World Health Organization cardiovascular disease risk charts: revised models to estimate risk in 21 global regions

The WHO CVD Risk Chart Working Group*

Summary

Background To help adapt cardiovascular disease risk prediction approaches to low-income and middle-income countries, WHO has convened an effort to develop, evaluate, and illustrate revised risk models. Here, we report the derivation, validation, and illustration of the revised WHO cardiovascular disease risk prediction charts that have been adapted to the circumstances of 21 global regions.

Methods In this model revision initiative, we derived 10-year risk prediction models for fatal and non-fatal cardiovascular disease (ie, myocardial infarction and stroke) using individual participant data from the Emerging Risk Factors Collaboration. Models included information on age, smoking status, systolic blood pressure, history of diabetes, and total cholesterol. For derivation, we included participants aged 40–80 years without a known baseline history of cardiovascular disease, who were followed up until the first myocardial infarction, fatal coronary heart disease, or stroke event. We recalibrated models using age-specific and sex-specific incidences and risk factor values available from 21 global regions. For external validation, we analysed individual participant data from studies distinct from those used in model derivation. We illustrated models by analysing data on a further 123 743 individuals from surveys in 79 countries collected with the WHO STEPwise Approach to Surveillance.

Findings Our risk model derivation involved 376 177 individuals from 85 cohorts, and 19 333 incident cardiovascular events recorded during 10 years of follow-up. The derived risk prediction models discriminated well in external validation cohorts (19 cohorts, 1096 061 individuals, 25 950 cardiovascular disease events), with Harrell’s C indices ranging from 0.685 (95% CI 0.629–0.741) to 0.833 (0.783–0.882). For a given risk factor profile, we found substantial variation across global regions in the estimated 10-year predicted risk. For example, estimated cardiovascular disease risk for a 60-year-old male smoker without diabetes and with systolic blood pressure of 140 mm Hg and total cholesterol of 5 mmol/L ranged from 11% in Andean Latin America to 30% in central Asia. When applied to data from 79 countries (mostly low-income and middle-income countries), the proportion of individuals aged 40–64 years estimated to be at greater than 20% risk ranged from less than 1% in Uganda to more than 16% in Egypt.

Interpretation We have derived, calibrated, and validated new WHO risk prediction models to estimate cardiovascular disease risk in 21 Global Burden of Disease regions. The widespread use of these models could enhance the accuracy, practicability, and sustainability of efforts to reduce the burden of cardiovascular disease worldwide.

Funding World Health Organization, British Heart Foundation (BHF), BHF Cambridge Centre for Research Excellence, UK Medical Research Council, and National Institute for Health Research.

Copyright © 2019 The Author(s). Published by Elsevier Ltd. This is an Open Access article under the CC BY 4.0 license.
set of studies, might be directly applicable only to specific populations (mainly in high-income countries), and might not predict the correct risk in the target population being screened (ie, poor calibration).8,13,15–18

Here, we provide derivation, validation, and illustration of updated WHO models for cardiovascular disease risk prediction. To enhance targeting of efforts to reduce the burden of cardiovascular disease, we have statistically adapted (ie, recalibrated)14,19 models to the contemporary circumstances of many different global regions using routinely available information. The aim of recalibration was to ensure that risk prediction models estimate risk for individuals in each region more accurately. To help make this approach more sustainable, we developed and describe here a method that can be used to regularly update risk prediction models using information about epidemiological trends in cardiovascular disease within different global regions. The WHO CVD Risk Chart Working Group, a cross-sectoral collaboration of academics, policy makers, and end users of risk scores, was convened to facilitate this development of revised models for prediction of cardiovascular disease risk more tailored to the needs of low-income and middle-income countries.

Methods

Study design

In our model revision initiative, several interrelated components were involved (figure 1). First, we derived risk prediction models using individual participant data from 85 prospective cohorts in the Emerging Risk Factors Collaboration (ERFC). Second, we adjusted models to the contemporary circumstances of multiple global regions, recalibrating models using age-specific and sex-specific incidences and risk factor values obtained from the Global Burden of Disease (GBD) studies29,30 and the Non-Communicable Disease Risk Factor Collaboration (NCD-RisC).22–24 Third, we completed external validation using individual participant data from a further 19 prospective cohorts that did not contribute to the model derivation. Fourth, models were applied to individual participant data from 79 countries collected with the WHO STEPwise Approach to Surveillance (STEPS).31 Fifth, we used this sequence of analyses to assess the potential value of pragmatic risk models (eg, those that include information on body-mass index [BMI] instead of serum lipid values), because laboratory measurements are not widely available in many low-income and middle-income countries.29,32

Data sources and procedures

The ERFC was selected for model derivation because it has collated and harmonised individual participant data from many long-term prospective cohort studies of cardiovascular disease risk factors and outcomes.29,30 Prospective studies in the ERFC were included in our analysis if they met all the following criteria: had recorded baseline information on risk factors necessary to derive risk prediction models (ie, age, sex, smoking status [current vs other], history of diabetes, systolic blood pressure, baseline cholesterol levels, and use of lipid-lowering or antihypertensive medication), and had follow-up data available on cardiovascular disease incidence and deaths.29,30

Evidence before this study

To update the 2007 WHO and International Society of Hypertension’s cardiovascular disease risk prediction approaches, WHO has convened an informal risk-chart working group. To inform this work, we searched PubMed, Scientific Citation Index Expanded, and Embase to identify existing risk prediction models for cardiovascular disease in the context of primary prevention published in any language up to May 15, 2019, using the relevant terms: “cardiovascular disease”, “risk score”, “risk equation”, “risk algorithm”, and “risk prediction”. We found many studies and reviews describing risk prediction models to estimate cardiovascular disease risk in a primary prevention context. However, none had combined the following key features necessary to develop reliable risk models relevant to low-income and middle-income countries: use of powerful and diverse global data, simple and generalisable methods to account for differences in populations (ie, to allow recalibration), and inclusion of information that is readily available in many low-income and middle-income countries.

Added value of this study

The newly developed risk models involve several features that should confer advantages compared with existing tools. First, they are underpinned by powerful, extensive, and complementary datasets of global relevance. Second, we used comprehensive contemporary estimates of cardiovascular disease incidence and risk factor values to adapt (ie, recalibrate) the risk models to many different populations using a simpler and more generalisable approach than that of previous studies. Third, these models provide estimates for the combined outcome of fatal and non-fatal events. Fourth, they include pragmatic models that do not assume availability of laboratory measurements (eg, serum lipid concentrations) that could be used as part of stepwise approaches to help target laboratory testing in people most likely to benefit from the extra information.

Implications of all the available evidence

We have derived, validated, and illustrated new WHO models for cardiovascular disease risk prediction adapted for the needs of low-income and middle-income countries, to support tools and guidance for cardiovascular disease prevention and control. The widespread use of these models could enhance the accuracy, practicability, and sustainability of efforts to reduce the burden of cardiovascular disease worldwide.
pressure, and total cholesterol or BMI, were approximately population-based (ie, did not select participants on the basis of having previous disease), had recorded cause-specific deaths and non-fatal cardiovascular disease events (ie, non-fatal myocardial infarction or stroke) with well defined criteria, and had at least 1 year of follow-up after baseline (which was deemed to be sufficient for estimation of risk factor–disease associations in the absence of non-proportional hazards). We did not use prospective cohort studies analysed as nested case-control studies. Details of the contributing studies are described in appendix 1 (pp 3–5, 37–38).

For the recalibration of models, we obtained age-specific and sex-specific incidences of myocardial infarction and stroke from the 2017 update of the GBD study for each of 21 global regions defined by GBD to maximise between-region variability and minimise heterogeneity within each region in mortality and major drivers of health outcomes (appendix 1 p 39).21,29 Age-specific and sex-specific risk factor values for each of these regions were estimated by averaging country-specific risk factor values provided by the NCD-RisC.20,22–24,30

We included prospective cohort studies in the external validation analysis if they met the following criteria: did not contribute to the model derivation stage, met the same methodological criteria as those described for the cohorts selected from the ERFC for the model derivation stage, and made individual participant data accessible for analysis to investigators in our working group. Studies used for external validation included the following: the Asia Pacific Cohort Studies Collaboration (APCSC),31 the New Zealand primary care-based PREDICT cardiovascular disease cohort (PREDICT-CVD),32 the Chinese Multi-Provincial Cohort Study,33 the Health Checks Ubon Ratchathani Study34 in Thailand, the Tehran Lipids and Glucose Study,35 and UK Biobank (appendix 1 p 6).

To mirror the populations typically targeted in primary prevention efforts for cardiovascular disease, risk model derivation included participants aged 40–80 years without a known baseline history of cardiovascular disease. Follow-up was until the first myocardial infarction, fatal coronary heart disease, or stroke event; outcomes were censored if a participant was lost to follow-up, died from non-cardiovascular disease causes, or reached 10 years of follow-up. Conventional cardiovascular disease risk factors were considered for selection as variables in risk models if they were known to be predictive of cardiovascular disease in different populations, were recorded in available survey data to allow systematic recalibration within each global region,21,23–29,30 and had been shown to be measurable at low cost in low-income and middle-income countries.30

We derived two types of new WHO risk prediction models for cardiovascular disease: a laboratory-based model including age, smoking status, systolic blood pressure, history of diabetes, and total cholesterol; and a non-laboratory-based model including age, smoking status, systolic blood pressure, diabetes, and BMI. Sex-specific models were derived separately for coronary heart disease (defined in the ERFC dataset as non-fatal myocardial infarction or fatal coronary heart disease), and stroke (any fatal or non-fatal cerebrovascular event) outcomes. Details of these endpoint definitions are shown in appendix 1 (p 7). Outcomes were modelled separately for coronary heart disease and stroke to allow separate recalibration to the disease-specific incidence in the target populations before combination in a single estimation equation for cardiovascular disease risk (appendix 1 pp 40–41). The assumption of independence between coronary heart disease and stroke risk was checked with data from ERFC cohorts (appendix 1 p 15).

**Statistical analysis**

We estimated hazard ratios (HRs) using Cox proportional hazards models, stratified by study and with duration (ie, time from entry into the study) as the
Summary of available data from the Emerging Risk Factors Collaboration used in WHO risk model derivation

<table>
<thead>
<tr>
<th>Study-level characteristics</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of studies</td>
<td>80</td>
<td>62</td>
</tr>
</tbody>
</table>

Baseline characteristics

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total participants</td>
<td>202,962</td>
<td>173,215</td>
</tr>
<tr>
<td>Age at baseline survey (years)</td>
<td>53 (48–60)</td>
<td>55 (49–63)</td>
</tr>
<tr>
<td>Systolic blood pressure (mm Hg)</td>
<td>132 (120–146)</td>
<td>130 (118–145)</td>
</tr>
<tr>
<td>Total cholesterol (mmol/L)</td>
<td>5.7 (5.0–6.5)</td>
<td>5.9 (5.2–6.7)</td>
</tr>
<tr>
<td>Current smoking status</td>
<td>76,943 (37.9%)</td>
<td>38,170 (22.0%)</td>
</tr>
<tr>
<td>History of diabetes</td>
<td>9,939 (4.9%)</td>
<td>8,008 (4.6%)</td>
</tr>
<tr>
<td>BMI (kg/m²)†</td>
<td>25.6 (23.5–28.0)</td>
<td>25.3 (22.8–28.6)</td>
</tr>
</tbody>
</table>

Cardiovascular outcomes‡

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal or non-fatal MI or CHD death§</td>
<td>18,987</td>
<td>7,226</td>
</tr>
<tr>
<td>Fatal or non-fatal stroke§</td>
<td>8,870</td>
<td>6,682</td>
</tr>
<tr>
<td>Follow-up to first cardiovascular disease event (years; median [5–95th percentile range])</td>
<td>10.3 (3.4–20.4)</td>
<td>13.1 (4.4–27.0)</td>
</tr>
</tbody>
</table>

Data are n (%) or median (25–75th percentile range), unless otherwise specified. Data are from a total of 85 cohorts with 376,177 participants. BMI=body-mass index. MI=myocardial infarction. CHD=coronary heart disease.

‡Specific International Classification of Diseases codes are given for each endpoint in the appendix (p 7). §Number of fatal or non-fatal stroke events during the first 10 years of follow-up: 9,456 in men and 3,515 in women. ¶Number of fatal or non-fatal MI events or CHD deaths occurring during the first 10 years of follow-up: 9,456 in men and 3,515 in women.

Table 1: Summary of available data from the Emerging Risk Factors Collaboration used in WHO risk model derivation

Timescale (in subsidiary analyses, models were also fitted with age as the timescale). Interactions between baseline age and other predictors were included because outcome associations commonly vary with age.

Continuous variables were centred to aid interpretation of regression model estimates and facilitate recalibration of the models to new populations, with age centred at 60 years (the midpoint of the defined 40–80 years age range), total cholesterol at 6 mmol/L, BMI at 25 kg/m², and systolic blood pressure at 120 mm Hg. Deviation from the proportional hazards assumption was either minimal or non-existent, assessed by fitting models including time-varying covariates. Between-study heterogeneity was assessed using the I² statistic. We used meta-regression to assess heterogeneity by geographical region and period of cohort enrolment.

For internal validation, we assessed risk discrimination using Harrell’s C index. This index estimates the probability of the model correctly predicting who will have a cardiovascular disease event first in a randomly selected pair of participants. To avoid optimism that might result from assessing risk discrimination in the data from which the model was derived, we used an internal–external validation approach in which each study was, in turn, left out of the model derivation and used to calculate a validation C index. The calibration of each model within studies with at least 10 years of follow-up in the derivation dataset was checked by comparing observed and predicted risk across deciles of predicted risk and by calculating a χ² statistic to quantify any evidence of lack of agreement or fit (appendix 1 p 40).

Recalibration was done separately for men and women (description in appendix 1 pp 16,40–41). This process involved the use of age-specific and sex-specific mean risk factor levels and annual incidence estimates of fatal or non-fatal myocardial infarction and stroke events in each of 21 global regions (appendix 1 p 43). Calibration of the new WHO models was assessed by comparing the predicted 10-year cardiovascular disease risk with the expected 10-year risk estimated from the 2017 GBD annual incidence estimates, across 5-year age groups. An additional external validation assessment was completed in the PREDICT-CVD cohort (the only nationally representative validation cohort available to us). Because fewer than 10 years of follow-up were available in this cohort, we recalibrated models to estimate 5-year risk. We assessed discrimination using all external validation cohorts by calculating study-specific C indices before pooling by country, weighting by number of events.

Additionally, we compared C indices for the same prediction models derived within datasets used for external validation with those calculated for the new WHO models. To compare the proportion of the population at different levels of cardiovascular disease risk, with the WHO models, across multiple countries, we applied the risk models to WHO STEPS surveys data. To allow comparison across countries, we restricted analysis to the latest survey year available for each country and to individuals aged 40–64 years, with total cholesterol between 2.6–10.3 mmol/L, and complete data on relevant variables (appendix 1 pp 8–9). These data were also used to compare risk estimates obtained with non-laboratory-based models with those obtained with laboratory-based models.

Our approach to model development and validation complies with the guideline for Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis (appendix 1 pp 44–45). Analyses were done with Stata, version 14, two-sided p values, and 95% CIs. The study was designed and done by the WHO CVD Risk Chart Working Group in collaboration with the ERFC academic coordinating centre and was approved by the Cambridgeshire Ethics Review Committee.

Role of the funding source

The academic investigators and representatives of WHO participated in the design and oversight of the project. The academic investigators at the coordinating centre had full access to all the data and had final responsibility for the decision to submit for publication. All authors gave approval to submit for publication.
Our risk model derivation involved 376,177 participants without preceding cardiovascular disease, recruited between 1960 and 2013 (table 1, appendix 1 pp 3–5,10). Mean age was 54 years (SD 9) among men and 56 years (9) among women. 247,699 (66%) of 376,177 participants were recruited in European countries, 85,098 (23%) in North America, and the remainder mostly in Japan and Australia. During the initial 10 years of follow-up (3·2 million person-years at risk) 19,333 cardiovascular disease events were observed (table 1, appendix 1 pp 3–5).

HRs for myocardial infarction or fatal coronary heart disease and stroke for each risk predictor included in the WHO models are provided in table 2. Associations of history of diabetes and current smoking status with cardiovascular disease diminished with age, particularly in women, among whom HRs for myocardial infarction or fatal coronary heart disease were reduced from 4·65 (95% CI 3·46–6·24) for history of diabetes and 5·58 (4·58–6·81) for smoking status at age 40 years to 2·31 (2·04–2·62) for history of diabetes and 2·05 (1·85–2·29) for smoking status at age 70 years (appendix 1 p 17). We found little to moderate heterogeneity in HRs across studies and no evidence to suggest differences in HRs according to geographical regions or period of cohort enrolment (appendix 1 p 11).

Calibration and goodness of fit for the prediction models were good within the ERFC dataset, both overall (appendix 1 p 18) and within specific regions and recruitment time periods (appendix 1 p 19). Internally validated C indices ranged from 0·666 (95% CI 0·661–0·672) in men with the non-laboratory-based model to 0·757 (0·749–0·765) in women with the laboratory-based model (appendix 1 p 12).

According to 2017 GBD estimates, the relative contribution of myocardial infarction and stroke differed...
substantially by region and sex (appendix 1 pp 20–22), reinforcing the need for separate recalibration of individual models for each endpoint. Myocardial infarction incidence was greater for men than for women in all regions, but the incidence of stroke was more similar between sexes (appendix 1 pp 23–24). The age-specific and sex-specific mean risk factor levels used for recalibration are presented by region in appendix 1.
Articles

The revised WHO charts for cardiovascular disease risk estimation in 21 global regions are shown in appendix 2 for the laboratory-based and non-laboratory-based models. The predicted 10-year cardiovascular disease risk estimated with the WHO models was within the expected 95% CI ranges, on the basis of uncertainty in GBD estimates (appendix 1 pp 30–31). Additionally, we observed a good agreement between 5-year predicted and observed risk in the PRECINCT-CVD cohort (appendix 1 p 32). The estimated absolute risk for a given age and combination of risk factors differed substantially across regions (figure 2). For example, the estimated 10-year cardiovascular disease risk for a 60-year-old male smoker without diabetes and with systolic blood pressure of 140 mm Hg and total cholesterol of 5 mmol/L ranged from 11% in Andean Latin America to 30% in central Asia. Similarly, the 10-year risk for a 60-year-old woman with the same risk factor profile ranged from 9% in Andean Latin America to 23% in eastern Europe, north Africa, and the Middle East.

External validation of risk models involved calculation of C indices with use of data from 1096 061 participants with no previous cardiovascular disease, recruited into 19 prospective cohorts (25 950 cardiovascular disease events observed; appendix 1 p 6). C indices indicated good discrimination, with values for the WHO laboratory-based risk model ranging from 0·685 (95% CI 0·629–0·741) to 0·833 (0·783–0·882; figure 3). Furthermore, deriving individual models of myocardial infarction or fatal coronary heart disease and stroke risk directly in the APCSC gave broadly similar HRs to those found in ERFC (appendix 1 p 13); C indices indicated such agreement; appendix 1 p 36).

The risk models described here involve several features that should confer advantages compared with existing tools.8,9,13,47–49 First, these models are underpinned by powerful, extensive, and complementary datasets of global relevance, used in a series of interrelated analyses for model derivation, recalibration, validation, and illustration of cardiovascular disease risk.20–24

### Discussion

We have developed, evaluated, and illustrated the use of revised prediction models for cardiovascular disease risk adapted for low-income and middle-income countries (appendix 2), with the aim of their incorporation into the WHO HEARTS package. These models have been systematically recalibrated to contemporary risk factor levels and disease incidences across 21 global regions, thereby enabling more accurate identification of individuals at high risk of cardiovascular disease in different settings.11,15,17,45 Because the approach to recalibration that we used allows rapid revision of cardiovascular disease models, it should enable flexible updating of models as relevant new epidemiological data emerge about cardiovascular disease trends in particular geographical areas.

The risk models described here involve several features that should confer advantages compared with existing tools. First, these models are underpinned by powerful, extensive, and complementary datasets of global relevance, used in a series of interrelated analyses for model derivation, recalibration, validation, and illustration of cardiovascular disease risk. In particular, the scale and geographical resolution of the datasets analysed have enhanced the validity and generalisability of risk models for each sex-specific and disease-specific (myocardial infarction and stroke) endpoint reported here.

### Table: C index (95% CI)

<table>
<thead>
<tr>
<th>Country</th>
<th>Participants</th>
<th>Cases</th>
<th>C index (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia*</td>
<td>2504</td>
<td>251</td>
<td>0·755 (0·726–0·784)</td>
</tr>
<tr>
<td>China†</td>
<td>18 694</td>
<td>1017</td>
<td>0·738 (0·722–0·754)</td>
</tr>
<tr>
<td>Iran‡</td>
<td>4921</td>
<td>400</td>
<td>0·770 (0·748–0·792)</td>
</tr>
<tr>
<td>Japan§</td>
<td>5570</td>
<td>114</td>
<td>0·685 (0·629–0·741)</td>
</tr>
<tr>
<td>New Zealand¶</td>
<td>254 680</td>
<td>7304</td>
<td>0·714 (0·707–0·721)</td>
</tr>
<tr>
<td>Singapore*</td>
<td>2424</td>
<td>105</td>
<td>0·833 (0·783–0·882)</td>
</tr>
<tr>
<td>Thailand</td>
<td>249 559</td>
<td>4704</td>
<td>0·722 (0·715–0·729)</td>
</tr>
<tr>
<td>UK</td>
<td></td>
<td></td>
<td>440 602</td>
</tr>
</tbody>
</table>

See Online for appendix 2
Figure 4: Distribution of 10-year cardiovascular disease risk according to recalibrated laboratory-based WHO risk prediction models for individuals aged 40–64 years from example countries. Data from all countries are from adults aged 40–64 years with total cholesterol concentrations of 2·6–10·3 mmol/L and from samples representative of the national population, unless otherwise specified as subnational (S) or community based (C).
A second feature is the simplicity of the recalibration approach we have developed. This approach entails fewer modelling steps and avoids reliance on sparse cohort or country-level data, providing recalibrated calculators tailored to the sex-specific cardiovascular disease rates and risk factor levels of each region. 

Because the approach can be used with aggregate (ie, group level) data on cardiovascular disease incidences and with average risk factor values for any target population to be screened, this means that descriptive epidemiological data can be readily incorporated to revise models according to country-specific cardiovascular disease incidence to reflect changes in disease incidences and risk factor profiles. To support periodic revisions, we have made openly accessible the statistical code needed to calculate, validate, and recalibrate these models using updated population data.

A third feature is that the risk models reported here provide estimates for the combined outcome of fatal and non-fatal events, thereby improving on risk calculators that predict fatal events alone. Although information on fatal event rates is often easier to obtain at a country-specific level, the use of mortality risk models might underestimate total cardiovascular disease risk, particularly for individuals in populations where the case-fatality rate is low (as is typically observed among younger individuals). Because the models reported here have been specifically derived for and recalibrated to the sex-specific and age-specific rates of myocardial infarction and stroke in each region, they should avoid inaccuracies that could arise from recalibration to overall cardiovascular disease rates, including inconsistencies in reporting softer endpoints (such as angina) across regions.

A fourth feature is the assessment of pragmatic models that do not assume availability of laboratory measurements (eg, serum lipid concentrations). Such simplified approaches could be used in resource-constrained settings as part of stepwise approaches to help target laboratory testing in people most likely to benefit from the extra information (eg, pre-selection tools). and used even when values for some risk factors are unavailable for individuals (when mean values from the relevant population can be used as crude surrogates). However, we found that an important limitation of such pragmatic scores was their poor performance among people with diabetes.

A fifth feature was that, because we could illustrate the performance of the new models with reference to surveillance data from 79 countries, our data have shown that the proportion of individuals across different risk categories is strikingly different across global regions. This finding suggests that our risk estimates should assist policy makers to make more appropriate and locally informed decisions about the allocation of prevention resources.

Finally, we have presented revised risk charts in an analogous manner to previous WHO–International Society of Hypertension (ISH) versions to help facilitate continuity of use. Nevertheless, the colour code has been revised to reflect the general lower estimated absolute risk levels compared with those of previous WHO–ISH models. Orange sections now indicate 10-year risk greater than 10%, whereas red sections indicate a risk greater than 20% (as opposed to >20% indicated in orange and >30% indicated in red previously).

The potential limitations of our study merit consideration. We derived risk prediction models from 85 cohorts mostly from high-income countries in the ERFC. Ideally, however, the derivation of risk models for low-income and middle-income countries would involve nationally representative, large-scale prospective cohort data from several of these countries, each cohort with long-term follow-up and validated fatal and non-fatal endpoints. Unfortunately, such data do not yet exist for most low-income and middle-income countries. Therefore, to inform recalibration, we used data from the GBD study and the NCD-RisC, acknowledging that these sources frequently do not have country-specific disease risk estimates because of the paucity or absence of such data. To provide external validation, we analysed data from 19 cohorts distinct from those used in model derivation. However, only one of them (PREDICT-CVD cohort) was nationally representative, whereas some of the other cohorts might have inadequately represented the epidemiology of cardiovascular disease in contemporary national populations of interest. Our risk models might have overestimated cardiovascular disease risk for primary prevention purposes because incidences from global regions used to recalibrate models were likely to include some recurrent events (although the extent of such overestimation is difficult to quantify). Conversely, our risk models might have underestimated cardiovascular disease risk because population data used to estimate incidences were likely to include some people already on cardiovascular disease prevention therapies (eg, statins or anti-hypertensive medication). However, data available to us were insufficient to explore this issue in detail. We could not compare the performance of our new risk models with risk equations already developed for use in specific high-income countries or regions because these equations typically contain some variables that are not available (or cannot be practically measured) in low-income and middle-income countries. Models were derived on participants with complete risk factor information, which, in principle, could cause a loss in efficiency and bias results. However, our analyses were well powered and should be unbiased under the reasonable assumption that the probability of an individual having complete risk factor information is independent of cardiovascular disease, given the variables included in the prediction model. 

For the statistical code see http://www.phpc.cam.ac.uk/ceu/erfc/programs/
In conclusion, we have derived, validated, and illustrated new WHO risk prediction models to estimate cardiovascular disease risk in 21 GBD regions. Because the risk prediction models reported here have been adapted to the contemporary circumstances of many different global regions and can be readily updated with routinely available information, their widespread use could enhance the accuracy, practicability, and sustainability of efforts to reduce the burden of cardiovascular disease worldwide.

**Contributors**
All authors contributed to data collection, study design, data analysis, interpretation, and drafting of the manuscript.

**WHO CVD Risk Chart Working Group writing committee**

*Contributed equally and is member of the working group.
†Contributed equally and is member of the working group.

**Affiliations**
Department of Public Health and Primary Care (S Kapote, L Pennells, S Bell, T Bolton, R Chowdhury, Q Guo, E Sofianopoulou, A Wood, J Danesh, E Di Angelantonio, P Willeit) and MRC Epidemiology Unit, University of Cambridge School of Clinical Medicine (N J Wareham), University of Cambridge, Cambridge, UK; Department of Public Health and Primary Care, Ghent University, Ghent, Belgium (D De Bacquer); St Vincent’s University Hospital School of Medicine, University College Dublin, Dublin, Ireland (M T Cooney); Department of Epidemiology, Erasmus MC, University Medical Center Rotterdam, Rotterdam, Netherlands (M Kavousi); World Health Organization, Geneva, Switzerland (G Stevens, L Riley, S Savin, C Varghese, T Khan, O Onuma); Department of Cardiology, Trakya University School of Medicine, Edirne, Turkey (S Altay); Institut Pasteur de Lille, Lille, France (P Amouyel); Assmann-Stiftung für Prävention, Münster, Germany (G Assmann); Population Health Sciences, Bristol University, Bristol, UK (Y Ben-Slimon); Harvard T H Chan School of Public Health (L Berkman, G Danaei, T A Gazzano) and Brigham & Women’s Hospital, Harvard Medical School (T A Gazzano, C O’Donnell, P M Ridker), Harvard University, Boston, MA, USA; Department of Epidemiology and Biostatistics, Amsterdam Public Health research institute, VU University Medical Center, Amsterdam, Netherlands (J W Beulens); Department of Public Health and Community Medicine, Primary Health Care, Institute of Medicine, University of Gothenburg, Gothenburg, Sweden (C Bijkerkuld); Johns Hopkins Ciccarone Center for the Prevention of Heart Disease, Johns Hopkins Hospital (M J Blaha) and Department of Epidemiology (M Woodward), Johns Hopkins University, Baltimore, MD, USA; Department of Psychiatry and Behavioral Sciences, Duke University Medical Center, Durham, NC, USA (D E Grobbee); Department of Public Health, University of Auckland, Auckland, New Zealand (R B Beaglehole, Y H Choi, R Jackson); Division of Clinical Epidemiology and Ageing Research, German Cancer Research Center, Heidelberg, Germany (H Brenner); Division of Preventive Oncology, German Cancer Research Center and National Center for Tumor Diseases, Heidelberg, Germany (H Brenner, B Schöttker), Network Aging Research, University of Heidelberg, Heidelberg, Germany (H Brenner, B Schöttker); Department of Epidemiology and Public Health (E J Brunner), BHF Laboratories (S Humphries), and Institute of Health Informatics (R B D P E Costa), University College London, London, UK; Department of Medicine, University of Padua, Padua, Italy (E Casiglia); Cardio-Metabolic Research Group, Department of Social Medicine, Sanpasitthiprasong Hospital, Ubon Ratchathani, Thailand (P Chamnann); Division of Cardiovascular Sciences, National Heart, Lung, and Blood Institute, Bethesda, MD, USA (S Coady); School of Community Health, Portland State University, OR, USA (M Kavousi); World Health Organization, Geneva, Switzerland (G Laughlin); San Jose Norte Health Centre, Zaragoza, Spain (T H Lam); Global Center of Excellence Program Study Group, Yamagata University (H Iso); Department of Endocrinology and Metabolism, Hiroaki University Graduate School of Medicine, Aomori, Japan (M Daimon); Department of Medicine, Columbia University Irving Medical Center, New York, NY, USA (K W Davidson); Department of Clinical Sciences in Malmö, Lund, Sweden (J W Jukema); Institute of Public Health and Clinical Medicine, Arctic University of Norway, Tromsø, Norway (S Grimsgaard); Julius Global Health, Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, Utrecht, Netherlands (D E Grobbee, K G M Moons); Faculty of Medicine, University of Iceland, Reykjavik, Iceland (V Gudnason); The Icelandic Heart Association, Kopavogur, Iceland (V Gudnason); Osaka University Graduate School of Medicine, Suita, Japan (H Ito); Department of Cardiology, Leiden University Medical Center, Leiden, Netherlands (J W Jukema); Institute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio, Finland (J Kauhanen); Non Communicable Diseases Research Unit, South African Medical Research Council, Cape Town, South Africa (A P Kengne); Prevention of Metabolic Disorder Research Center, Research Institute for Endocrine Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran (D Khliali); School of Population and Global Health, University of Western Australia, Perth, WA, Australia (M Knausin); Deutsches Herzzentrum München, Technische Universität München, Munich, Germany (W Koenig); German Centre for Cardiovascular Research (DZHK), partner site Munich Heart Alliance, Munich, Germany (W Koenig); Yale School of Medicine, Yale University, New Haven, CT, USA (H M Krausmol); School of Public Health, University of Hong Kong, Hong Kong, China (T H Lam); Family Medicine & Public Health, University of California, San Diego, CA, USA (G Laughlin); San Jose Norte Health Centre, Zaragoza, Spain (T H Lam);

Investigators of additional studies used in external validation

Declaration of interests
SK reports grants from UK Medical Research Council, British Heart Foundation, and UK National Institute of Health Research, during the conduct of the study. PA reports personal fees from Servier, Total, Genoscreen, and Fondation Alzheimer, outside the submitted work. MJB reports grants from US National Institutes of Health (NIH), US Food and Drug Administration (FDA), American Heart Association, Aetna Foundation, and Aetna Foundation; and personal fees from Amgen Foundation Sanofi, Regeneron, Novartis, Novo Nordisk, and Bayer, outside the submitted work. TAB reports grants from Novartis, United Healthcare, and NIH; and personal fees from Teva and Takeda, outside the submitted work. SJ reports grants from the British Heart Foundation (PG08/008), during the conduct of the study. JW [and his department] has received research grants from or was speaker (with or without lecture fees) on Continuing Medical Education-accredited meetings sponsored by Amgen, Athera, AstraZeneca, Biotronik, Boston Scientific, Daiichi Sankyo, Lilly, Medtronic, Merck-Schering-Plough, Pfizer, Roche, Sanofi Aventis, The Medicine Company, Netherlands Heart Foundation, CardioVascular Research the Netherlands, Interuniversity Cardiology Institute of the Netherlands, and the European Community Framework KPP Programme, during the conduct of the study. HMR reports grants from Medtronic and FDA, Medtronic and Johnson and Johnson, and Shenzhen Center for Health Information; personal fees from National Center for Cardiovascular Disease in Beijing, UnitedHealth, IBM Watson Health, Element Science, Aetna, Arnold & Porter, Ben C Martin Law Firm, and Facebook; ownership (with spouse) of Hugo; and contracts from the Centers for Medicare & Medicaid Services, outside the submitted work. WK reports personal fees from AstraZeneca, Novartis, Pfizer, The Medicines Company, DaCor, Kowa, Amgen, Sanofi, Berlin-Chemie, Roche Diagnostics, Beckmann, Singulex and Abbott; and non-financial support from Roche Diagnostics, Beckmann, Singulex and Abbott, outside the submitted work. PJN reports personal fees from NIH, during the conduct of the study. AP reports grants from Australian National Health and Medical Research Council (NHMRC), during the conduct of the study. PMR reports grants from Novartis, Amgen, Pfizer, and Kowa; and personal fees from Novartis, Pfizer, AstraZeneca, Merck, outside the submitted work. RR reports grants from Sanofi, Eli Lilly, MSD, AstraZeneca, and Servier; personal fees from Sanofi, Eli Lilly, MSD, Novo Nordisk, Physigenex, AstraZeneca, Abbott, Medtronic, and Servier; and non-financial support from Sanofi and Novo Nordisk, outside the submitted work. JS is an Advisory board member for Tritm. JES reports grants from Commonwealth Department of Health and Aged Care, Abbott Australasia, Alphapharm, AstraZeneca, Aventis Pharmaceutical, Bristol-Myers Squibb Pharmaceuticals, Eli Lilly (Aust), GlaxoSmithKline, Janssen-Cilag (Aust), Merck Liptha, Merck Sharp & Dohme (Aust), Novartis Pharmaceutical (Aust), Novo Nordisk Pharmaceutical, Pharmacia and Upjohn, Pfizer, Sanofit Synthelabo, Servier Laboratories (Aust), Australian Kidney Foundation, and Diabetes Australia, during the conduct of the study; and personal fees from AstraZeneca, Mylan, Boehringer Ingelheim, Sanofi, Merck Sharp & Dohme, Novo Nordisk and Eli Lilly, outside the submitted work. VS reports a research collaboration with funding to their institute from Bayer, a conference trip from Novo Nordisk, and personal fees from Novo Nordisk, outside the submitted work. MW reports personal fees from Amgen and Kirin, outside the submitted work. ME reports a charitable grant from AstraZeneca Young Health Programme, and personal fees from Prudential, Scot, and Third Bridge, outside the submitted work. RJ reports grants from Health Research Council of New Zealand, during the conduct of the study. JD report grants from Merck Sharp & Dohme, Novartis, British Heart Foundation, European Research Council, National Institute for Health Research (NIHR), National Health Service (NHS) Blood and Transplant, Pfizer, UK MRC, Wellcome Trust, and AstraZeneca; personal fees from Merck Sharp & Dohme and Novartis; and non-financial support from Merck Sharp & Dohme and Novartis, outside the submitted work. EDA reports grants from NHS Blood and Transplant, British Heart Foundation, UK Medical Research Council, and NIHR, outside the submitted work. All other members of the writing committee declare no competing interests.

Acknowledgments
This work was commissioned to the coordinating center (Department of Public Health and Primary Care, University of Cambridge, Cambridge, UK) by WHO to revise the 2007 WHO–International Society of Hypertension cardiovascular disease risk prediction charts and was done through an informal technical working group convened by WHO. The coordinating centre was supported by underpinning funding from the British Heart Foundation (BHF; SP/09/002, RG/13/13/30194, and RG/18/13/33946), BHF Cambridge Centre for Research Excellence (RF/13/6/30830), UK Medical Research Council (MR/M003120/1), and the National Institute for Health Research (NIHR; Cambridge Biomedical Research Centre at the Cambridge University Hospitals NHS Foundation Trust). This work was also supported by Health Data Research UK, which is funded by the UK Medical Research Council, Engineering and Physical Sciences Research Council, Economic and Social Research Council, Department of Health and Social Care (England), Chief Scientist Office of the Scottish Government Health and Social Care Directorates, Health and Social Care Research and Development Division (Welsh Government), Public Health Agency (Northern Ireland), BHF, and Wellcome. JD is supported by a BHF Personal Professorship and an NIHR Senior Investigator Award. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health and Social Care. This research has been done using the UK Biobank Resource under application number 26865. The coordinating centre provides links to websites of the component studies (or consortia), many of which describe their funding.

References


