimated glucose disposal rate [16]. A count of metabolic abnormalities captures several modifiable domains and is less dependent on one laboratory measure. We therefore examined both the component count and TyG change.

Using nationally representative longitudinal data from the China Health and Retirement Longitudinal Study (CHARLS), we investigated change in five metabolic syndrome components between 2011 and 2015 and subsequent transitions among CVD-free, CVD, and all-cause death states through 2020. We hypothesized that metabolic deterioration would be associated most strongly with transition from CVD-free to CVD and that metabolic improvement would be associated with lower odds of this transition.

Methods

Study design and population

CHARLS is an ongoing nationally representative cohort of community-dwelling Chinese adults aged 45 years or older and their spouses, selected through multistage probability sampling [17]. Blood collection, assay procedures, and quality control for the 2015 biomarker wave have been described in detail [18]. We used 2011 and 2015 examinations to define metabolic change and set 2015 as a landmark to avoid using post-outcome exposure information. Outcomes were assessed over the 2015–2018 and 2018–2020 intervals.

This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

Participants entered the metabolic-change cohort if they had valid identifiers and complete measurements for all five metabolic components in both 2011 and 2015. Of 6,744 participants with paired metabolic assessments, 2,028 lacked at least one component at either wave, leaving 4,716

participants at the 2015 landmark (Fig. 1). Interval-specific models used complete covariate and endpoint data for the relevant transition; consequently, model denominators varied by transition.

Because cardiovascular status was assessed at survey waves rather than on exact event dates, each follow-up interval was treated as a discrete observation period. Participants who remained alive could contribute a record to each eligible interval. Risk sets were defined by state at the beginning of an interval: only participants free of cardiovascular disease were eligible for cardiovascular disease onset or direct death, whereas only participants with cardiovascular disease were eligible for death after cardiovascular disease. After entering the cardiovascular disease state, participants were no longer eligible for a cardiovascular disease-free transition; death ended further observation.

Metabolic exposures

At each exposure wave, metabolic burden was defined as the number (0–5) of abnormal components. Central obesity was waist circumference ≥ 102 cm in men or ≥ 88 cm in women. Elevated triglycerides were ≥ 150 mg/dL; low high-density lipoprotein cholesterol was < 40 mg/dL in men or < 50 mg/dL in women; elevated blood pressure was systolic pressure ≥ 130 mm Hg or diastolic pressure ≥ 85 mm Hg; and elevated fasting glucose was ≥ 100 mg/dL. Blood pressure was the mean of at least two valid readings. Triglycerides and glucose were restricted to fasting samples and prespecified biologically plausible ranges.

The primary exposure was the 2015 count minus the 2011 count. Positive values represented deterioration and negative values improvement. For categorical analyses, participants were classified as improved (< 0), stable ($= 0$), or deteriorated (> 0). The TyG index was calculated as $\ln[\text{fasting triglycerides (mg/dL)} \times \text{fasting glucose (mg/dL)} / 2]$; change between 2011 and 2015 was standardized and examined as an alternative exposure.

Cardiovascular and vital states

State 0 was alive without a self-reported physician diagnosis of heart disease or stroke; state 1 was alive with a current or previous physician diagnosis of either condition; and state 2 was death from any cause. CVD history was carried forward after first report, preventing an implausible transition back to the CVD-free state. Death was absorbing. We did not label any death as cardiovascular death because CHARLS did not provide consistently adjudicated cause of death across the complete follow-up period.

Covariates

Covariates were selected a priori and measured in 2011: age, sex, education (less than primary, primary, middle school, or high school and above), marital status, rural hukou, current smoking, usual sleep

duration, and baseline metabolic component count. Follow-up period (2015–2018 or 2018–2020) was also included. Baseline diabetes was used for a prespecified sensitivity analysis.

Statistical analysis

Characteristics were summarized by metabolic-change category. We created one record for each observed interval in which a participant was alive at interval start. Separate discrete-time logistic models were fitted for CVD-free to CVD, CVD-free to death, and CVD to death, following the event-history formulation for grouped observation times [19]. For each transition, the alternative terminal event was treated as competing and excluded from that transition-specific binary risk set. Coefficients are therefore reported as transition-specific odds ratios, not hazard ratios. Robust standard errors were clustered by participant to account for repeated intervals [20].

The primary model estimated the OR per one-component increase in metabolic burden. Secondary models compared improved and deteriorated groups with the stable group and examined standardized TyG change. All models adjusted for the prespecified covariates. Competing-risk principles informed construction of the transition-specific risk sets [21]. We controlled the false discovery rate across key exposure-transition tests using the Benjamini-Hochberg procedure [22].

Models were fitted separately for each transition because associations were allowed to differ according to the state from which a participant was at risk and the state subsequently entered. The resulting odds ratios describe conditional odds within the observed survey intervals; they are not instantaneous hazard ratios or cumulative risks. Observed transition counts and interval proportions were therefore reported with the adjusted estimates.

Sensitivity analyses used 2015 blood-sample weights; stabilized inverse-probability-of-observation weights estimated from metabolic, demographic, behavioral, period, and origin-state variables and truncated at the 1st and 99th percentiles [23]; excluded participants with baseline diabetes; and restricted analyses to 2018–2020. We also reconstructed the metabolic component count using Asian-specific central-obesity thresholds (waist circumference ≥ 90 cm in men and ≥ 80 cm in women) and repeated the transition models with the revised continuous and categorical exposures. Analyses were conducted in R version 4.6.0. All tests were two-sided; $P < .05$ was considered nominally significant, with FDR-adjusted results emphasized for multiple comparisons.

Results

Participant characteristics and transitions

Of 4,716 participants with complete metabolic-change data, 1,855 (39.3%) improved, 1,730 (36.7%) remained stable, and 1,131 (24.0%) deteriorated. Mean age was approximately 59 years in each category. Women represented 60.7% of the deteriorated group compared with approximately 53% of the

other groups. By construction, the mean metabolic count fell from 2.65 to 1.27 in the improved group and rose from 1.26 to 2.59 in the deteriorated group (Table 1 and eFigure 1 in Additional file 1).

Table 1
Participant characteristics according to metabolic-change category

Characteristic	Stable	Improved	Deteriorated
Participants, n	1730	1855	1131
Age, years	59.0 (8.6)	59.1 (8.6)	58.5 (8.8)
Women	891 (52.6%)	974 (53.1%)	670 (60.7%)
Married	1455 (85.9%)	1564 (85.3%)	941 (85.2%)
Rural hukou	1409 (83.2%)	1561 (85.1%)	943 (85.6%)
Current smoking	665 (38.5%)	710 (38.3%)	371 (32.8%)
Sleep duration, hours/day	6.3 (1.8)	6.4 (1.9)	6.4 (1.9)
High school or above	169 (10.0%)	154 (8.4%)	107 (9.7%)
Diabetes at baseline	104 (6.1%)	111 (6.1%)	60 (5.3%)
Waist circumference, cm	85.1 (10.0)	86.5 (10.2)	85.3 (9.6)
Systolic blood pressure, mm Hg	128.6 (21.5)	133.2 (20.5)	125.3 (18.9)
Diastolic blood pressure, mm Hg	74.9 (12.1)	77.5 (12.0)	73.6 (11.2)
Triglycerides, mg/dL	120.6 (94.7)	157.3 (133.3)	110.3 (58.7)
HDL cholesterol, mg/dL	52.2 (15.4)	48.5 (15.5)	52.4 (13.4)
Fasting glucose, mg/dL	107.5 (32.9)	114.6 (36.9)	105.0 (30.1)
Triglyceride-glucose index	8.6 (0.6)	8.9 (0.7)	8.5 (0.5)
Metabolic components in 2011	1.7 (1.3)	2.6 (1.2)	1.3 (1.1)
Metabolic components in 2015	1.7 (1.3)	1.3 (1.1)	2.6 (1.2)
Change in component count	0.0 (0.0)	-1.4 (0.6)	1.3 (0.6)
Cardiovascular disease in 2015	289 (16.7%)	302 (16.3%)	158 (14.0%)
Known death through 2020	117 (7.2%)	146 (8.5%)	79 (7.5%)
Values are mean (SD) or n (%), unless otherwise indicated. Percentages use available observations. CVD, cardiovascular disease.			

The trajectory groups differed more in baseline metabolic profile than in age. Participants who later improved had the highest mean baseline systolic pressure (133.2 mm Hg), triglycerides (157.3 mg/dL), fasting glucose (114.6 mg/dL), and metabolic component count (2.65). Those who deteriorated began

with the lowest component count (1.26), lower systolic pressure (125.3 mm Hg), and lower fasting glucose (105.0 mg/dL); they also included a higher proportion of women. Mean waist circumference varied little across groups (85.1–86.5 cm). Because the change categories were partly determined by their starting values, all transition models included the 2011 component count.

The average four-year change was – 1.38 components in the improved group and + 1.32 components in the deteriorated group, whereas the stable group had no net count change. The corresponding group trajectories are shown in eFigure 3 in Additional file 1. Baseline CVD prevalence ranged from 14.0% in the deteriorated group to 16.7% in the stable group. Known mortality through 2020 was 7.2% in the stable group, 8.5% in the improved group, and 7.5% in the deteriorated group; these unadjusted percentages should not be interpreted as exposure effects because the groups differed substantially in baseline metabolic burden.

There were 8,732 effective interval records. Across both intervals, 939 transitions from CVD-free to CVD, 220 from CVD-free directly to death, and 103 from CVD to death were observed. In 2015–2018, 724 of 3,819 initially CVD-free interval records transitioned to CVD and 139 to death; in 2018–2020, the corresponding numbers were 215 and 81. Among records beginning in the CVD state, 43 deaths occurred in 2015–2018 and 60 in 2018–2020. Overall, 342 participants had a known death through 2020, while vital status in 2020 was unknown for 315.

Conditional transition proportions changed across intervals. Among CVD-free records, the observed proportion moving to CVD declined from 19.0% in 2015–2018 to 7.5% in 2018–2020, while direct death declined from 3.6% to 2.8%. Among records beginning with CVD, death occurred in 6.0% during the first interval and 4.5% during the second (eTable 2 in Additional file 1 and Fig. 3). These percentages describe observed interval records rather than cumulative participant risks; a participant surviving the first interval could contribute again in the second.

Metabolic change and CVD onset

In the fully adjusted primary model, each one-component increase in metabolic burden was associated with 14% higher odds of transition from CVD-free to CVD (OR, 1.14; 95% CI, 1.06–1.21; $P < .001$; FDR-adjusted $P = .002$) (Table 2 and Fig. 2). Compared with metabolic stability, improvement was associated with lower odds of CVD onset (OR, 0.79; 95% CI, 0.66–0.94; $P = .007$; FDR-adjusted $P = .045$). Deterioration as a category was not significantly associated with CVD onset, a pattern that may reflect heterogeneity within the broad > 0 category and differences in baseline burden.

Table 2
Adjusted associations of metabolic change with state transitions

Transition	Exposure	Adjusted OR (95% CI)	P value	FDR P	Participants	Events
CVD-free to CVD	Per one-component increase	1.14 (1.06–1.21)	< 0.001	0.002	3,553	905
CVD-free to CVD	Improved vs stable	0.79 (0.66–0.94)	0.007	0.045	3,553	905
CVD-free to CVD	Deteriorated vs stable	1.08 (0.89–1.31)	0.434	0.474	3,553	905
CVD-free to CVD	TyG change, per SD	1.06 (0.99–1.14)	0.116	0.279	3,553	905
CVD-free to death	Per one-component increase	1.08 (0.93–1.25)	0.293	0.439	2,984	212
CVD-free to death	Improved vs stable	1.28 (0.88–1.85)	0.194	0.363	2,984	212
CVD-free to death	Deteriorated vs stable	1.55 (1.05–2.29)	0.027	0.108	2,984	212
CVD-free to death	TyG change, per SD	1.10 (0.95–1.28)	0.212	0.363	2,984	212
CVD to death	Per one-component increase	0.91 (0.74–1.12)	0.374	0.449	1,374	101
CVD to death	Improved vs stable	0.95 (0.59–1.51)	0.823	0.823	1,374	101
CVD to death	Deteriorated vs stable	0.74 (0.39–1.40)	0.354	0.449	1,374	101
CVD to death	TyG change, per SD	0.83 (0.66–1.05)	0.115	0.279	1,374	101
Models adjusted for 2011 metabolic component count, age, sex, education, marital status, rural hukou, current smoking, sleep duration, and follow-up period, with robust standard errors clustered by participant. For each transition, the competing terminal event was excluded from that binary transition risk set. FDR P values use the Benjamini-Hochberg procedure. CI, confidence interval; CVD, cardiovascular disease; FDR, false discovery rate; OR, odds ratio; SD, standard deviation; TyG, triglyceride-glucose index.						

Metabolic change and mortality transitions

Continuous metabolic change was not associated with transition directly from CVD-free to death (OR, 1.08; 95% CI, 0.93–1.25; P=.293) or from CVD to death (OR, 0.91; 95% CI, 0.74–1.12; P=.374).

Deterioration versus stability was nominally associated with direct death from the CVD-free state (OR, 1.55; 95% CI, 1.05–2.29; $P=.027$), but this association did not remain significant after FDR correction and was not supported by the continuous exposure. It was therefore considered exploratory. Neither improvement nor deterioration was associated with death after CVD.

Alternative exposure and sensitivity analyses

Standardized change in TyG was not significantly associated with any transition (all nominal $P>.11$). The primary CVD-onset finding was essentially unchanged with inverse-probability-of-observation weighting (OR, 1.14; 95% CI, 1.06–1.21), remained evident with blood-sample weighting (OR, 1.14; 95% CI, 1.04–1.24), after excluding baseline diabetes (OR, 1.14; 95% CI, 1.06–1.23), and when restricted to 2018–2020 (OR, 1.19; 95% CI, 1.03–1.37) (eTable 1 and eFigure 2 in Additional file 1). Observation-weighted mortality-transition models remained null for continuous metabolic change. When Asian-specific waist thresholds were used, the continuous estimate for CVD onset was essentially unchanged (OR, 1.14; 95% CI, 1.06–1.21), while the estimates for direct death from the CVD-free state (OR, 1.03; 95% CI, 0.89–1.20) and death after CVD (OR, 0.93; 95% CI, 0.75–1.14) remained compatible with no association (eTable 4 in Additional file 1). The revised definition reclassified 676 participants (14.3%) across metabolic-change categories. The improvement-versus-stability estimate for CVD onset was attenuated to 0.84 (95% CI, 0.70–1.00; $P=.052$), indicating that categorical estimates were more sensitive to the waist definition than the continuous result. For direct death from the CVD-free state, both improved and deteriorated categories had elevated odds under the Asian definition, whereas the continuous estimate remained null; this discordance indicates threshold-dependent classification rather than a graded mortality association.

The CVD-onset estimate changed little across the sensitivity analyses. Mortality estimates were less precise and crossed the null in each analysis, reflecting in part the smaller numbers of direct and post-CVD deaths.

Results for all three transitions are reported in eTable 3 in Additional file 1. For direct death from the CVD-free state, estimates remained close to the null under observation weighting (OR, 1.09; 95% CI, 0.94–1.26), blood-sample weighting (OR, 1.10; 95% CI, 0.94–1.30), exclusion of diabetes (OR, 1.06; 95% CI, 0.90–1.24), and restriction to the late interval (OR, 1.19; 95% CI, 0.94–1.51). For death after CVD, the primary estimate was below 1 but imprecise; neither observation weighting nor exclusion of diabetes materially changed that conclusion. The blood-sample-weighted estimate was 0.82 (95% CI, 0.64–1.03), which remained compatible with no association.

Categorical estimates were less consistent than estimates from the continuous model (eFigure 4 in Additional file 1). Improvement was associated with lower odds of CVD onset, whereas deterioration versus stability was not. For direct death from the CVD-free state, deterioration yielded a nominally elevated OR, but improvement also had an OR above 1 and the continuous trend was null. After FDR correction, the categorical result no longer met the significance threshold. These results do not support a graded association with mortality.

Discussion

During follow-up of Chinese middle-aged and older adults, an increase in metabolic burden over four years was related chiefly to new physician-diagnosed heart disease or stroke among participants initially free of CVD. A decrease in burden was associated with lower odds of the same transition. The CVD-onset estimate changed little after sampling and attrition weighting, exclusion of diabetes, or restriction to the later follow-up interval. Continuous metabolic change was not clearly related to direct all-cause death from the CVD-free state or to death after CVD.

The observed transition pattern also changed between follow-up intervals. Cardiovascular disease onset was more frequent during 2015–2018 than during 2018–2020, while direct and post-cardiovascular disease death remained less common in both periods. These descriptive proportions may reflect differences in interval length, aging, survey participation, and depletion of susceptible participants; they should not be interpreted as population transition probabilities over a fixed period.

The association with CVD onset is compatible with earlier cohort evidence. European studies linked metabolic syndrome with cardiovascular morbidity, diabetes, and mortality [24–27]. North American cohorts reported higher risks of incident CVD and diabetes [28–30], while other analyses examined the relative contribution of obesity and metabolic syndrome to cardiovascular risk [31, 32]. The Hisayama Study reported a similar association in a Japanese population [33]. Unlike most of these studies, our analysis updated metabolic status before follow-up and classified events according to the state from which they occurred. CVD onset and death before or after CVD were therefore estimated separately rather than combined into one endpoint.

The transition-specific pattern adds information beyond a conventional composite endpoint. Metabolic deterioration may act most detectably during disease initiation through cumulative effects on vascular inflammation, endothelial dysfunction, arterial stiffness, atherogenic dyslipidemia, and glycemic injury. Once CVD is established, short-term survival may depend more strongly on disease severity, treatment, frailty, renal function, and acute events than on earlier change in a simple component count. The smaller number of post-CVD deaths also limited precision, so a true association in that transition cannot be excluded.

The inverse association observed for metabolic improvement should be interpreted cautiously. Adjustment for the baseline component count compared participants with a similar initial burden but different subsequent trajectories. Regression to the mean, treatment initiation, and unmeasured changes in health behavior may still explain part of the association, and reducing the component count cannot be assumed to lower CVD risk on the basis of this observational analysis. The Asian-waist sensitivity analysis further qualified this finding: the continuous association with CVD onset was unchanged, but the categorical improvement estimate moved toward the null. Thus, the evidence is stronger for an incremental association across the change score than for a threshold-independent benefit of belonging to the improved category.

TyG change was not associated with any transition. Earlier CHARLS reports evaluated baseline or adiposity-modified TyG measures [7, 10, 13], cumulative TyG-BMI [8], longitudinal TyG-BMI change [9], and TyG combined with inflammatory markers [14, 15]. Those exposures reflect baseline level or sustained burden, whereas a four-year difference may be more sensitive to within-person laboratory variation. The present null result applies specifically to TyG change among participants with paired fasting measurements after covariate adjustment.

The nominal association between categorical deterioration and direct death was not supported by the FDR-adjusted or continuous analyses, and the number of direct-death events was limited. It should therefore be regarded as exploratory and examined in cohorts with denser follow-up and adjudicated causes of death. Under the Asian waist definition, categorical direct-death estimates also varied despite a null continuous estimate. The threshold-dependent and internally discordant findings do not support an inference about cardiovascular mortality.

Strengths and limitations

Strengths include repeated objective metabolic measurements, a prospective landmark design, explicit decomposition of clinically meaningful transitions, adjustment for baseline metabolic burden, participant-clustered inference, and several sensitivity analyses addressing sampling and attrition. The multistate perspective distinguishes preservation of CVD-free survival from prognosis after CVD and avoids presenting all events as biologically equivalent.

Several limitations merit consideration. First, heart disease and stroke were based on self-reported physician diagnoses; undiagnosed disease and recall error could misclassify states. Second, states were observed only at survey waves, so exact event dates and transient events were unavailable. Third, assigning missing CVD reports as absence and carrying diagnosed CVD forward may introduce classification error, although the latter prevents implausible recovery of disease history. Fourth, paired blood measurements selected a healthier and more adherent subset; weighting cannot eliminate residual selection bias. Fifth, 315 participants had unknown 2020 vital status, although observation weighting produced similar estimates. Sixth, approximately 100 post-CVD deaths limited power. Seventh, residual confounding from medication changes, diet, physical activity, healthcare access, disease severity, and treatment remains possible. Finally, discrete-time ORs can differ from risk or hazard ratios when outcomes are common, and findings may not generalize beyond middle-aged and older Chinese adults with paired fasting measurements.

The exposure also summarized abnormalities as an unweighted count. This approach is transparent and clinically interpretable, but it assumes that a one-component change has a comparable meaning regardless of which component changed. Central-obesity prevalence and categorical change assignments varied with the waist threshold, although the continuous CVD-onset estimate was stable when Asian-specific cutoffs were applied. The available data did not support stable estimation of every component-specific transition association, particularly for death after cardiovascular disease.

Clinical and research implications

Repeated measurement of adiposity, blood pressure, lipids, and glycemia may add information to cardiovascular risk assessments based on a single examination [34]. Whether improvement is followed by longer CVD-free survival requires studies with more precise event timing, medication histories, adjudicated causes of death, and formal multistate survival models.

Conclusion

Among Chinese middle-aged and older adults, four-year worsening in the number of metabolic abnormalities was consistently associated with subsequent CVD onset but not with mortality transitions. Metabolic improvement was associated with lower odds of moving from CVD-free to CVD. The findings support further study of whether repeated metabolic assessment improves prediction of cardiovascular disease-free survival.

Declarations

Ethics approval and consent to participate

The original CHARLS survey obtained ethics approval and written informed consent from all participants. The present study used publicly available, deidentified data and did not require additional ethics approval or consent.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

LL and XG conceived and designed the study. LL performed the statistical analysis and drafted the manuscript. QD, CD, and JL contributed to data interpretation and provided administrative, technical, or material support. XG supervised the study. All authors critically revised the manuscript, read and approved the final version, and agree to be accountable for the work.

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Use of artificial intelligence-assisted technologies

OpenAI Codex was used to assist with English-language editing and manuscript formatting. The authors reviewed and verified the manuscript, references, analyses, and interpretations and take full responsibility for the submitted content.

Data Availability

Deidentified CHARLS data and data dictionaries are available to registered users through the official CHARLS website (<https://charls.pku.edu.cn/>). The authors are not permitted to redistribute participant-level CHARLS data. Analysis code and derived nonidentifiable outputs are available from the corresponding author on reasonable request and in accordance with CHARLS data-use requirements.

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Figures

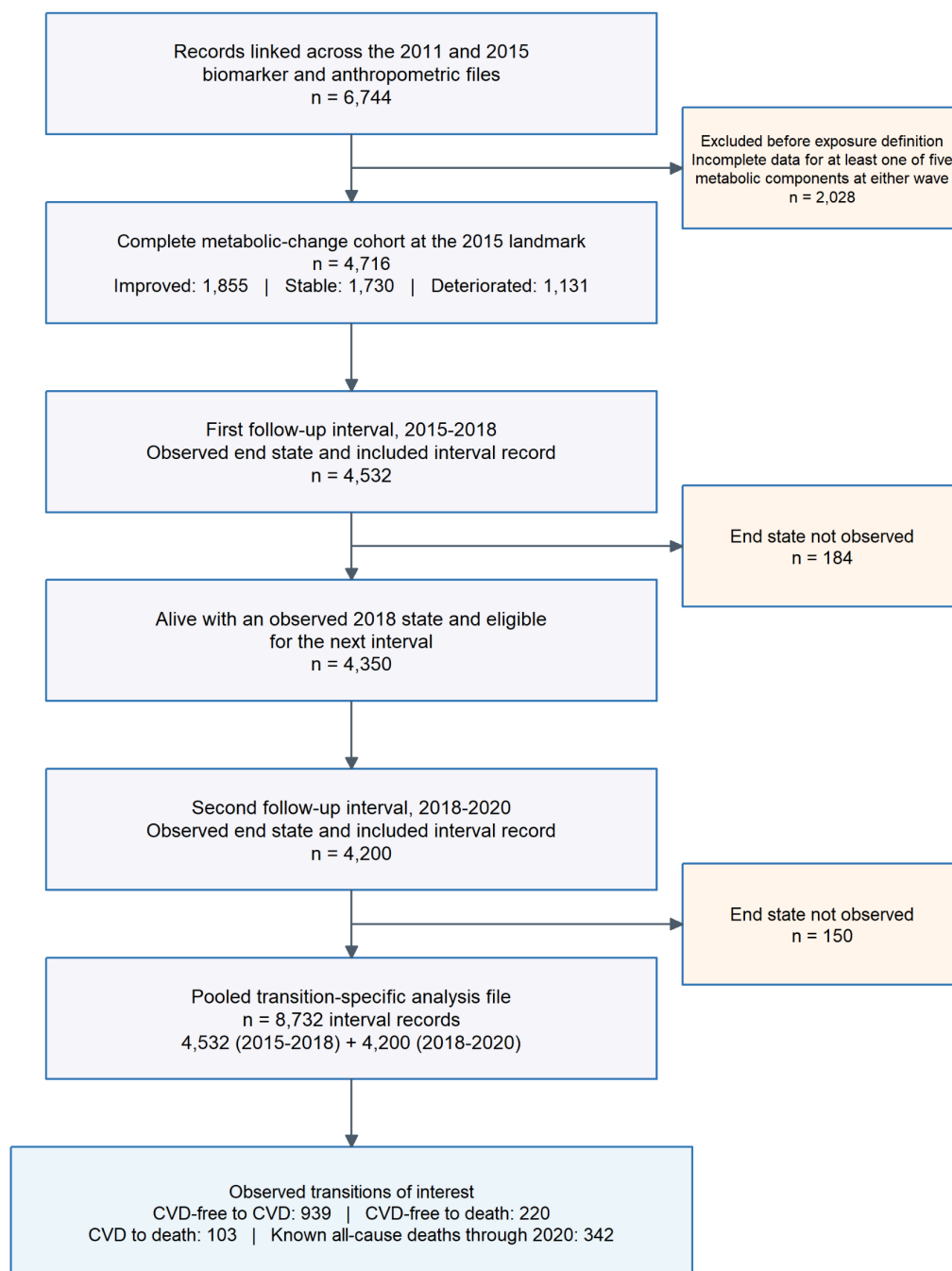


Figure 1

Participant inclusion and construction of transition records.

The cohort required complete measurement of all 5 metabolic components in both 2011 and 2015. Interval records required an observed end state. CVD indicates cardiovascular disease.

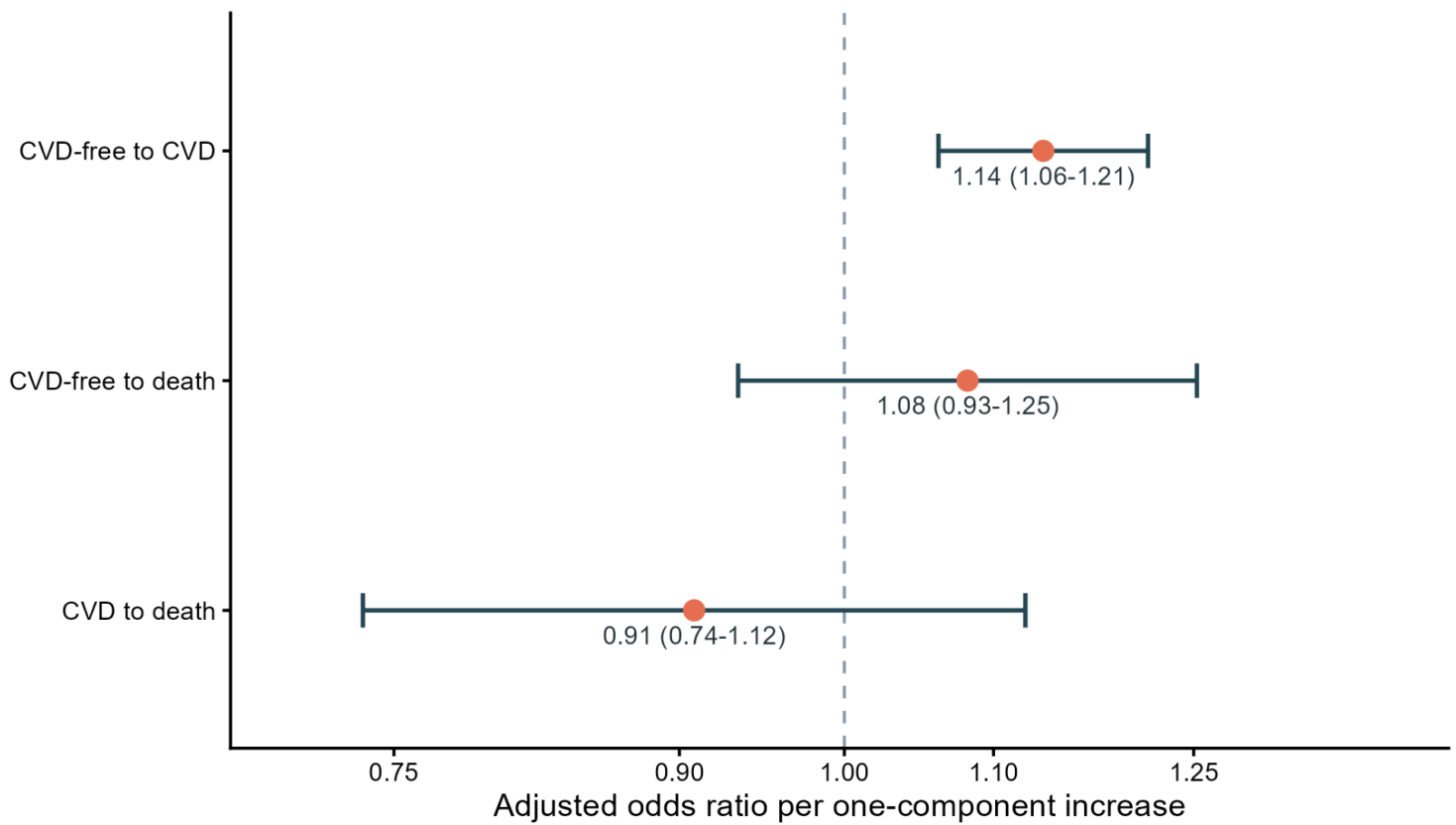


Figure 2

Adjusted Odds Ratios for the 3 Primary Transitions per 1-Component Increase in Metabolic Burden

Points show adjusted odds ratios, and horizontal bars show 95% CIs from transition-specific discrete-time logistic models. The dashed vertical line indicates the null value of 1. CVD indicates cardiovascular disease.

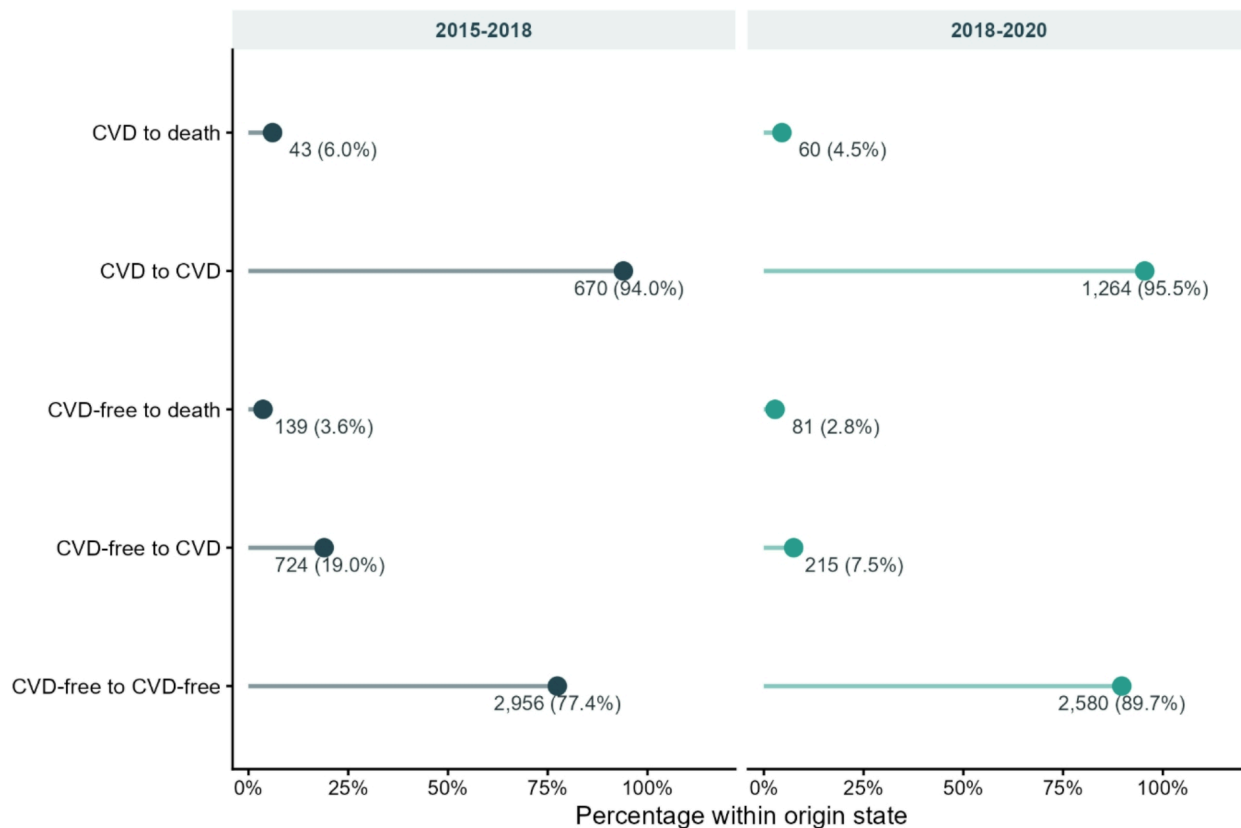


Figure 3

Observed State-Transition Records by Follow-up Interval

Bars show transition counts during 2015-2018 and 2018-2020. Percentages conditional on origin state are provided in eTable 2 in Additional file 1. CVD indicates cardiovascular disease.

Supplementary Files

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