

Seven anthropometric indices of adiposity and incident cardiovascular disease in China and England: a harmonised two- cohort study

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Abstract

Background

Body-mass index (BMI) does not capture body-fat distribution, and evidence comparing alternative measured adiposity indices for cardiovascular risk remains fragmented across single indices, single countries and self-reported measurements. We aimed to compare seven anthropometric indices head-to-head and to test whether the resulting risk signals and prediction models generalise between China and England.

Methods

Prospective analysis of two nationally representative ageing cohorts with measured anthropometry: CHARLS (China, $n = 10,557$) and ELSA (England, $n = 5,231$), yielding 15,788 adults aged ≥ 45 years free of cardiovascular disease (CVD) at baseline and 3,175 incident CVD events. Cox models with a pre-specified adjustment gradient estimated dose-response associations; mediation analysis, quantile g-computation, Fine-Gray competing-risk models and restricted-mean-time-lost analyses characterised mechanisms and absolute effects; and gradient-boosted models trained in one country were externally validated in the other with TreeSHAP interpretation.

Results

All seven indices showed independent, monotonic associations with incident CVD (fully adjusted top-versus-bottom tertile hazard ratios 1.13–1.49). Blood pressure and cardiometabolic disease jointly mediated 32.4% of the BMI-CVD association (China 40.6%; England 22.7%). A simultaneous one-tertile increase in the adiposity-blood-pressure mixture yielded a joint hazard ratio of 1.59 (95% CI 1.49–1.70). The highest BMI tertile lost 0.132 years of CVD-free time over 7 years. Prediction models transported bidirectionally (C-index 0.623 China→England; 0.618 England→China; combined-model 5-year time-dependent AUC 0.680 in China and 0.739 in England) with preserved discrimination but imperfect calibration. Adding the seven indices to conventional risk factors improved the C-index by 0.010 (95% CI 0.008–0.014).

Conclusions

Measured waist circumference and the weight-adjusted waist index should complement BMI in cardiovascular risk assessment. Adiposity signals generalise across populations with very different adiposity distributions, but absolute-risk deployment requires country-specific recalibration.

Clinical trial registration

Clinical trial number: not applicable.

Background

Obesity is a well-established, modifiable risk factor for cardiovascular disease (CVD), but the conventional metric—body-mass index (BMI)—does not distinguish fat mass from lean mass and, more importantly, does not capture body-fat distribution. Visceral and ectopic adiposity, better reflected in abdominal anthropometry, are more strongly related to cardiometabolic risk than total adiposity alone [1–3]. A family of anthropometric indices has therefore been proposed: waist circumference (WC) as the simplest indicator of central adiposity; waist-to-height ratio (WHtR), which scales waist to stature; the a body shape index (ABSI), which adjusts waist for height and weight to capture body shape independent of size; the weight-adjusted waist index (WWI); the body roundness index (BRI), a geometric transformation of the waist–height ellipse; and the conicity index (CI) [4–8].

Evidence linking these indices to CVD remains fragmented. Most prospective studies examine one or two indices in a single country, often with self-reported height, weight or waist; cut-offs, adjustment sets and follow-up structures vary, making it difficult to judge which indices carry independent information, whether associations are linear, and whether they generalise across populations with very different adiposity distributions and health systems. Few studies quantify the *mechanism*—how much of the adiposity–CVD association is transmitted through blood pressure and glycaemic pathways—within a formal mediation framework, and few test the *robustness* of these associations to death as a competing event or express them as absolute CVD-free time lost, although both bear directly on clinical communication in older populations.

China and England offer a sharp contrast for cross-country validation. Mean BMI and the prevalence of abdominal obesity differ markedly between the two populations, as do health-system contexts, yet both CHARLS and ELSA provide measured (not self-reported) anthropometry and blood pressure in harmonised ageing cohorts [9,10]. We therefore analysed harmonised individual-level data from 15,788 adults free of CVD at baseline to: (1) estimate and compare dose–response associations of seven adiposity indices with incident CVD; (2) characterise non-linearity and estimate risk thresholds; (3) quantify mediation by systolic and diastolic blood pressure, diabetes and hypertension; (4) estimate the joint effect of the adiposity–blood-pressure mixture by quantile g-computation; (5) verify robustness to death as a competing event and express effects as absolute CVD-free time lost; and (6) test bidirectional, cross-country external validity of adiposity-based CVD prediction with interpretable machine learning.

Methods

Study design and data sources

This is a prospective cohort study reported in accordance with the STROBE statement for cohort studies [11], using individual-level harmonised data from two ongoing nationally representative surveys of community-dwelling adults: CHARLS and ELSA, which share a common assessment framework and variable harmonisation [9,10]. CHARLS waves 1–4 (2011–2018) were used with baseline at wave 1 (2011); ELSA waves 2–10 (2002–2022) were used with baseline at wave 2 (2002–2004), the first ELSA wave with nurse-measured anthropometry and blood pressure. The study was conducted in accordance with the Declaration of Helsinki and relevant institutional and national guidelines and regulations. CHARLS is approved by the Institutional Review Board of Peking University, ELSA is approved by its host-institution research ethics committee, and all participants in both cohorts provided written informed consent. Because the analytic samples were drawn from pre-existing harmonised public-use datasets with de-identified data, the present secondary analysis was exempt from full ethical review.

Study population

We included adults aged ≥ 45 years at baseline with valid measured height, weight and waist circumference, non-missing baseline CVD status, and positive follow-up time. After applying these criteria, the analytic sample comprised 15,788 participants (China 10,557; England 5,231) (Fig. 1). CHARLS baseline measurements were taken by trained technicians; ELSA baseline measurements were taken by nurses.

Exposures: seven adiposity indices

Seven indices were computed from baseline measured height (m), weight (kg) and waist circumference (cm, at the level of the navel or midway between the lowest rib and the iliac crest): BMI (weight/height², kg/m²); WC (cm); WHtR (waist/height); ABSI (waist/(BMI^(2/3)×height^(1/2))); WWI (waist/√weight); BRI (364.2 – 365.5×√(1 – (waist/(π × height))²)); and CI (1.09×√(waist/(0.45×height))). WHtR, BRI and CI are mathematically redundant for a given waist and height (BRI and CI are deterministic monotone transformations of waist-to-height ratio), so their near-identical effect estimates reflect this algebraic relationship rather than independent evidence. Implausible anthropometric values were set to missing (height 1.2–2.1 m; weight 30–250 kg); for participants with one of height/weight missing, the missing component was back-computed from measured BMI where available. Each index was analysed continuously (per SD, standardised in the pooled analytic sample) and as study-specific tertiles with cut-points fixed in the observed data: BMI 22.45/26.14 kg/m²; WC 82.0/92.4 cm; WHtR 0.513/0.576; ABSI 0.080/0.084; WWI 10.68/11.37; BRI 3.63/4.91; CI 1.164/1.233.

Outcomes

The primary outcome was incident CVD, defined as the first self-reported physician diagnosis of stroke or heart disease during follow-up. Secondary outcomes were stroke and heart disease analysed

separately. Follow-up time ran from baseline to the year of first CVD event; participants were censored at loss to follow-up or the final available wave. Death was identified from harmonised interview-status variables and treated as a competing event in Fine–Gray models and in the cumulative-incidence analysis; in the competing-risk coding a participant whose CVD report and death occurred in the same follow-up wave was counted as a death.

Covariates

The adjustment set was defined a priori in four progressive models: **M1** crude (country-stratified baseline hazard only); **M2** plus demographics (age, sex, education, marital status); **M3** plus behavioural factors (ever-smoking, ever-drinking); and **M4** plus clinical factors (systolic and diastolic blood pressure, self-reported diabetes, self-reported hypertension diagnosis). Mediation analyses used the M3 adjustment set to avoid adjusting for mediators. Urban/rural residence (China only) was absorbed by country-stratified hazards.

Statistical analysis

All inferential analyses used multiple imputation by chained equations ($m = 5, 10$ iterations, seed 2026) with passive imputation of derived indices (only components were imputed; indices were recomputed within each iteration), implemented in the mice package [12]. Given the low item missingness (BMI 2.2%, waist circumference 1.1%; Supplementary Table S6), five imputations are sufficient for the fractional missing information in these data; trace plots were inspected to confirm convergence of the imputation algorithm. Pooled estimates follow Rubin's rules.

Dose–response. Cox proportional-hazards models with country-stratified baseline hazards estimated tertile HRs (M1–M4) with P for trend, and per-SD HRs. The proportional-hazards assumption was checked by Schoenfeld residuals. For every index, the exposure term satisfied the proportional-hazards assumption (all exposure-term $P > 0.05$); the global Schoenfeld test was significant in all models, driven by time-varying effects of covariates (age, sex, smoking, hypertension diagnosis) rather than by the exposure terms (Supplementary Table S1). Restricted cubic splines (4 knots) visualised dose–response shapes; a two-piece linear spline anchored at the curve nadir estimated per-SD HRs below and above the nadir.

Mediation. The Cox product method decomposed the BMI–CVD and WC–CVD associations (M3 adjustment) into indirect effects through each of four mediators—systolic blood pressure, diastolic blood pressure, diabetes and hypertension diagnosis—with delta-method confidence intervals. Because single-mediator proportions are non-additive when mediators are strongly correlated, the primary reporting quantity is the joint proportion mediated, computed as (total–direct)/total effect after simultaneous adjustment for all four mediators; single-mediator proportions are given in Supplementary Table S7.

Mixture analysis. Quantile g-computation [13] was implemented for the five-component mixture of BMI, WC, WHtR, systolic and diastolic blood pressure (each scored into tertiles, 0/1/2, cut-points from the observed data). The joint hazard ratio for a simultaneous one-tertile increase in all components is $\exp(\Sigma\beta)$ from the adjusted Cox model; component weights are $\beta_i/\Sigma\beta$. Because the mixture components (particularly BMI, WC and WHtR) are highly intercorrelated, these weights describe relative effect-size contributions under a joint one-tertile exposure shift and should not be interpreted as causal attribution. Because systolic and diastolic blood pressure are mixture components, the adjustment set was M3. The joint-effect variance follows Rubin's rules for a linear combination.

Competing risk and absolute effects. Fine–Gray subdistribution hazards models [14] (M4 adjustment) estimated per-SD subdistribution HRs (SHRs) for each index with death as the competing event, using the inverse-probability-weighted start–stop construction with cluster-robust variance. Cumulative incidence functions by BMI tertile were estimated non-parametrically, and the restricted mean time lost (RMTL; $\int \text{CIF}(t)dt$ to year 7, the maximum Chinese follow-up) [15] quantified absolute CVD time loss, with bootstrap percentile intervals (200 replicates, stratified by country) for between-tertile differences.

Machine learning and cross-country validation. Gradient-boosted trees (XGBoost [16]; maximum depth 4, learning rate 0.03, subsampling 0.8, early stopping on a 20% validation split; no class reweighting, so that predicted probabilities remain interpretable as absolute 7-year risks) predicted 7-year CVD risk from the seven adiposity indices plus age, sex, education, marital status, blood pressure, diabetes, hypertension diagnosis, smoking and drinking. Models were trained in China and externally validated in England, and vice versa; a combined model was validated within each country. Discrimination was summarised by the concordance index on the 7-year event window, and calibration by predicted-risk deciles versus Kaplan–Meier 7-year risk. TreeSHAP values (exact computation for tree ensembles) [17] ranked feature importance, and SHAP dependence plots for the leading adiposity indices were compared with the spline shapes. Quantitative calibration was summarised by the calibration slope and intercept (logistic regression of the 7-year event indicator on the logit of predicted risk) and the Brier score, and clinical utility by decision-curve analysis (net benefit across threshold probabilities against treat-all and treat-none strategies) (Supplementary Table S8, Supplementary Figure S3). Time-dependent AUC, risk-stratified Kaplan–Meier analysis, decile calibration curves and a censored survival decision-curve analysis of the combined model are reported in Supplementary Tables S14a–c and Supplementary Figures S4–S6.

Sensitivity and subgroup analyses. We repeated the per-SD M4 analyses (i) excluding events within the first 2 years (landmark); (ii) in the complete-case sample without imputation; (iii) excluding waist values < 50 cm as implausible; (iv) weighting countries equally; and (v) using Chinese (24/28 kg/m², the Working Group on Obesity in China cut-points [18]) and WHO (25/30 kg/m² [19]) BMI cut-points. Effect modification was tested across age, sex, smoking, drinking, diabetes and hypertension with interaction terms; given the number of interaction tests, subgroup findings were treated as exploratory. To verify that the significant global Schoenfeld tests reflected time-varying effects of covariates rather than of the exposures, we refitted each M4 model allowing linear time-varying coefficients for age, sex, smoking and

hypertension diagnosis via time-by-covariate interaction terms, and compared the per-SD exposure estimates with the main analysis (Supplementary Table S10).

Incremental value of adiposity indices. We compared nested Cox models for 7-year CVD on the common 7-year follow-up window: a base model containing the conventional risk factors only (age, sex, education, marital status, ever-smoking, ever-drinking, systolic and diastolic blood pressure, diabetes and hypertension diagnosis) versus the base model plus all seven adiposity indices, or plus WWI and WC alone. Incremental discrimination was quantified by the change in C-index (percentile bootstrap, 200 resamples) and by the category-free net reclassification improvement (NRI) and integrated discrimination improvement (IDI), computed within each imputation and pooled (Supplementary Table S9).

Analyses were performed in R 4.5.3 (survival, mice, rms, cmprsk, xgboost and related packages). Two-sided $P < 0.05$ was considered significant.

Results

Cohort

The analytic sample comprised 15,788 adults (China 10,557; England 5,231). Over a median follow-up of 7 years in China and 11 years in England, 3,175 participants developed incident CVD (stroke 941; heart disease 2,506) and 1,089 died without prior CVD. Participants in higher BMI tertiles were younger in China but older in England; as expected from pooled cut-points applied within each country, Chinese participants concentrated in the lower tertiles and English participants in the higher tertiles (Table 1).

Table 1
Baseline characteristics by country and BMI tertile (medians [IQR] or n (%)).

Characteristic	China T1	China T2	China T3	England T1	England T2	England T3	P
n	4725	3703	2129	542	1540	3149	
Age, years (median [IQR])	59.00 [53.00, 67.00]	56.00 [50.00, 63.00]	56.00 [49.00, 62.00]	65.00 [57.00, 74.00]	63.00 [58.00, 71.00]	63.00 [57.00, 71.00]	< 0.001
Female, n (%)	2112 (44.7)	1990 (53.7)	1334 (62.7)	355 (65.5)	869 (56.4)	1714 (54.4)	< 0.001
Education level, n (%)							< 0.001
1	2496 (52.8)	1613 (43.6)	930 (43.7)	203 (37.5)	497 (32.3)	1265 (40.2)	
2	1028 (21.8)	809 (21.8)	420 (19.7)	5 (0.9)	17 (1.1)	46 (1.5)	
3	817 (17.3)	810 (21.9)	517 (24.3)	239 (44.1)	776 (50.4)	1414 (44.9)	
4	384 (8.1)	471 (12.7)	262 (12.3)	95 (17.5)	250 (16.2)	424 (13.5)	
Married, n (%)	3808 (80.6)	3146 (85.0)	1851 (86.9)	322 (59.4)	1045 (67.9)	2196 (69.7)	< 0.001
Systolic blood pressure, mmHg (median [IQR])	122.50 [110.50, 137.50]	126.00 [114.50, 140.50]	132.00 [120.00, 146.50]	128.50 [115.50, 143.00]	131.50 [119.00, 144.00]	135.00 [124.50, 147.50]	< 0.001
Diastolic blood pressure, mmHg (median [IQR])	71.50 [64.50, 79.50]	75.00 [68.00, 83.00]	79.00 [71.50, 87.50]	71.00 [64.00, 79.00]	74.00 [67.50, 81.00]	77.00 [70.00, 84.00]	< 0.001
BMI, kg/m ² (median [IQR])	20.44 [19.16, 21.49]	24.06 [23.25, 25.00]	28.03 [27.01, 29.66]	21.10 [19.90, 21.85]	24.57 [23.65, 25.43]	29.73 [27.74, 32.41]	< 0.001
Waist circumference, cm (median [IQR])	77.30 [73.00, 81.60]	87.00 [83.00, 91.00]	96.30 [91.60, 101.00]	77.50 [72.65, 82.65]	87.72 [82.10, 93.60]	101.15 [94.20, 108.45]	< 0.001
Waist-to-height ratio (median [IQR])	0.49 [0.46, 0.52]	0.55 [0.52, 0.58]	0.61 [0.58, 0.64]	0.47 [0.45, 0.50]	0.53 [0.50, 0.56]	0.61 [0.57, 0.65]	< 0.001
A body shape index (median [IQR])	0.08 [0.08, 0.09]	0.08 [0.08, 0.09]	0.08 [0.08, 0.09]	0.08 [0.08, 0.08]	0.08 [0.08, 0.08]	0.08 [0.08, 0.08]	< 0.001

Characteristic	China T1	China T2	China T3	England T1	England T2	England T3	P
Weight-adjusted waist index (median [IQR])	10.83 [10.32, 11.45]	11.13 [10.64, 11.69]	11.45 [10.96, 11.93]	10.38 [9.89, 10.88]	10.69 [10.22, 11.17]	11.10 [10.67, 11.52]	< 0.001
Body roundness index (median [IQR])	3.15 [2.66, 3.71]	4.30 [3.77, 4.94]	5.67 [4.99, 6.42]	2.86 [2.43, 3.36]	3.92 [3.43, 4.46]	5.62 [4.83, 6.60]	< 0.001
Conicity index (median [IQR])	1.14 [1.10, 1.17]	1.20 [1.17, 1.24]	1.27 [1.24, 1.30]	1.12 [1.09, 1.15]	1.18 [1.15, 1.21]	1.27 [1.23, 1.31]	< 0.001
Ever smoked, n (%)	2241 (47.4)	1369 (37.0)	617 (29.0)	345 (63.7)	928 (60.3)	1944 (61.7)	< 0.001
Ever drank alcohol, n (%)	2005 (42.4)	1492 (40.3)	693 (32.6)	473 (87.3)	1415 (91.9)	2814 (89.4)	< 0.001
Diabetes, n (%)	127 (2.7)	195 (5.3)	184 (8.6)	14 (2.6)	51 (3.3)	274 (8.7)	< 0.001
Hypertension diagnosis, n (%)	622 (13.2)	795 (21.5)	785 (36.9)	136 (25.1)	427 (27.7)	1323 (42.0)	< 0.001
Incident CVD during follow-up, n (%)	710 (15.0)	651 (17.6)	526 (24.7)	96 (17.7)	350 (22.7)	842 (26.7)	< 0.001
Follow-up time, years (median [IQR])	7.00 [7.00, 7.00]	7.00 [7.00, 7.00]	7.00 [7.00, 7.00]	10.00 [7.00, 15.00]	12.00 [7.00, 16.00]	11.00 [6.00, 14.00]	< 0.001

Independent, monotonic dose–response associations

All seven adiposity indices were associated with incident CVD in adjusted dose–response fashion (Table 2, Fig. 2). In the fully adjusted model (M4), the highest versus lowest tertile HRs were: BMI 1.49 (95% CI 1.34–1.65), WC 1.49 (1.35–1.65), WHtR 1.42 (1.29–1.56), ABSI 1.13 (1.03–1.25), WWI 1.28 (1.17–1.41), BRI 1.43 (1.30–1.58) and CI 1.42 (1.29–1.56); P for trend ≤ 0.014 for all seven indices. Effect sizes were similar for stroke (e.g., BMI 1.40, 1.16–1.69; WC 1.46, 1.23–1.75) and heart disease (BMI 1.51, 1.35–1.70; WC 1.51, 1.35–1.68) analysed separately (Supplementary Tables S2–S3). Adjustment for blood pressure, diabetes and hypertension (M3→M4) attenuated HRs by roughly one quarter—evidence that part of the association is mediated—while demographic and behavioural adjustment had smaller effects. Schoenfeld residual tests supported the proportional-hazards assumption for the exposure term of every index (all exposure-term P > 0.05; minimum 0.080); the global test was significant in all models but this reflected time-varying effects of covariates—principally age, sex, smoking and hypertension diagnosis—rather than of the adiposity exposures (Supplementary Table S1). Associations were directionally consistent between the two countries, an agreement in relative risks

rather than in absolute adiposity levels, which differ between countries under the pooled cut-points (Table 1).

Table 2
Hazard ratios (95% CI) for incident CVD across adiposity-index tertiles, Cox models with country-stratified baseline hazards, MICE pooled (m = 5).

Index	M1: T3 vs T1	M2: T3 vs T1	M3: T3 vs T1	M4: T2 vs T1	M4: T3 vs T1	P trend (M4)
BMI	1.63 (1.48–1.79)	1.79 (1.62–1.97)	1.79 (1.63–1.98)	1.20 (1.09–1.32)	1.49 (1.34–1.65)	< 0.001
WC	1.75 (1.60–1.92)	1.77 (1.61–1.94)	1.77 (1.61–1.94)	1.22 (1.11–1.34)	1.49 (1.35–1.65)	< 0.001
WHtR	1.76 (1.61–1.93)	1.67 (1.53–1.84)	1.68 (1.53–1.84)	1.25 (1.14–1.38)	1.42 (1.29–1.56)	< 0.001
ABSI	1.37 (1.25–1.50)	1.20 (1.09–1.32)	1.20 (1.09–1.32)	1.21 (1.10–1.32)	1.13 (1.03–1.25)	0.014
WWI	1.64 (1.50–1.79)	1.44 (1.31–1.58)	1.44 (1.31–1.58)	1.17 (1.07–1.28)	1.28 (1.17–1.41)	< 0.001
BRI	1.77 (1.62–1.94)	1.69 (1.54–1.85)	1.69 (1.54–1.86)	1.26 (1.14–1.38)	1.43 (1.30–1.58)	< 0.001
Conicity index	1.76 (1.61–1.93)	1.67 (1.53–1.84)	1.68 (1.53–1.84)	1.25 (1.14–1.38)	1.42 (1.29–1.56)	< 0.001

Non-linearity and thresholds

Restricted cubic splines indicated mild but significant non-linearity for BMI ($P = 0.0006$), WC ($P = 0.022$) and BRI ($P = 0.013$), with shallow J-shaped curves—risk rising modestly at the lowest adiposity values, consistent with reverse causation by pre-existing illness—before increasing monotonically across the population range; WHtR, ABSI, WWI and CI showed no significant departure from linearity (Fig. 3). Two-piece spline analyses confirmed monotonically increasing risk above the curve nadir for every index (per-SD HRs 1.07–1.24; e.g., WC 1.24, 1.18–1.29); below-nadir estimates were unstable because the nadirs fell at the extreme lower edge of the distributions (Supplementary Table S4).

Mediation by blood pressure and cardiometabolic disease

The blood-pressure/diabetes pathway explained a substantial fraction of the adiposity–CVD association (Supplementary Table S12, Fig. 4). For BMI, the joint proportion mediated was 32.4% overall (China 40.6%; England 22.7%); for WC, 30.0% (China 35.9%; England 29.0%). The single-mediator proportions (largest for hypertension diagnosis and diabetes, smaller for systolic blood pressure) are shown in Supplementary Table S7; as expected from the strong mutual correlation of the mediators, they overlap and are not additive, and several exceed 100% when considered in isolation—hence the joint proportion

is the interpretable quantity. The pattern—stronger mediation in China than England—was consistent across indices.

Mixture effects, competing risk and absolute time lost

Treating adiposity and blood pressure as a five-component mixture, quantile g-computation gave a joint HR of 1.59 (95% CI 1.49–1.70) for a simultaneous one-tertile increase in all components (M3 adjustment; Fig. 5A, Supplementary Table S11). All weights were positive, led by WC (31.5%), followed by BMI (29.7%), systolic blood pressure (26.5%), diastolic blood pressure (8.3%) and WHtR (4.0%); given the high intercorrelation of the adiposity components, these weights indicate relative contributions under a joint exposure shift rather than independent causal effects.

Accounting for death as a competing event changed little: per-SD subdistribution HRs under Fine–Gray models (BMI 1.17, 1.13–1.22; WC 1.20, 1.15–1.26; WHtR 1.17; BRI 1.17; CI 1.16; WWI 1.08; ABSI 1.04, 0.999–1.08) were close to the corresponding Cox estimates, and the highest BMI tertile carried a subdistribution HR of 1.50 (1.35–1.66). The ABSI association was borderline under the competing-risk model (SHR 1.04, 95% CI 0.999–1.08), consistent with it being the weakest index in the primary Cox analysis (Supplementary Table S11). Cumulative incidence of CVD rose steeply and monotonically across BMI tertiles in both countries (Fig. 5B). In absolute terms, the highest BMI tertile lost 0.132 years of CVD-free time over 7 years compared with the lowest tertile (95% CI 0.096–0.173; $\approx$ 48 days); the excess was larger in China (0.193 years) than in England (0.050 years), reflecting both steeper relative risks and higher baseline incidence in China (Fig. 5C).

Robustness and effect modification

Every sensitivity analysis reproduced the main findings (Supplementary Table S13): per-SD BMI HRs ranged from 1.16 (equal country weighting) to 1.18 (complete case), and per-SD WC HRs from 1.19 to 1.25; a 2-year landmark analysis gave HRs of 1.17 (BMI) and 1.19 (WC); excluding participants with waist < 50 cm left estimates unchanged (BMI 1.17; WC 1.24). Allowing time-varying coefficients for age, sex, smoking and hypertension diagnosis left every per-SD exposure estimate essentially unchanged (all seven indices directionally consistent; e.g., BMI 1.14→1.15, WC 1.20→1.21 per SD), confirming that the significant global Schoenfeld tests reflect covariate, not exposure, non-proportionality (Supplementary Table S10). Using Chinese (24/28 kg/m²) or WHO (25/30 kg/m²) BMI cut-points, obesity carried an HR of 1.48 (1.34–1.64) or 1.44 (1.29–1.62) versus normal weight, with a clear overweight gradient (HR 1.29 for both classifications). Subgroup analyses were consistent across age, sex, smoking, drinking and diabetes strata. Two of the six formal BMI interaction tests reached nominal significance: the BMI association was stronger in women (P-interaction = 4.4×10^{-6}) and weaker in participants with treated hypertension (P-interaction = 0.002); both remained significant after Benjamini–Hochberg correction within these six tests ($q = 2.6 \times 10^{-5}$ and $q = 0.006$, respectively; Supplementary Figure S1). Given the larger number of subgroup and interaction analyses performed across indices, these findings are nevertheless treated as exploratory.

Cross-country machine-learning validation

Gradient-boosted models transported bidirectionally: discrimination in the external cohort was C-index 0.623 for China→England and 0.618 for England→China. Across predicted-risk deciles, observed 7-year risk rose with predicted risk in both countries, but the quality of absolute-risk calibration differed between them (Fig. 6C, Supplementary Table S5). In China, observed risk increased monotonically across deciles and tracked predictions closely in the middle of the range, with mild overprediction at the lowest deciles (decile 1: predicted 13.9% vs observed 6.4%) and some underprediction at the highest (decile 10: 24.1% vs 37.8%). In England, calibration was clearly poorer: predicted risk overestimated observed risk two- to four-fold in the lowest deciles (decile 1: 14.3% vs 3.5%; decile 2: 15.2% vs 5.6%), the observed curve was non-monotonic in the middle deciles (observed 7-year risk in decile 7, 13.3%, fell below that in decile 6, 18.4%), and the highest decile was underestimated (23.8% vs 32.2%). This pattern is consistent with the China-dominant case-mix of the combined training sample. Discrimination was nonetheless preserved in both countries, and absolute-risk deployment would require country-specific recalibration.

Models trained on the combined cohort achieved C-indexes of 0.656 (China) and 0.701 (England). TreeSHAP ranked hypertension diagnosis and age as the dominant predictors; among adiposity indices, WWI contributed most (third overall), followed by WC, WHtR, BMI and ABSI (Fig. 6A–B). SHAP dependence plots for WWI and ABSI showed monotonically increasing risk with flattening at high values in England and a shallow J-shape in China, mirroring the spline curves (Supplementary Figure S2). Quantitative calibration confirmed the decile pattern, with calibration slopes of 1.39 (95% CI 1.29–1.49) in China and 1.82 (1.63–2.01) in England and Brier scores of 0.138 and 0.104 (Supplementary Table S8). Decision-curve analysis showed positive net benefit of the model over both treat-all and treat-none strategies across threshold ranges of 5–60% in China and 6–49% in England; at a 10% risk threshold the net benefit was 0.100 (China) and 0.046 (England) (Supplementary Figure S3). Discrimination was stable over follow-up: time-dependent AUC at 3 and 5 years was 0.685 and 0.680 in China and 0.744 and 0.739 in England (Supplementary Table S14a). Predicted-risk tertiles showed clear separation of CVD-free survival in both countries (high versus low hazard ratio 3.68, 95% CI 3.24–4.17 in China; 5.86, 4.51–7.62 in England; Supplementary Figure S4), and a censored survival decision-curve analysis complemented the binary-window analysis, supporting model net benefit across threshold probabilities (Supplementary Figure S6; estimand definitions in the Supplementary Notes).

Incremental value of adiposity indices

Adding the seven adiposity indices to a base model of conventional risk factors improved the C-index for 7-year CVD from 0.631 to 0.641 (Δ C 0.010, 95% CI 0.008–0.014), with category-free NRI 0.070 (95% CI 0.029–0.107) and IDI 0.005 (0.001–0.008); adding only WWI and WC gave a similar increment (Δ C 0.008, 0.006–0.012; NRI 0.060, 0.031–0.096; IDI 0.005, 0.001–0.007) (Supplementary Table S9). The increment is statistically robust but modest in absolute terms: adiposity indices refine, rather than replace, conventional risk-factor assessment.

Discussion

Principal findings

In two nationally representative ageing cohorts with measured anthropometry, seven adiposity indices showed independent, monotonic dose–response associations with incident CVD, with broadly consistent effect sizes across indices and countries. Roughly one third of the BMI-associated risk was statistically explained by blood pressure and cardiometabolic disease, the highest adiposity group lost about seven weeks of CVD-free life within seven years, and adiposity-based prediction models transported with stable discrimination, albeit with imperfect absolute-risk calibration, across the two health systems.

Comparison with prior work

The evidence linking individual adiposity indices to cardiovascular outcomes has accumulated one index at a time. WHtR outperformed BMI and WC in a meta-analysis of cardiometabolic risk factors [3]; ABSI predicted mortality independently of BMI [4]; BRI was derived to track visceral adipose tissue [5]; and WWI predicted cardiovascular mortality in US adults [7] and incident CVD in two further US cohorts [8]. Each study, however, used a different population, adjustment set and outcome, so it has remained unclear whether the indices differ in the independent information they carry. By estimating all seven indices in the same individuals under a common, pre-specified adjustment gradient, we show that they convey broadly similar information for incident CVD (fully adjusted highest-versus-lowest tertile HRs 1.13–1.49), with simple WC and BMI at the top and ABSI weakest—consistent with ABSI capturing body *shape* rather than adipose mass per se. The study closest in design, an analysis of BRI trajectories and incident CVD in CHARLS [20], used a single index in a single country; our harmonised two-country analysis demonstrates that the dose–response is not a China-specific artefact but replicates in England despite markedly different adiposity distributions, health systems and baseline incidence. Finally, cross-country transportability of adiposity-based prediction has rarely been tested; our bidirectional external validation (C-index ≈ 0.62 in both directions), in line with recent explainable machine-learning cardiovascular prediction in Chinese adults [21], shows that the adiposity signal generalises across populations even though absolute calibration remains country-specific.

Mechanistic interpretation

Our observational design cannot establish that these pathways operate causally, but the pattern of associations is mechanistically informative. Roughly one third of the adiposity–CVD association was statistically explained by blood pressure and cardiometabolic disease (joint mediated proportion 32.4% for BMI and 30.0% for WC)—quantitatively consistent with the $\approx 25\%$ attenuation observed when blood pressure, diabetes and hypertension were added to the model (M3→M4). Hypertension diagnosis and diabetes carried the largest mediator shares, but because diagnosis, measured blood pressure and diabetes are strongly intercorrelated, single-mediator proportions are overlapping and non-additive (each exceeding 100% when summed); we therefore emphasise the joint proportion. The notably stronger mediation in China (40.6%) than in England (22.7%) may reflect a steeper adiposity–blood-pressure

gradient in middle-aged Chinese adults, lower rates of effective hypertension treatment at baseline, or residual differences in detection and coding of cardiometabolic disease. The direct association that persists after removing all four mediators (two thirds of the total effect) implies additional pathways not captured in our data, including atherogenic lipids, chronic low-grade inflammation, insulin resistance and glycaemia, left-atrial enlargement and atrial fibrillation, obstructive sleep apnoea and chronic kidney disease[22]. Two interaction findings support the blood-pressure-centred interpretation: the association was stronger in women—whose central adiposity is more strongly lipolytically active[23]— weaker in participants with treated hypertension, in whom treatment partially blocks the proximal pathway[24]. The mixture analysis reinforces the same hierarchy: in the joint adiposity–blood-pressure model, WC contributed the largest weight (31.5%) and a simultaneous one-tertile increase in all components yielded a joint HR of 1.59.

Outcome ascertainment and residual bias

A cautious interpretation of the absolute effect sizes is warranted because incident CVD was ascertained by self-reported physician diagnosis without linkage to medical records or registers. Validation studies of self-reported cardiovascular history against medical records have generally found substantial agreement for myocardial infarction and stroke but weaker agreement for broader heart-disease categories [25], and outcome misclassification in our data is therefore likely to be non-differential with respect to adiposity. Such non-differential misclassification would, if anything, attenuate the relative associations towards the null, so the reported HRs are plausibly conservative; conversely, if higher adiposity increases healthcare contact and hence the probability of receiving a diagnosis, detection bias could inflate associations, and we cannot exclude this competing source. The consistency of the dose–response across two health systems with very different diagnosis probabilities, its persistence after 2-year landmark exclusion, and the agreement between self-reported-event Cox estimates and Fine–Gray estimates treating death as a competing event all argue that the associations are not an artefact of outcome ascertainment, but the absolute RMTL values should be read as approximate.

Strengths and limitations

Strengths include measured (not self-reported) anthropometry and blood pressure in both countries, harmonised outcome and death ascertainment, a pre-specified model gradient, multiple imputation with passive recomputation of derived indices, and triangulation across Cox, Fine–Gray, mixture and machine-learning frameworks with bidirectional external validation. Limitations include self-reported incident CVD outcomes (undetected events; reverse causation cannot be excluded despite landmark analyses), the J-shaped low-adiposity limb likely reflecting pre-existing illness, residual confounding by lipids and medication (unavailable at baseline in one cohort), tertile cut-points fixed on the pooled distribution (so within-country groups differ in absolute adiposity), single-baseline exposure measurement (regression dilution), and the use of one imputed dataset for machine-learning analyses. Finally, CHARLS follow-up ended in 2018 (ELSA in 2022), and pooled analyses were aligned to a common 7-year window; although

the relative dose–response associations we describe are biologically stable and the screening frameworks we discuss remain current, absolute risks should be re-estimated on more recent waves before operational use.

Implications

Three implications follow. For clinical screening, measured WC and, where available, WWI should complement BMI in cardiovascular risk assessment, echoing the consensus recommendation that waist circumference be routinely measured as a vital sign [2]. The case is strongest in Chinese and other Asian populations, in whom risk began to rise at BMI values well below conventional obesity thresholds: with Chinese-specific cut-points (24/28 kg/m²), obesity carried a fully adjusted HR of 1.48, and the pooled-tertile analysis showed a clear gradient from the lowest adiposity group upwards.

At the health-system level, the absolute scale of the effect is material. The highest BMI tertile lost 0.132 years (about seven weeks) of CVD-free time within seven years, nearly fourfold more than the corresponding loss in England (0.193 vs 0.050 years), reflecting both steeper relative risks and higher baseline incidence in China; a simultaneous one-tertile increase in adiposity and blood pressure jointly raised CVD risk by 59%, supporting combined lifestyle and blood-pressure management targets in both health systems.

For risk prediction, adiposity-based models transported across countries with preserved discrimination but imperfect absolute-risk calibration, particularly in England, where low-decile risks were overestimated two- to four-fold. WWI emerged as the leading adiposity predictor and warrants inclusion alongside conventional risk factors, but the modest external C-indexes (≈ 0.62) and the calibration pattern caution that absolute risk prediction requires country-specific recalibration before deployment. Incremental-value analyses quantify this trade-off: adding the seven adiposity indices to conventional risk factors raised the C-index for 7-year CVD by only 0.010 (95% CI 0.008–0.014), with consistent NRI and IDI, so their role is to refine, rather than replace, conventional risk assessment.

Conclusions

In two nationally representative ageing cohorts with measured anthropometry, seven adiposity indices showed independent, monotonic dose–response associations with incident CVD, with broadly consistent effects across indices and countries. Blood pressure and cardiometabolic disease statistically explained about one third of the BMI-associated risk. Measured waist circumference and the weight-adjusted waist index should complement BMI in cardiovascular risk assessment, particularly in Chinese and other Asian populations. Adiposity-based prediction models transported across the two health systems with preserved discrimination but imperfect absolute-risk calibration, so absolute-risk deployment requires country-specific recalibration; the indices refine, rather than replace, conventional risk-factor assessment.

Declarations

Ethics approval and consent to participate

This study is a secondary analysis of de-identified, publicly available harmonised data (CHARLS and ELSA) and was conducted in accordance with the Declaration of Helsinki and relevant institutional and national guidelines and regulations. CHARLS is approved by the Institutional Review Board of Peking University, ELSA is approved by its host-institution research ethics committee, and all participants in both cohorts provided written informed consent. The present secondary analysis of de-identified public-use data was exempt from full ethical review.

Clinical trial registration

Clinical trial number: not applicable.

Consent for publication

Not applicable.

Availability of data and materials

CHARLS and ELSA harmonised data are available to registered researchers via the Gateway to Global Aging Data (<https://g2aging.org/>) and the respective study websites (<http://charls.pku.edu.cn/>; <https://www.elsa-project.ac.uk/>). Analysis code (R) is available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

JunCong Mao: conceptualisation, data curation, formal analysis, methodology, software, writing—original draft. Yunfei Hong: conceptualisation, validation, writing—review and editing. Shujing Yang: methodology,

validation, writing—review and editing. Yerui Cai: supervision, writing—review and editing, correspondence. All authors read and approved the final manuscript.

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Figures

Figure 1. Flow chart of study inclusion and follow-up outcomes

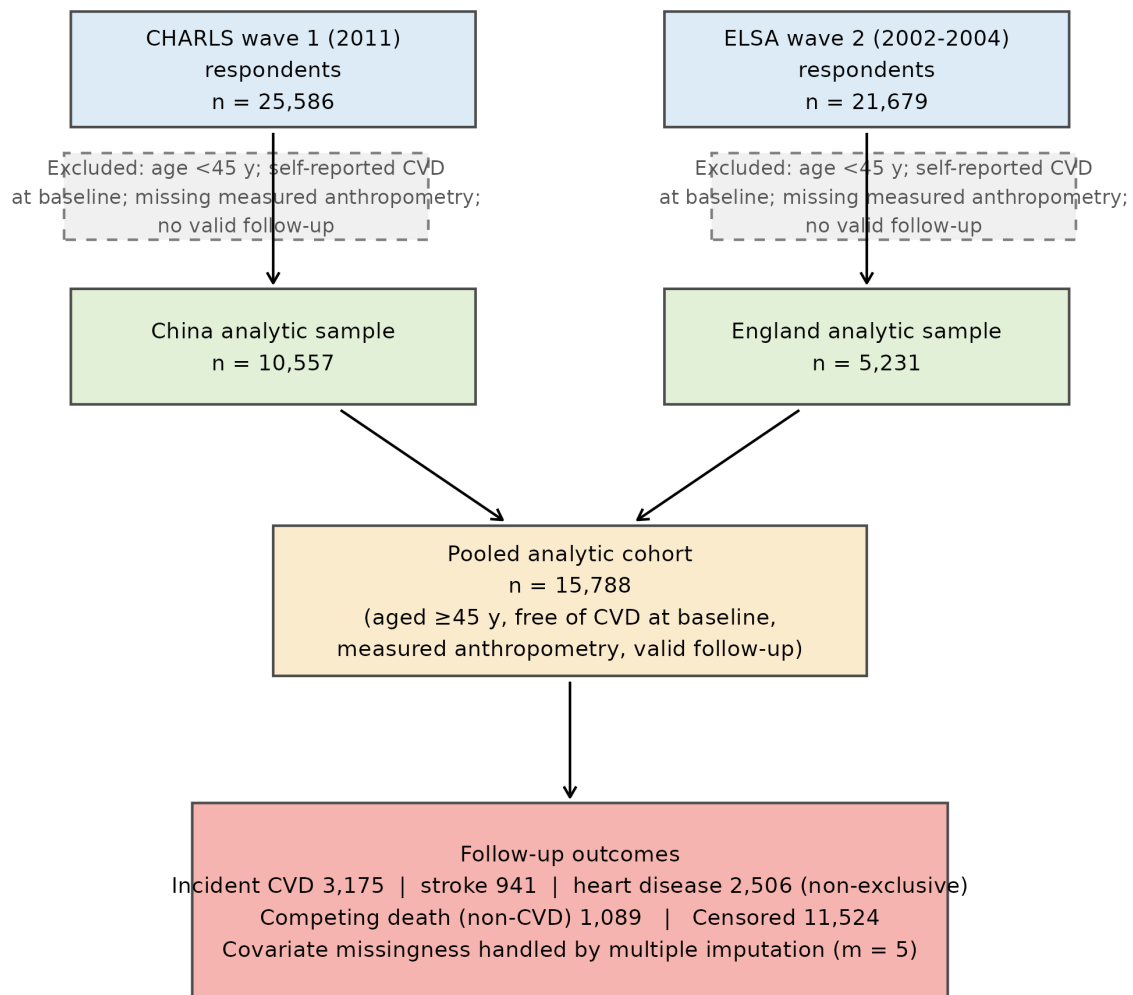


Figure 1

Flow chart of study inclusion and follow-up outcomes. CHARLS wave 1 (2011) respondents (n=25,586) and ELSA wave 2 (2002–2004) respondents (n=21,679) were screened; after exclusion of participants aged <45 years, with self-reported CVD at baseline, missing measured anthropometry or without valid follow-up, the pooled analytic cohort comprised 15,788 participants (China 10,557; England 5,231), with 3,175 incident CVD events (including 941 strokes and 2,506 heart-disease cases, categories not additive), 1,089 competing deaths and 11,524 censored during follow-up.

Tertiles of anthropometric indices and incident CVD

Model 4 (fully adjusted), strata(country), MICE pooled

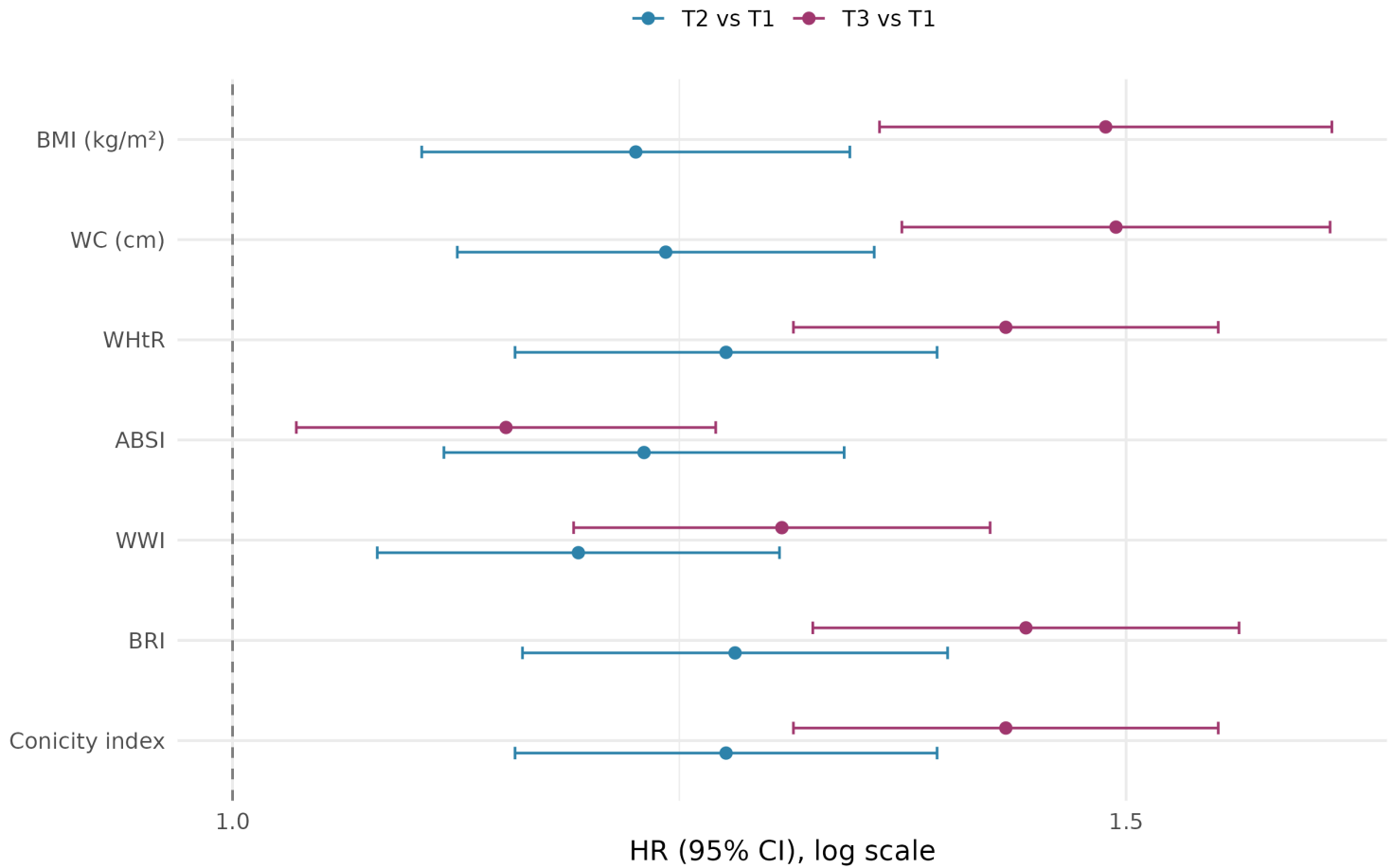


Figure 2

Forest plot of fully adjusted (M4) hazard ratios for the highest versus lowest tertile of each adiposity index, for CVD, stroke and heart disease.

Dose-response between anthropometric indices and incident CVD (RCS, 3 knots)
 Model 4 adjustment; strata(country) for combined curve; first imputed dataset

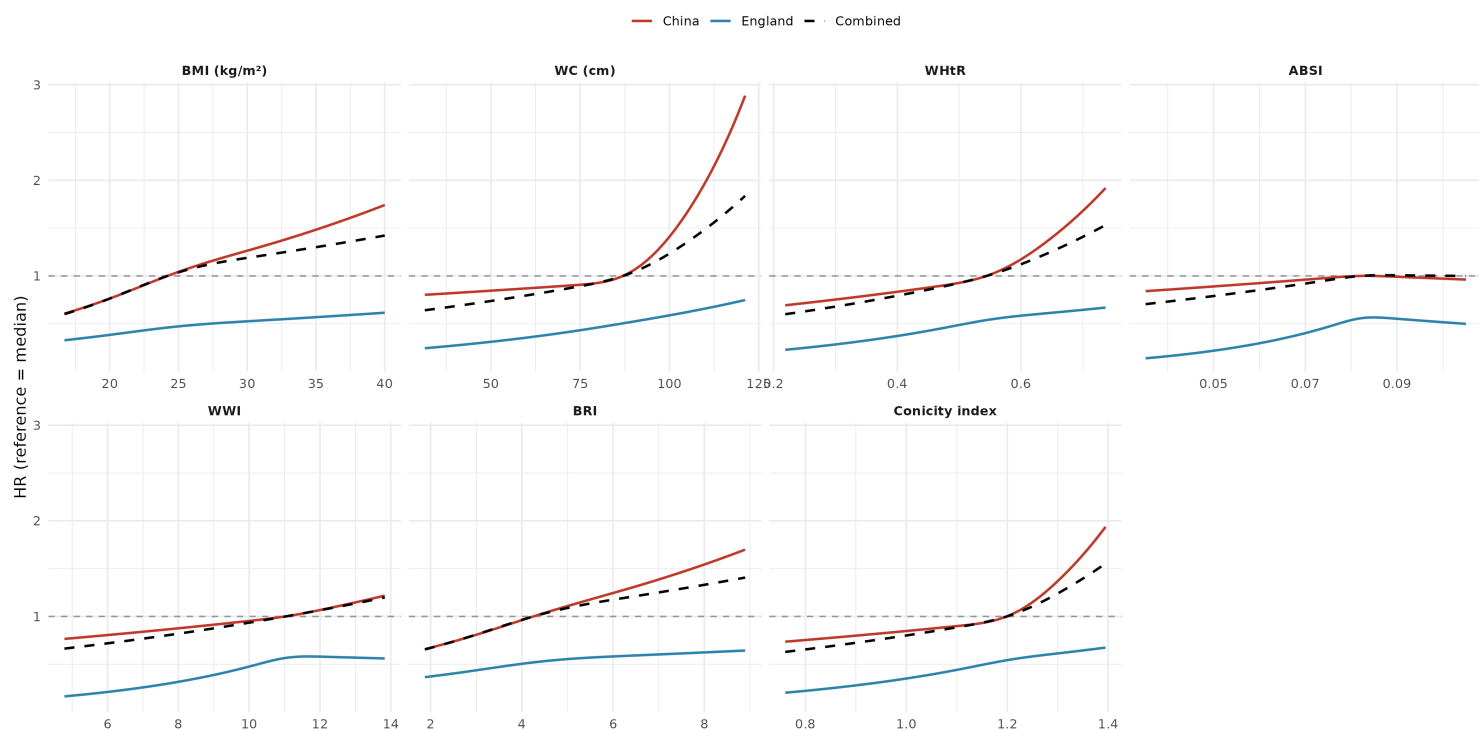


Figure 3

Restricted cubic spline dose–response curves for the seven adiposity indices, China and England overlaid.

Mediation of the obesity–CVD association by BP and cardiometabolic disease
Product method on Cox models; M3 adjustment; MICE pooled. Individual proportions are non-additive

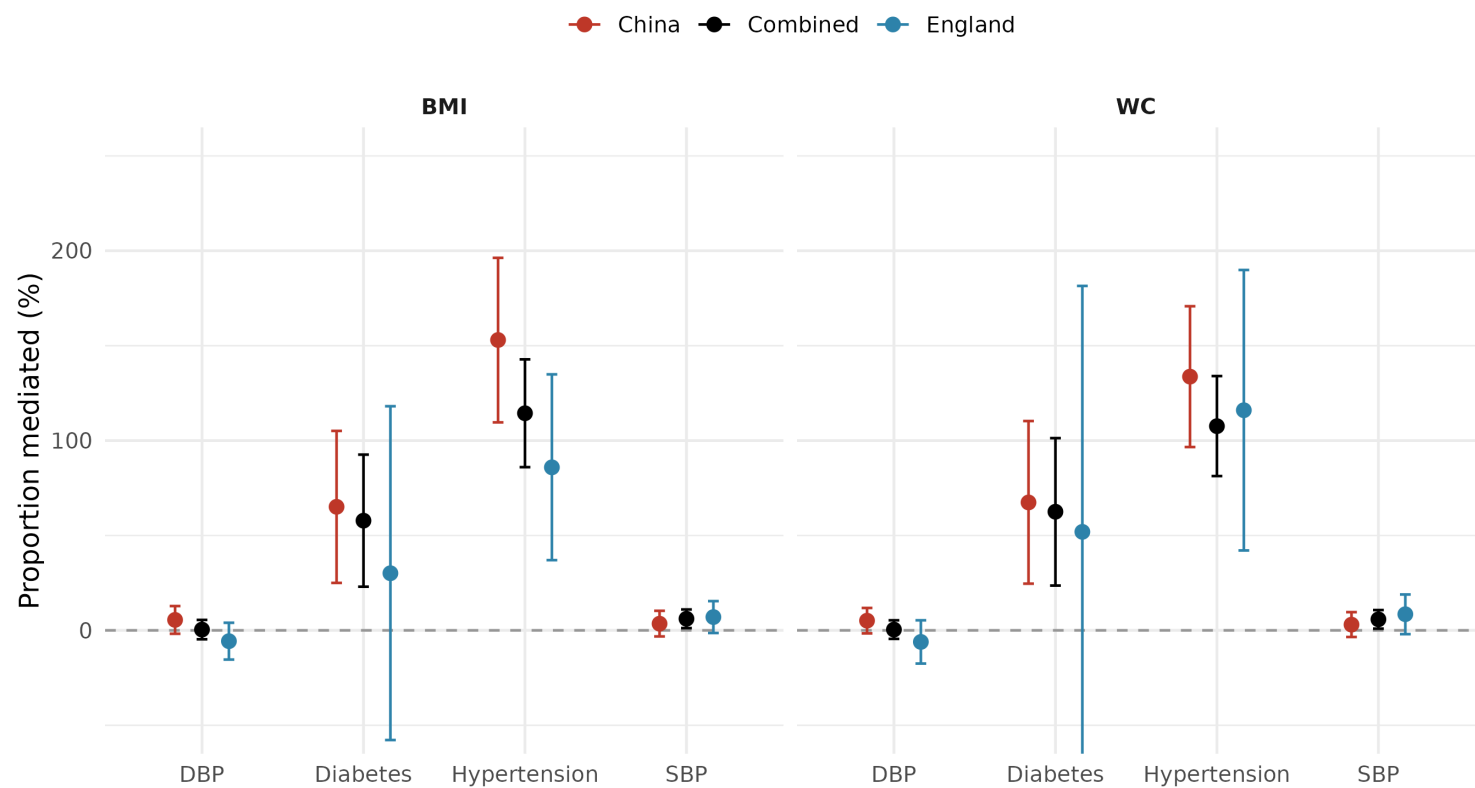


Figure 4

Mediation of the BMI–CVD and WC–CVD associations by blood pressure, diabetes and hypertension diagnosis: joint proportion mediated and (non-additive) single-mediator proportions, by country; the single-mediator detail is given in Supplementary Table S7.

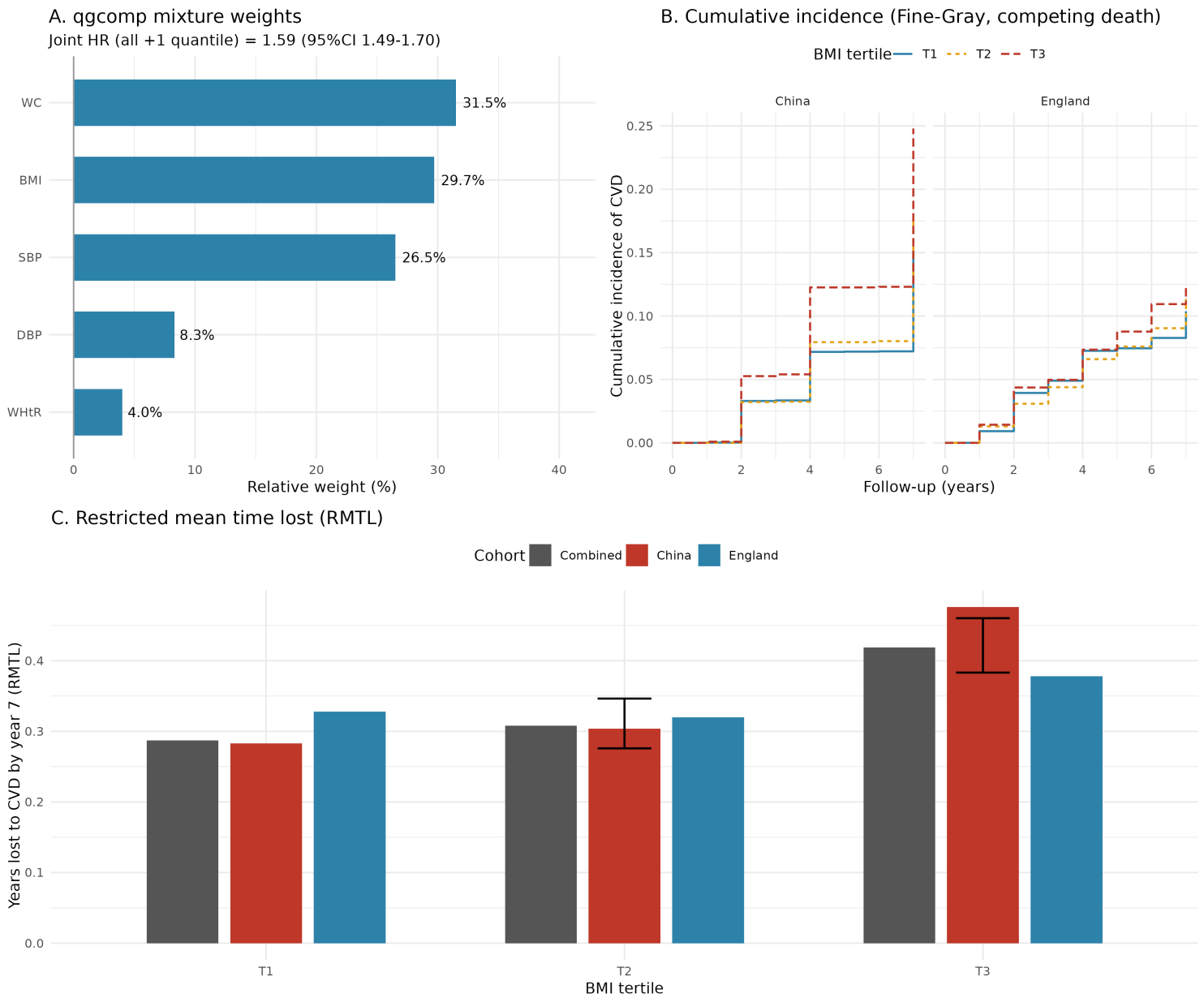


Figure 5

(A) Quantile g-computation weights for the five-component adiposity–blood-pressure mixture with joint hazard ratio; (B) cumulative incidence functions of CVD by BMI tertile, by country; (C) restricted mean time lost to CVD by year 7, by BMI tertile and cohort.

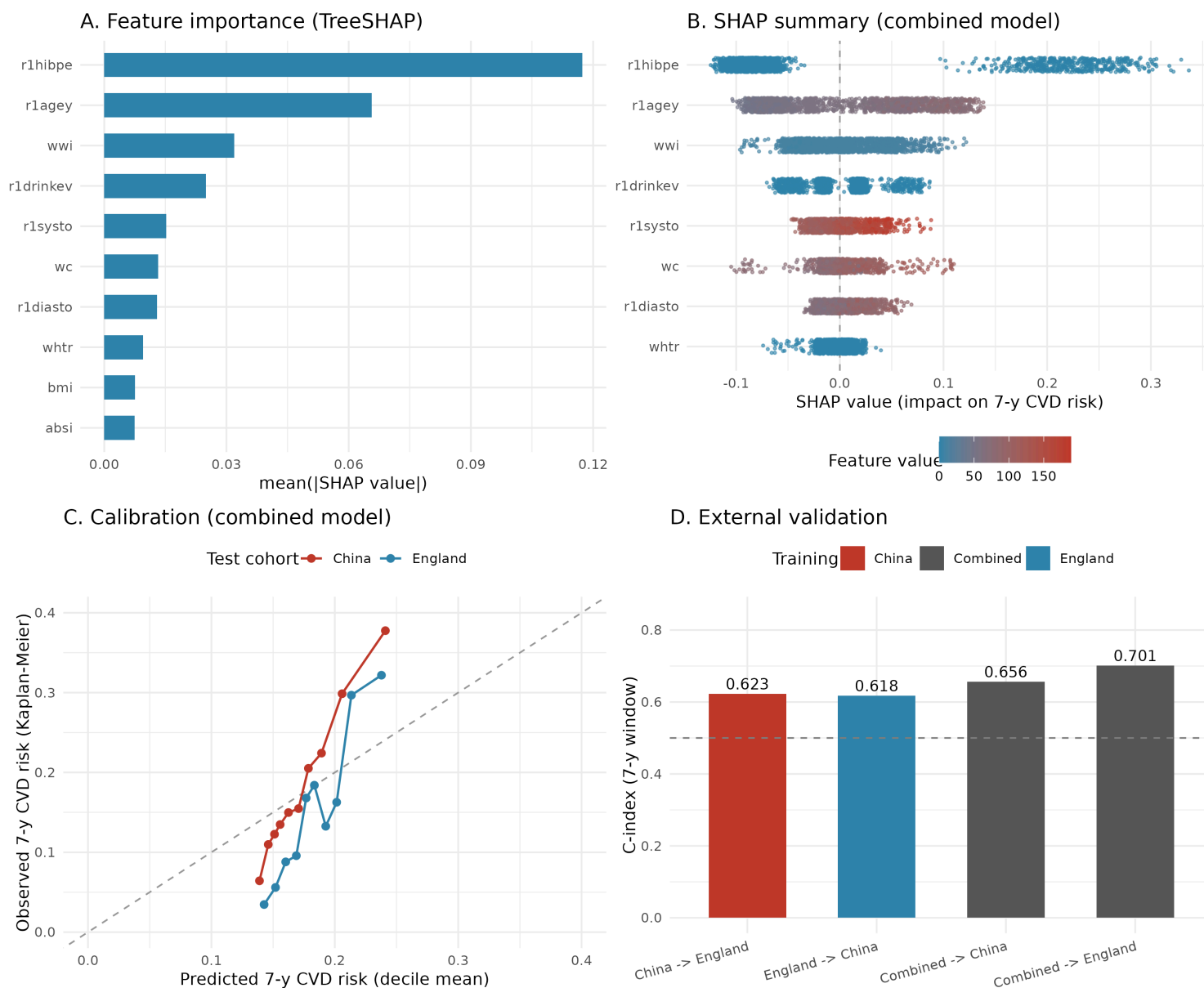


Figure 6

(A) TreeSHAP feature importance; (B) SHAP summary (beeswarm); (C) calibration of the combined model; (D) C-index of bidirectional external validation.

Supplementary Files

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