Environment International 181 (2023) 108226

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Global, regional and national burdens of non-melanoma skin cancer attributable to occupational exposure to solar ultraviolet radiation for 183 countries, 2000–2019: A systematic analysis from the WHO/ILO Joint Estimates of the Work-related Burden of Disease and Injury

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ARTICLE INFO

Handling Editor: Paul Whaley

Keywords:
Occupational risk factor
Carcinogens
Global burden of disease
Solar ultraviolet radiation
Skin neoplasms
Non-melanoma skin cancer
Health inequalities

ABSTRACT

Background: A World Health Organization (WHO) and International Labour Organization (ILO) systematic review reported sufficient evidence for higher risk of non-melanoma skin cancer (NMSC) amongst people occupationally exposed to solar ultraviolet radiation (UVR). This article presents WHO/ILO Joint Estimates of global, regional, national and subnational occupational exposures to UVR for 195 countries/areas and the global, regional and national attributable burdens of NMSC for 183 countries, by sex and age group, for the years 2000, 2010 and 2019.

Methods: We calculated population-attributable fractions (PAFs) from estimates of the population occupationally exposed to UVR and the risk ratio for NMSC from the WHO/ILO systematic review. Occupational exposure to UVR was modelled via proxy of occupation with outdoor work, using 166 million observations from 763 cross-sectional surveys for 96 countries/areas. Attributable NMSC burden was estimated by applying the PAFs to WHO's estimates of the total NMSC burden. Measures of inequality were calculated.

Results: Globally in 2019, 1.6 billion workers (95 % uncertainty range [UR] 1.6–1.6) were occupationally exposed to UVR, or 28.4 % (UR 27.9–28.8) of the working-age population. The PAFs were 29.0 % (UR 24.7–35.0) for NMSC deaths and 30.4 % (UR 29.0–31.7) for disability-adjusted life years (DALYs). Attributable NMSC burdens were 18,960 deaths (UR 18,180–19,740) and 0.5 million DALYs (UR 0.4–0.5). Men and older age groups carried larger burden. Over 2000–2019, attributable deaths and DALYs almost doubled.

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https://doi.org/10.1016/j.envint.2023.108226
Received 2 May 2023; Received in revised form 11 September 2023; Accepted 20 September 2023
Available online 8 November 2023

Conclusions: WHO and the ILO estimate that occupational exposure to UVR is common and causes substantial, inequitable and growing attributable burden of NMSC. Governments must protect outdoor workers from hazardous exposure to UVR and attributable NMSC burden and inequalities.

1. Introduction

The World Health Organization (WHO) International Agency for Research on Cancer has established that solar ultraviolet radiation (UVR) causes non-melanoma skin cancer (NMSC) and classified it as carcinogenic to humans (Group 1), with "sufficient evidence" for both basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) of the skin (International Agency for Research on Cancer, 1992; International Agency for Research on Cancer, 2012). WHO and the International Labour Organization (ILO) have theorized the causal pathways through which *occupational* exposure to UVR causes *work-related* NMSC (Fig. 1) (Paulo et al., 2019; World Health Organization, 2021). WHO and the ILO, supported by a working group of individual experts, have conducted a systematic review and *meta*-analysis of the risk of NMSC prevalence, incidence and mortality among people with any (or high) occupational exposure to UVR, compared with people with no (or low) occupational exposure (Paulo et al., 2019; World Health Organization, 2021). They reported evidence of moderate quality for an increased risk among occupationally exposed people for incident NMSC and judged this body of evidence to provide "sufficient evidence of harmfulness" (Table S1 in the Supplementary Material) (World Health Organization, 2021).

WHO has produced estimates of the global and regional burdens of NMSC attributable to any exposure to UVR, for environmental and occupational exposure pathways combined (Lucas et al., 2008; Lucas et al., 2010). There are however no official global, regional or national estimates of the *work-related* NMSC burdens attributable to *occupational* exposure to UVR. Accurate and transparent official estimates of occupational exposure to UVR and the attributable burden of NMSC provide the evidence base for planning, designing, costing, implementing and evaluating policies and systems that protect workers from occupational exposure to UVR, to prevent the attributable NMSC burden and inequalities. Five previous studies have reported national-level estimates of the NMSC burdens attributable to occupational exposure to UVR (Table 1) (Fritschi and Driscoll, 2006; Nurminen and Karjalainen, 2001; Peters et al., 2019b; Saeedi et al., 2022; Young, Rushton and British Occupational Cancer Burden Study Group, 2012). These studies had some limitations: two studies extracted risk ratios from a study of a small number of selected occupations in one country only (Nurminen and Karjalainen, 2001; Young, Rushton and British Occupational Cancer Burden Study Group, 2012); one study applied sex-specific population-attributable fractions (PAFs) (Murray et al., 2004) from one of the other studies (Fritschi and Driscoll, 2006); one study sourced risk ratios from a previous *meta*-analysis (Peters et al., 2019b); one study applied the PAFs from WHO's abovementioned estimates (Lucas et al., 2008; Lucas et al., 2010) of NMSC burden attributable to environmental and occupational exposures combined (Saeedi et al., 2022); and only one study (Young, Rushton and British Occupational Cancer Burden Study Group, 2012) reported uncertainty ranges for estimates. Only three studies reported estimated numbers of attributable deaths (Nurminen and Karjalainen, 2001; Young, Rushton and British Occupational Cancer Burden Study Group, 2012) or disability-adjusted life years (DALYs) (Saeedi et al., 2022).

WHO and the ILO produce the WHO/ILO Joint Estimates of the

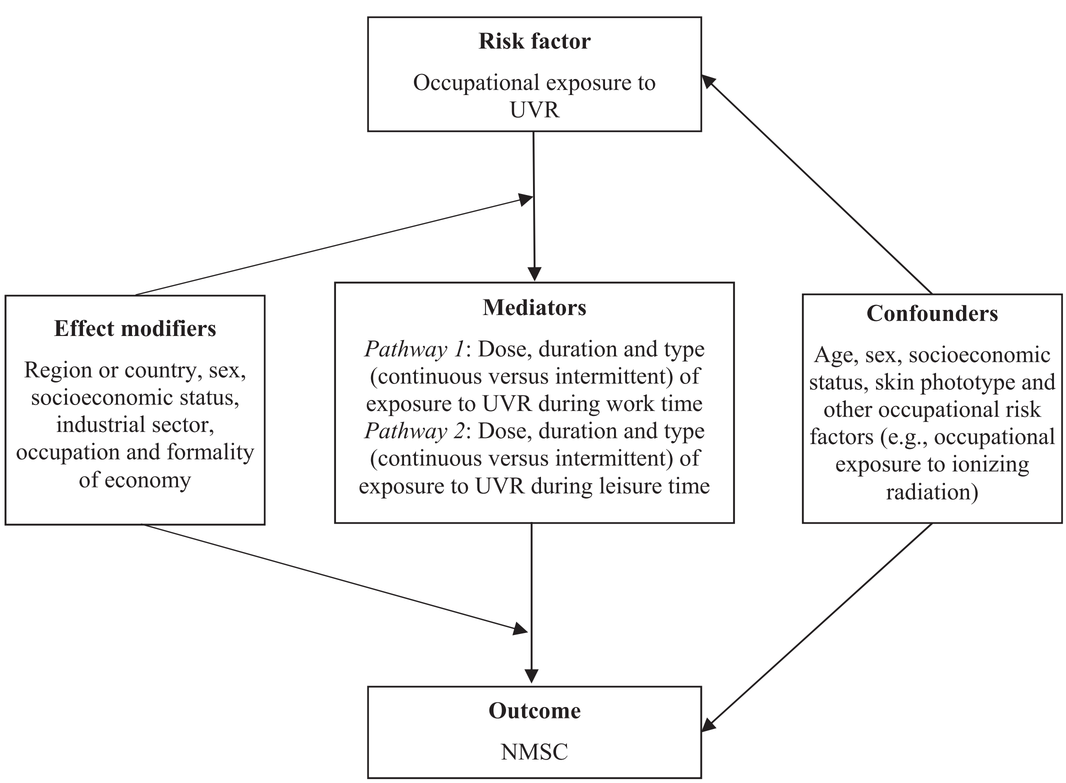

Fig. 1. Conceptual model of the relationship between occupational exposure to UVR and NMSC.
Footnote: NMSC non-melanoma skin cancer; UVR solar ultraviolet radiation. Adapted from World Health Organization (2021).

Table 1
Studies estimating the national burdens of NMSC attributable to occupational exposure to UVR.

Study, country	Estimation year (time window of exposure)	Exposure estimates	Risk ratio estimates	PAF (by sex and other reported disaggregation)	Number of attributable NMSC deaths, DALYs or cases
Nurminen and Karjalainen (2001), Finland	1996 (1960–1996)	The proportion of the population occupationally exposed to UVR and the exposure level were extracted from the Finnish Information System on Occupational Exposure (FINJEM) database (Kauppinen et al., 2014). The annual average exposure was estimated as the product of the proportion of the population exposed and the mean level of exposure among the exposed (Peters et al., 2019a), by occupation and period. For the proportion of the population exposed, the applied age range was 25–64 years.	The risk ratio was extracted from one study of one occupation (i.e., seafarers) in Finland between 1967 and 1992 (Pukkala and Saarni, 1996).	NMSC deaths: 8.3 % (UR unclear); Women: 3.8 % (UR unclear); Men: 13.1 % (UR unclear)	NMSC deaths: 2 (UR unclear)
Fritschi and Driscoll (2006), Australia	2002 (unclear)	There was no direct measure of exposure.	No risk ratio was used. Instead, the PAF calculated for Finland by Nurminen and Karjalainen (2001) was applied (see row above).	NMSC deaths: 8.3 % (UR unclear); Women: 3.8 % (UR unclear); Men: 13.1 % (UR unclear)	NMSC cases: 34,000 (UR unclear); Women: 6000 (UR unclear); Men: 28,000 (UR unclear)
Peters et al. (2019b), Canada	2011 (1961–2001)	The number of the population occupationally exposed to UVR was extracted from the CARcinogen EXposure (CAREX) Canada database (Peters et al., 2015). Using a job-exposure matrix, CAREX Canada assigns occupational exposure to UVR based on industrial sector, occupation, population exposed, level of exposure (lowest [2–4 h of outdoor work per day], mid-level [4–6 h/day], highest [$\geq$6 h/day], unexposed), province and sex. The proportion of the population exposed was calculated as the number of workers alive in 2011 who were ever exposed during the time window of exposure divided by the total population of workers in 2011 having a working age during the time window of exposure.	The risk ratio was extracted from a previous *meta*-analysis (Bauer et al., 2011).	NMSC cases: 6.3 % (UR 5.7–12.1); BCC: 5.3 % (UR 4.2–11.8); SCC: 9.2 % (UR 6.7–18.6); Women BCC: 1.2 % (UR 0.9–3.7); Women SCC: 1.7 % (UR 1.2–5.2); Men BCC: 9.0 % (UR 6.4–20.4); Men SCC: 14.0 % (UR 9.3–28.8)	NMSC cases: 4556 (UR unclear)
Saeedi et al. (2022), Iran (Islamic Republic of)	2005–2019 (unclear)	There was no direct measure of exposure. PAFs were extracted from WHO estimates of burden of NMSC attributable to the combined environmental and occupational exposures to UVR (Lucas et al., 2008; Lucas et al., 2010). WHO produced these PAFs using the modified annual mean erythemally weighted daily dose values for environmental and occupational exposures to UVR (Lucas et al., 2010). Therefore, this study in effect assigned any exposure to UVR as occupational exposure to UVR.	No risk ratio was used. Instead, the WHO PAFs were applied (Lucas et al., 2006; Lucas et al., 2010). These WHO PAFs were based on a review of risk ratios from several studies across countries (Lucas et al., 2006; Lucas et al., 2010).	Light-skinned populations SCC: 50.0–70.0 %; Light-skinned populations BCC: 50.0–90.0 %; Intermediately and deeply pigmented populations: unclear from the study record which PAF was used	DALYs (in 2019): 2907 (UR unclear)
Young, Rushton and British Occupational Cancer Burden Study Group (2012), United Kingdom of Great Britain and Northern Ireland	2005 (1956–1995)	The number of outdoor workers ever occupationally exposed to UVR over the time window of exposure was extracted from the CAREX database (Kauppinen et al., 2000). Using a job-exposure matrix, CAREX assigned occupational exposure to UVR via proxy of outdoor work, mixed indoor/outdoor work and farming and agriculture, respectively. The proportion of the population exposed to UVR in the time window of exposure was calculated as the number of people ever occupationally exposed to UVR in each relevant industrial sector or occupation divided by the total number of people ever employed.	The risk ratio was extracted from one study of multiple occupations classified as outdoor workers, mixed indoor/outdoor workers and farmers, and compared with indoor workers, in 24 states of the United States of America between 1984 and 1995 (Freedman et al., 2002).	NMSC cases: 2.4 % (UR 1.2–3.8 %); Women: 0.7 % (UR 0.2–1.4 %); Men: 3.6 % (UR 1.9–5.5)	NMSC deaths: 13 (UR unclear); Women: 2 (UR 0–3); Men: 11 (UR 5–16) NMSC cases: 1541 (UR unclear); Women: 229 (UR 57–416); Men: 1312 (UR 678–2003)

Footnotes: BCC basal cell carcinoma; DALYs disability-adjusted life years; NMSC non-melanoma skin cancer; PAF population-attributable fraction; SCC squamous cell carcinoma; UR 95 % uncertainty range; UVR solar ultraviolet radiation; WHO World Health Organization.

Work-related Burden of Disease and Injury (WHO/ILO Joint Estimates; https://www.who.int/teams/environment-climate-change-and-health/monitoring/who-ilo-joint-estimates/) (Pega et al., 2021; Pega et al., 2022; World Health Organization and International Labour Organization, 2021a; World Health Organization and International Labour Organization, 2021b). This article presents WHO/ILO Joint Estimates of global, regional, national and subnational occupational exposures to UVR, for 195 countries/areas, and the global, regional and national attributable burdens of NMSC (deaths and DALYs), for 183 countries, by sex and age group, for the years 2000, 2010 and 2019. These are the first official global, regional and national estimates of occupational exposures to UVR and the attributable burdens of NMSC.

2. Materials and methods

2.1. Overview

The WHO/ILO Joint Estimates are produced within the global Comparative Risk Assessment framework (Ezzati et al., 2004; Murray et al., 2004) and reported according to the *Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER)* (Stevens et al., 2016). We developed definitions of occupational exposure to UVR, the risk factor categories and the theoretical minimum risk exposure level (Table S2 in the Supplementary Material) (Paulo et al., 2019; World Health Organization, 2021). ILO labour statisticians and occupational hygienists and WHO occupational epidemiologists, supported by a technical advisory group of individual experts (i.e., the Technical Advisory Group on Occupational Burden of Disease Estimation), assigned exposure categories of *always* exposed (Table S3 in the Supplementary Material) or *occasionally* exposed (Table S4 in the Supplementary Material) via proxy of occupation with outdoor work, classifying the 436 occupation unit groups codes of the International Standard Classification of Occupations [ISCO] (International Labour Organization, 2012) (job-exposure matrix). By combining the exposure distribution in the population cohorts with the risk ratio derived from the recent WHO/ILO systematic review and *meta*-analysis specifically conducted for this official estimation (World Health Organization, 2021), we generated estimates of the PAFs. Estimates were produced and reported for population cohorts defined by country, sex (total, female, male), age group (≥15, 15–19, 20–24, …, 90–94, ≥95 years) and

Table 2
Description of the input data and the data sources.

	Input Data	Data source	Details about data extracted
1	**Cross-sectional data on the proportion of survey participants working in an occupation assigned as exposed or unexposed to UVR**	WHO/ILO Global Cross-sectional Occupation Database • 166 million observations from 763 surveys for 96 countries/areas collected between 01 January 1996 and 31 December 2021 • Data from at least one survey were available for 49.2 % of all countries/areas globally • One third (35.9 %) of the global working-age (≥15 years) population in 2019 were covered with data from at least one survey • At least 38.0 % of countries/areas in each region were covered by at least one survey • At least 30.7 % of regional populations were covered; the only exception was that data were available for just 6.0 % of the population of the Western Pacific Region • Official LFSs conducted by national/area-level statistical offices and shared by countries with the ILO or Eurostat	• Microdata on the proportion of survey respondents who reported an occupation that experts judged to be occupationally exposed to UVR (see Tables S3 and S4 in the Supplementary Material) • Data were weighted using the survey weights produced by national/area-level statistics offices for their country/area • Aggregated by population cohort defined by year, country/area, sex and age group • All workers were covered except unpaid domestic workers • Further details can be found in Tables S6 and S7 in the Supplementary Material
2	**Longitudinal data on the proportion of survey participants working in an occupation assigned as exposed or unexposed to UVR**	WHO/ILO Global Longitudinal Occupation Database • Over 8 million observations from over 1035 quarterly survey data sets on 247 year-to-year transitions for 31 countries collected between 1 January 2000 and 31 December 2020 • Data from at least one survey were available for 16.0 % of all countries globally • Almost one fifth (18.5 %) of the global working-age (≥15 years) population in 2019 were covered with data from at least one survey • At least 3.7 % of countries in each region were covered by at least one survey • Coverage of regional populations varied between 4.7 % for the Western Pacific Region and 40.3 % for the European Region • Official LFSs conducted by national statistical offices and shared by countries with the ILO or Eurostat	• Repeated measures from the same survey that were available for participants over consecutive years • Because the microdata did not include individual participant identifiers, data were probabilistically linked longitudinally, with matching by household number, household sequence number, sex and birth year • Microdata on the proportion of the population exposed were extracted, weighted using survey weights and aggregated by population cohort defined by year, country, sex and age group • Further details can be found in Tables S8 and S9 in the Supplementary Material
3	**Estimates of the total population**	United Nations world population prospects (United Nations, 2019)	Estimates of the total number of the population cohort defined by year, country/area, sex and age group for the years 1950–2019
4	**Estimates of the probability of death**	United Nations life tables (United Nations, 2022)	Estimates of the probability of death by year, country/area, sex and age group for the years 1950–2019
5	**Estimate of the pooled risk ratio for NMSC among people occupationally exposed to UVR, compared with occupationally unexposed people**	WHO/ILO systematic review and *meta*-analysis (World Health Organization, 2021)	This systematic review reported sufficient evidence for an effect of occupational exposure to UVR on incident NMSC (Table S1 in the Supplementary Material)
6	**Estimates of the total numbers of deaths and of DALYs for NMSC**	WHO Global Health Estimates (World Health Organization, 2020)	Estimates of the total numbers of deaths and of DALYs for NMSC by country, sex and age group, for the years 2000, 2010 and 2019

Footnotes: DALYs disability-adjusted life years; ILO International Labour Organization; LFSs Labour Force Surveys; NMSC non-melanoma skin cancer; UVR solar ultraviolet radiation; WHO World Health Organization.

year (2000, 2010, 2019). Table S5 in the Supplementary Material shows the programmatic allocation of countries/areas to the WHO Regions (African Region, Region of the Americas, Eastern Mediterranean Region, European Region, South-East Asian Region and Western Pacific Region). Modelling was carried out using the software *R*, with the code presented in Supplementary File 2.

2.2. Data sources

The estimates were produced using six sets of input data. Table 2 details these data and their sources. Fig. S1 in the Supplementary Material shows how data sources, input data and models were combined to produce outputs and estimates. Additionally, Tables S6-S9 in the Supplementary Material provide detailed descriptions of the input databases compiled from surveys.

Data on the proportions of people in occupations classified as exposed were obtained from WHO/ILO databases compiled from cross-sectional and longitudinal official Labour Force Surveys (LFSs) providing information of the proportions of people in occupations (by ISCO codes) within cohorts over time (Input Data 1 and 2). Estimates of the total population (Input Data 3) and the probability of death (Input Data 4) came from the United Nations world population prospects (United Nations, 2019) and life tables (United Nations, 2022), respectively. Estimates of risk ratios of the effect of occupational exposure to UVR on NMSC (Input Data 5) came from the recent WHO/ILO systematic review and *meta*-analysis produced specifically for this estimation (World Health Organization, 2021). Estimates of the total numbers of deaths and of DALYs for NMSC (WHO burden of disease code "*II.A.8.b Non-melanoma skin cancer*", comprising ICD-10 code C44) by country, sex and age group for the years 2000, 2010 and 2019 (Input Data 6) were sourced from the WHO Global Health Estimates (World Health Organization, 2020).

As for previous estimates (Pega et al., 2021), we applied the following *a priori* criteria to select the "best" effect estimate (risk ratio for morbidity versus for mortality) based on strength of evidence ratings: first, if there is any evidence for fatal or non-fatal events of the outcome that was rated as "sufficient evidence for harmfulness" (using standard Navigation Guide ratings) (Woodruff et al., 2011), proceed to selection of "best" estimate. Second, if there is such sufficient evidence:

- only for *either* fatal events *or* non-fatal events of the outcome (i.e., not both), select the risk ratio for the event type with any such evidence.
- for *both* fatal and non-fatal events, prioritize the risk ratio for fatal events.

The externally, independently peer-reviewed WHO/ILO systematic review produced estimates of the risk ratios of the effects of occupational exposure to UVR on morbidity (i.e., incidence) and mortality, respectively (World Health Organization, 2021). As in previous burden of disease studies (Ezzati et al., 2002) and WHO/ILO Joint Estimates (Pega et al., 2021), we only proceeded to estimation, if the effect estimate identified in the systematic review was statistically significant ($P < 0.05$) and the strength of evidence was rated as "sufficient evidence for harmfulness". This was the case for morbidity (i.e., incidence), but not for mortality (rated "inadequate evidence of harmfulness") (Table S1 in the Supplementary Material). The risk ratio for NMSC incidence (pooled RR 1.60, 95 % confidence interval 1.21–2.11) was therefore used as the best effect estimate risk ratio (Table S1 in the Supplementary Material) (World Health Organization, 2021). Because there was no evidence for effect modification by region, sex or age group (World Health Organization, 2021), the best effect estimate was assigned to all population cohorts defined by country, sex and age group.

2.3. Statistical modelling

The estimation strategy modelled the input data using four distinct models that consecutively built on each other (Models 1–4, Fig. S1 in the Supplementary Material) to generate estimates of occupational exposure to UVR and the attributable burden of NMSC (deaths and DALYs). Models 1, 2 and 4 have been used for producing previous WHO/ILO Joint Estimates (Pega et al., 2021). Model 3 has been newly developed for the current estimates. All models are described in full in the Table 3.

In brief, Model 1 was a multilevel model used to estimate the proportion of the working-age (≥15 years) population exposed to UVR by year, using cross-sectional LFS data (Input Data 1). Longitudinal LFS data (Input Data 2) were used in Model 2 to produce transition probabilities between exposure categories. The resulting outputs from Models 1 and 2 were used in combination with estimates of the total population (Input Data 3) and the probability of death (Input Data 4) by Model 3 to estimate the proportion of the population exposed over the time window of exposure. Model 3′s output, the risk ratio of the effect of occupational exposure to UVR on NMSC (Input Data 5) and estimates of the total numbers of deaths and of DALYs for NMSC (Input Data 6) were used in Model 4 to produce the estimates of the burden of NMSC that is attributable to occupational exposure to UVR.

Based on current evidence (Table 4), the approach assumed a 20-year lag between exposure and health loss from NMSC and adopted a 20-year time window of exposure (centred on exposure year, as defined in Fig. S2 in the Supplementary Material) to identify the exposure category to apply to the relevant exposure year. We used microflow simulation that originates from material flow analysis and is commonly used in industrial ecology and sustainability science (Duchin and Levine, 2008; Kosseva, 2013) to simulate flows of worker cohorts grouped by exposure category over the time window.

Consistent with previous WHO estimates (de Onis et al., 2004; Bonjour et al., 2013; Wolf et al., 2013; Wolf et al., 2019) and WHO/ILO Joint Estimates (Pega et al., 2021), for all estimates (exposure, PAF, death, DALYs), we used bootstrapping to derive uncertainty (or prediction) ranges at the 2.5th and 97.5th percentiles of the resulting random deviates (Efron, 1979). Uncertainty in input parameters was propagated across all four models. The risk ratio was log normally distributed and modelled accordingly. All other input parameters were assumed and modelled to be normally distributed. For each estimate, we report the point estimate and its 95 % uncertainty range (UR).

2.4. Health inequalities analyses

We also calculated absolute and relative measures of inequality to estimate differences between regions, sexes and age groups in the burdens of NMSC attributable to occupational exposure to UVR. We always used the global total number of deaths or of DALYs per 100,000 working-age population (i.e., death or DALY rate) as the reference. As an absolute measure of inequality, for each death rate and DALY rate for each category of region, sex and age group, we calculated the difference from the reference rate (global rate). As a relative measure of inequality, we calculated the rate ratios as the fraction of the reference rate for each death and DALY rate, for each category (World Health Organization, 2013).

2.5. Sensitivity analyses

To test the assumptions made for estimates for the year 2019 (Table 4; lag time of 20 years; time window of exposure of 20 years from 1989 to 2008; and exposure assignment via proxy of occupation classified as *always* exposed), we conducted the following sensitivity analyses (the years in brackets are the time window of exposure):

- Reduced the lag time to 10 years (1999–2018).
- Increased the lag time to 30 years (1979–1998).
- Reduced the time window of exposure to 10 years (1994–2003).
- Increased the time window of exposure to 30 years (1984–2013).

Table 3
Description of the models.

Model	Description of the model	Model equation(s)
Model 1: Multilevel model to estimate the proportion of the population exposed by year	For each year between 1950 and 2019 for each population cohort defined by country/area, sex and age group, we produced estimates of the proportion (P_i) of the population in the exposed category ($i = 1$) and the unexposed category ($i = 0$). As a proxy for occupational exposure to UVR, we compiled a list of ISCO codes that we judged to *always* carry out work outdoors (see Table S3 in the Supplementary Material). A second list was compiled of occupations *occasionally* working outdoors. As for other WHO estimates (Bonjour et al., 2013; Wolf et al., 2013; Wolf et al., 2019) and WHO/ILO Joint Estimates (Pega et al., 2021), we modelled the estimates of the proportion of the population exposed based on Input Data 1 using an established multilevel model that predicts the proportion of the population exposed over time and in the WHO Region (Leyland and Goldstein, 2001; Goldstein, 2010). This method is used by WHO to produce Sustainable Development Goal indicators (e.g., indicator 3.9.1; see https://unstats.un.org/sdgs/metadata/files/Metadata-03–09-01.pdf) and has therefore passed the approval of the United Nations Statistical Commission. It creates continuous estimates over the specified time period and estimates an average intercept and an average slope with residual variances across countries. Where there are reliable survey data from a specific country/area, the country/area curve will closely follow these data; where there are few country/area data points or high within-country/area variability, estimates will be close to these survey data points, but the trend will tend to follow the overall mean of the WHO Region. Because P_i was strongly non-linearly dependent on *age*, we linearized *age* by 5th order orthogonal polynomials to prevent collinearity. For countries/areas and years without any data on occupation, estimates were produced using multilevel modelling based on data from countries/areas within the WHO Region with such data.	$P_i(y_t, c) = A_i(c(r)) + B_i(c(r)) \cdot y_s$ where: i is the exposure category, with $i = \{0,1\}$; P_i is the proportion of the population cohort in exposure category i; y_t is the year at time t; c is the population cohort defined by country/area, sex and age group; r is the WHO Region; A_i and B_i, dependent on *country*, *sex and age*, are estimated using a multilevel model with *country* as fixed effects and with *sex* and *age* as random effects, nested in the *country* within the WHO Region (r), with regions treated independently; and y_s is the survey year. Source: Pega et al. (2021); World Health Organization (2021); Náfrádi et al. (2022)
Model 2: Model of the transition probabilities between the exposure categories	For each population cohort defined by country/area, sex and age group, we estimated the probability (T_j) of transitioning between the categories of exposed and unexposed from year y_t to year y_{t+1}. The j denotes one of the four possible year-to-year transitions (i.e., exposed-exposed, exposed-unexposed, unexposed-unexposed and unexposed-exposed). The unexposed category ($i = 0$) included survey participants who had ISCO codes not classified as outdoor occupations or were labour market inactive. We adopted the methods developed by Eurostat for calculating these transition probabilities (Kiiver and Espelage, 2016). Using Input Data 2, we scaled the survey weights for the target year (y_{t+1}) to represent the correct labour market status by country/area, sex and age group for the index year (y_t) and the target year. We then adjusted the complete sample in the target year to match margins for labour market status in both years, using iterative raking by sex. Eurostat derived transition probabilities covering 20 countries based on sub-samples of the European Union LFSs using Model 2, and it shared these transition probabilities with WHO and ILO. For population cohorts defined by country/area, sex and age group for whom T_j could not be calculated because the required longitudinal data were unavailable, T_j was imputed. The imputed T_j was the mean of all transition probabilities of the population cohort defined by the same sex and age group in the same WHO Region, weighted by the number of observations contributing to the transition probabilities.	$T_j(c) = \frac{exp^{\beta_{cj} X_j}}{1 + \sum_{\alpha} exp^{\beta_{c\alpha} X_j}}$ where: j is the transition from an exposure category i in year y_t to an exposure category i in year y_{t+1}, with $i = \{0,1\}$ and $j = \{0\_0, 0\_1, 1\_1, 1\_0\}$; T_j is the probability of the transition j as a function of the population cohort, with the sum of the $T_j = 1$; c is the population cohort defined by country/area, sex and age group; *exp* is the exponential; β_j is the set of regression coefficients describing the longitudinal weights associated with the transition j; x_j is a set of explanatory variables (*sex* and *age* as a 2-degree fractional polynomial) associated with the transition j; and the summation (index α) goes through all possible transitions of j (except the transition $j = 0\_0$ which was chosen as a pivot outcome). Source: Pega et al. (2021); World Health Organization (2021); Náfrádi et al. (2022)
Model 3: Microflow simulation model to estimate the proportion of the population exposed over the time window	For each population cohort defined by country/area, sex and age group, we estimated the proportion ($Q_{i=1}$) of the population ever exposed to UVR over the time window of exposure ($i = 1$). Our modelling assumptions and the evidence supporting these are presented in Table 4. The approach assumed a 20-year latency between exposure and occurrence of an NMSC case and adopted a 20-year time window of exposure (centred on exposure year) to identify exposure if it occurred in any year within the window (Fig. S2 in the Supplementary Material). For example, to estimate the attributable NMSC burden in 2019, the relevant exposure year was 1999; we assumed the person was exposed if they were exposed ($i = 1$) in any year during the time window of exposure, 1989–2008. In effect, this considered occupational turnover, with someone exposed at any year during the 20-year window considered at-risk for 1999. We used a microflow simulation model that originates from material flow analysis and is commonly used in industrial ecology and sustainability science (Duchin and Levine, 2008; Kosseva, 2013). Microflow simulation models are used to simulate technical and natural systems by quantifying their respective inflows, outflows and internal stocks and changes in these elements over time. As shown in Fig. S3 in the Supplementary Material, we simulated microflows of worker cohorts grouped by exposure category over time. We simulated cohort flows between exposure categories and through consecutive age groups and censored based on modelled probabilities (e.g., for death). Fig. S3 in the Supplementary Material shows the tracking of the population exposed in the microflow simulation model. In the first year of the simulation ($y_{t=1}$), the population was set to 100 %, and based on the Model 1 output the population was	$S_{i=1}(y_t, c) = S_{i=1}(y_{t-1}, c) + Inflow_{i=1}(y_t, c) - Outflow_{i=1}(y_t, c)$ with $Inflow_{i=1}(y_t, c) = P_{i=1}(y_{t=1}, c) + \sum_{i=0}^{1} [S_i(y_{t-1}, c) \cdot T_{j=i\_1}(c)]$ $Outflow_{i=1}(y_t, c) = (S_{i=1}(y_{t-1}, c) \cdot X(y_t, c)) + S_{i=1}(y_{t-1}, c) \cdot T_{j=1\_0}(c)$ $reference(y_t) = reference(y_{t-1}) + 100^{i(y_t)}$ where: $S_{i=1}$ is the stock of the population in the exposed category ($i = 1$) for a specific population cohort; i is the exposure category, with $i = \{0,1\}$; c is the population cohort defined by country/area, sex and age group; $P_{i=1}$ (output from Model 1) is the population in the exposed category ($i = 1$) at the first year of the microflow simulation ($y_{t=1}$); n is the number of exposure categories (i), with $n = 2$; $T_{j=i\_1}$ (output from Model 2) are the transition probabilities from an exposure category (i) to the exposed category ($i = 1$) as a function of the

(*continued on next page*)

Table 3 (*continued*)

Model	Description of the model	Model equation(s)
	assigned to either the unexposed category ($i = 0$; grey box in Fig. S3 in the Supplementary Material) or the exposed category ($i = 1$; orange box). For each consecutive year, the model applied the transition probabilities T_j (e.g., from unexposed to exposed: $T_{j=0\_1}$) to transfer a share of the population between the two exposure categories. As shown in Fig. S3 in the Supplementary Material, the model tracked the exposed category ($i = 1$) by using a tracking reference number based on the sum of the exponents of all visited exposure categories to a base of 100. For instance, a reference number of “129″ indicated that this part of the population was exposed for one year and unexposed for 29 years during the 30-year study period ($y_{t=1}$ to $y_{t=30}$). This resulted in the splitting of the population into increasingly smaller groups, based on their reference number and current exposure category. As shown in Fig. S3 in the Supplementary Material, at the end of the simulation, all population groups that were in the exposed category for at least one year during the time window of exposure (i.e., where the reference number is above 100) were then summed up and divided by the remaining population (considering censoring), to arrive at the proportion of the population exposed ($Q_{i=1}$) for the estimation year ($y_{t=30}$) that was further used as input to Model 4. Fig. S4 in the Supplementary Material shows the assumed in- and outflows for the two exposure categories (stocks) and the stepwise transition probabilities between these two categories, as well as the censoring of the population. This microflow simulation model performed better (e.g., up to 20-fold faster) than our previously used microsimulation model (Pega et al., 2021; World Health Organization, 2021; Náfrádi et al., 2022) and had the additional benefit that it produced deterministic results rather than a stochastic switch of individuals.	population cohort; $T_{j=1\_0}$ (output from Model 2) is the transition probability from the exposed category ($i = 1$) to the unexposed category ($i = 0$) as a function of the population cohort; and X is the probability of the population being censored for death as a function of the population cohort. Source: Duchin and Levine (2008); Kosseva (2013) As shown in Figs. S3 and S4 in the Supplementary Material, the output of this microflow simulation model is $Q_{i=1}$, the proportion of the population in the estimation year ($y_{t=30}$) that has followed an exposure flow with at least one year spent in the exposed category ($i = 1$).
Model 4: Burden of disease estimation model	The Comparative Risk Assessment framework (Murray et al. 2004) was used to estimate the burden of NMSC attributable to occupational exposure to UVR. We estimated the proportional reduction in deaths or DALYs that would occur if exposure was reduced to the unexposed category ($i = 0$) with a minimum risk (i.e., no [or low] occupational exposure to UVR), while other conditions remained unchanged. The population distribution of occupational exposure to UVR was combined with the increased risk of developing NMSC that was attributable to occupational exposure to UVR. Using estimates outputted from Model 3 and Input Data 5 (i.e., the risk ratio from the WHO/ILO systematic review and *meta*-analysis [World Health Organization, 2021] of 1.60, 95 % confidence interval 1.21–2.11), we calculated the PAF, the proportion of the health loss from NMSC seen in each population that could be attributed to occupational exposure to UVR, using Model 4. Applying this fraction to the total NMSC burden (Input Data 6) gave the attributable disease burden. To be specific, the PAF was calculated for each population cohort defined by country/area, sex and age group; this was then applied to the total disease burden envelope for NMSC also by country/area, sex and age population cohort to get the respective burden for this specific population cohort. As there was no evidence that suggested that the risk ratio for mortality and morbidity was different, we assumed the PAFs were the same for non-fatal and for fatal NMSC cases and applied the same individual cohort-level PAFs to generate numbers of deaths and of DALYs (Ezzati et al., 2004); however, once individual population cohorts were combined (e.g., to give cohorts for regional, global, all ages or, both sexes), resulting PAFs for deaths and for DALYs differred due to the different envelopes.	$PAF(y_{t=30},c) = \frac{Q_{i=1}(y_{t=30},c)\cdot(RR_{i=1}-1)}{Q_{i=1}(y_{t=30},c)\cdot(RR_{i=1}-1)+1}$ where: PAF is the PAF; y_t is the year at time t; c is the cohort defined by country/area, sex and age group; $Q_{i=1}$ (output from Model 3) is the proportion of the population in the estimation year ($y_{t=30}$) that has followed an exposure flow with at least one year in the exposed category ($i = 1$)); and $RR_{i=1}$ is the risk ratio for the exposed category ($i = 1$). Source: Pega et al. (2021); World Health Organization, (2021); Náfrádi et al. (2022); Wolf et al. (2023)

Footnotes: DALYs disability-adjusted life years; ILO International Labour Organization; ISCO International Standard Classification of Occupations; LFSs Labour Force Surveys; NMSC non-melanoma skin cancer; PAF population-attributable fraction; UVR solar ultraviolet radiation; WHO World Health Organization. Fig. S1 in the Supplementary Material shows which input data are used in each model and which outputs they produce for use in subsequent models or reporting. The input data for Models 1 and 2 are confidential microdata and can therefore not be shared. Input data for Models 3 and 4 are presented in Tables S19-S27 in the Supplementary Material and United Nations world population prospects (United Nations, 2019) and life tables (United Nations, 2022). The output for Model 2 is confidential and cannot be shared. Outputs of Models 1, 3 and 4 are presented in Tables S10-S63 in the Supplementary Material.

Table 4
Modelling assumptions and the evidence base.

	Variable	Assumption in the main analysis (sensitivity analyses)	Explanation	Example for burden of disease estimates for the year 2019	Evidence base
1	Exposure assignment	Assigned exposure via proxy of occupation pre-classified as (*always*) occupationally exposed to UVR (sensitivity analysis used occupations pre-classified as *always* or *occasionally* occupationally exposed to UVR)	As we did not have direct exposure measurements, we assumed that people were occupationally exposed to UVR if they reported an occupation that we had pre-classified as (*always*) exposed.	Construction Supervisor was an occupation pre-classified as (*always*) occupationally exposed to UVR. If survey participants reported this occupation, they were classified as occupationally exposed.	The *always* and *occasionally* exposed occupations were pre-specified by ILO labour statisticians and occupational hygienists and reviewed by WHO epidemiologists and the Technical Advisory Group on Occupational Burden of Disease Estimation before any work on the estimates commenced. Assignment of exposure via proxy of occupation is common for modelling occupational exposure to UVR. CAREX Canada, for example, identified occupations in which workers were expected to be outside ≥75 % of the workday and assigned these as being in the "high-exposure" category for UVR. A 2020 study developed a job-exposure matrix for occupatonal exposure to UVR based on occupations and industrial sectors (Boiano et al., 2020). Another study also assigned exposure via proxy of occupation that was also measured using ISCO codes but the list of included occupations was not made available (Guenel et al., 2001). The full lists of occupations we assigned as *always* and *occasionally* occupationally exposed to UVR are shown in Tables S4 and S5 in the Supplementary Material.
2	Lag time	Assumed 20 years (sensitivity analyses assumed 10 and 30 years)	For an outcome event in the estimation year ($y_{t=30}$), the exposure was assumed to have occurred in the lag year ($y_{t=10}$) (see also Fig. S2 in the Supplementary Material).	Burden of NMSC (deaths or DALYs) in 2019 was attributable to exposure 20 years earlier, with the lag year being 1999.	Previous burden of disease studies have also included a latency period between occupational exposure to UVR and the occurrence of NMSC. Both the British Occupational Cancer Burden Study (Rushton et al., 2012; Young, Rushton and British Occupational Cancer Burden Study Group, 2012) and Peters et al. (2019b) assumed a latency of 10–50 years since first occupational exposure to UVR. Studies that estimated the effect of occupational exposure to UVR on NMSC also included lag time to allow for disease latency (e.g., 20-, 25- and 30-year lag periods in Surdu et al. (2013)).
3	Time window of exposure	Assumed 20 years (sensitivity analyses assumed 10 and 30 years)	Rather than occurring in the lag year ($y_{t=10}$) only, exposure occurred in any year during a "critical" time window of the length of 20 years (i.e., years $y_{t=1}$ to $y_{t=20}$), and exposure within any year in this time window could still cause the disease outcome in the estimation year ($y_{t=30}$) (see also Fig. S2 in the Supplementary Material).	To estimate burden of NMSC in 2019, we modelled exposure over a 20-year time window.	Both the British Occupational Cancer Burden Study (Rushton et al., 2012; Young, Rushton and British Occupational Cancer Burden Study Group, 2012) and Peters et al. (2019b) used a time window of exposure of 40 years (exposure occurred 10–50 years before the cancer event).
4	Spacing of the time window of exposure around the lag year	Spaced the time window of exposure symmetrically around the lag year (no sensitivity analysis)	The time window of exposure was equally spaced around the "lag year" of the average lag period ($y_{t=10}$), so that the time window of exposure is defined as between years $y_{t=1}$ and $y_{t=20}$ (Fig. S2 in the Supplementary Material).	To estimate burden of NMSC in 2019, we modelled exposure over the time window of 1989–2008.	Symmetrical spacing of the time window is common practice in studies estimating burden of disease attributable to exposure to occupational risk factors. The British Occupational Cancer Burden Study (Rushton et al., 2012; Young, Rushton and British Occupational Cancer Burden Study Group, 2012), for example, spaced the time window of occupational exposure to carcinogens symmetrically around the lag year. Previous WHO/ILO Joint Estimates also modelled the time window of exposure as symmetric around the lag year (Pega et al., 2021).
5	Assignment of the exposure category	Assigned the person to "exposed" if they were exposed in any year over the time window of exposure (no sensitivity analysis)	For each worker, if they were exposed in any year over the time window they were assigned as exposed over the window.	Over the years 1991–2000, Worker A was working in an occupation considered exposed to UVR in 1989–1991 and 2000–2008 and in an occupation considered unexposed in 1992–1999; therefore, we assign Worker A to the category of occupationally exposed to UVR.	For diseases with long latency periods, which is possible for NMSC, once the cancer process has started, the worker continues to be at risk, even if exposure levels are reduced. Both the British Occupational Cancer Burden Study (Rushton et al., 2012; Young, Rushton and British Occupational Cancer Burden Study Group, 2012) and Peters et al. (2019b) considered those "ever exposed over the risk exposure period".
6	Assignment of the effect estimate	Assigned the "best" effect estimate (no sensitivity analysis)	For estimating the numbers of deaths and of DALYs and for all population cohorts defined by country, sex and age group, we assigned the same "best" pooled effect estimate derived from the WHO/ILO *meta*-analysis of NMSC incidence.	To estimate burden of NMSC in 2019, for each population cohort defined by country, sex and age group, we used the pooled effect estimate for NMSC incidence (Table S1 in the Supplementary Material).	The WHO/ILO systematic review reported no evidence for effect modification by country (or WHO Region), sex or age group in the subgroup analyses (World Health Organization, 2021). As there is no evidence to suggest that the risk ratio for mortality and morbidity is different, we assumed that the PAFs were the same for non-fatal and for fatal NMSC events, and applied the same individual cohort-level PAFs to generate numbers of deaths and of DALYs (Ezzati et al., 2004). Therefore, we assigned the pooled effect estimate from the main WHO/ILO *meta*-analysis (World Health Organization, 2021). This is the same approach used in previous WHO burden of disease studies (Murray et al., 2004) and WHO/ILO Joint Estimates (Pega et al., 2021).

Footnotes: DALYs disability-adjusted life years; ILO International Labour Organization; ISCO International Standard Classification of Occupations; NMSC non-melanoma skin cancer; PAF population attributable fraction; UVR solar ultraviolet radiation; WHO World Health Organization.

- Added occupations classified as *occasionally* exposed to the exposed group (Table S4 in the Supplementary Material).

3. Results

Global exposure and burden of disease estimates for 2019 are provided below. All regional and national estimates by sex and age group are provided in Tables S10-S63 in the Supplementary data files 1 and 3.

3.1. Estimates of the population occupationally exposed to UVR

Globally in 2019, an estimated 1.6 billion workers (UR 1.6–1.6) were occupationally exposed to UVR. This is 28.4 % (UR 27.9–28.8) of the working-age (≥15 years) population (Table 5). Tables S10-S18 in the Supplementary Material present all exposure estimates (output from Model 1). Males and adults of late young adulthood and early middle age were more commonly exposed (Fig. 2). Between 2000 and 2019, the global proportion of the population occupationally exposed to UVR decreased from 41.9 % (UR 40.9–43.0) to 28.4 % (UR 27.9–28.8), a decrease by 32.4 % (UR −34.3–-30.3) (Table 5, output from Model 1).

In 2019, the regional proportion of the population exposed to UVR was largest for the African Region (33.0 %, UR 32.5–33.6) and the South-East Asian Region (32.3 %, UR 31.1–33.5) and lowest for the European Region (18.5 %, UR 18.4–18.7) (Table S16 in the Supplementary Material). Over the 2000–2019 period, the proportion decreased in all regions, except the European Region, where it increased, and the Eastern Mediterranean Region, where there was very little change. The Western Pacific Region had the largest regional decrease. Fig. 3A presents a map of the proportion of the population exposed by country/area.

3.2. Burden of NMSC attributable to occupational exposure to UVR

3.2.1. Deaths

Globally in 2019, an estimated total of 65,440 NMSC deaths occurred (World Health Organization, 2020). The PAF was 29.0 % (UR 24.7–35.0, Table S34 in the Supplementary Material, output from Model 4). Thus, 18,960 (UR 18,180–19,740) of the NMSC deaths were attributable to occupational exposure to UVR (Table S52 in the Supplementary Material). Males carried a larger burden, and the number and rate of death increased with age up to 65–69 years due to disease latency (Fig. 4). Between 2000 and 2019, the PAF remained comparable over time, at 28.8 % (UR 21.6–42.5), 29.4 % (UR 24.2–37.2) and 29.0 % (UR 24.7–35.0), in 2000, 2010 and 2019, respectively (Tables S28-S36 in the Supplementary Material). However, between 2000 and 2019, NMSC deaths attributable to occupational exposure to UVR increased by 87.9 % (UR 78.0–98.5) (Table 5). This almost doubling of attributable NMSC deaths was driven by the almost doubling of the total NMSC deaths.

Regionally in 2019, the Western Pacific Region had the largest number of NMSC deaths attributable to occupational exposure to UVR (6337 deaths, UR 5562–7012) (Table S52 in the Supplementary Material). The Eastern Mediterranean Region had the lowest (1558 deaths, UR 1449–1667). Fig. 3B presents the rate of death from NMSC attributable to occupational exposure to UVR by country. Tables S46-S54 provide the full set of estimates of the number of attributable deaths in the Supplementary Material.

3.2.2. DALYS

Globally in 2019, of the 1.5 million DALYs lost from NMSC in total (World Health Organization, 2020), 0.5 million DALYs (UR 0.4–0.5) were attributable to occupational exposure to UVR (Table 5). In 2000, 2010 and 2019, the PAF was 30.2 % (UR 29.1–31.4), 30.5 % (UR 29.3–31.7) and 30.4 % (UR 29.0–31.7), respectively (Table 5). From 2000 to 2019, attributable DALYs increased by 77.1 % (UR 67.8–86.9). Fig. 3C presents a map of the rate of DALYs from NMSC that are attributable to occupational exposure to UVR by country. Tables S55-S63 show the full estimates set for the number of attributable DALYs (see Supplementary Material).

3.3. Health inequalities

3.3.1. Deaths

In absolute terms, males had an NMSC death rate (0.4 deaths per 100,000 working-age population, UR 0.4–0.5) higher than the global rate (0.3, UR 0.3–0.4). The death rate for females was lower (0.2, UR 0.2–0.3). Compared with the global death rate, the African Region, the Region of the Americas and the Western Pacific Region had higher rates, whereas the European and South-East Asian Regions had lower rates (Figure S5A in the Supplementary Material). These absolute differences to the global rate by WHO Region ranged from 0.1 deaths per 100,000 working-age population in the African Region to −0.1 deaths per 100,000 working-age population in the South-East Asian Region (Figure S5B in the Supplementary Material). Death rates for age groups up to and including 50–54 years were below the global death rate and for older age groups were above the global rate (Figure S6A in the Supplementary Material). These rate differences by age group (compared with the global rate) ranged from 7.9 deaths per 100,000 working-age population in the age group of ≥95 years to –0.3 deaths per 100,000 working-age population in the age groups of 15–19, 20–24 and 25–29 years (Figure S6B in the Supplementary Material).

These patterns were also reflected in the relative inequalities, measured with the ratios of rates for the population of interest to the global rate. They were higher for males (rate ratio of 1.3) than females (0.7). Additionally, they were highest for the African Region (1.4) and lowest for the South-East Asian Region (0.6) (Figure S5C in the Supplementary Material). For age groups, the highest ratio was for the age group of ≥95 years (24.9) (Figure S6C in the Supplementary Material).

3.3.2. DALYS

In absolute terms, males had an NMSC DALY rate (10.6 DALYs per 100,000 working-age population, UR 10.1–11.2) higher than the global rate (8.0, UR 7.7–8.4); the DALY rate for females was lower (5.4, UR 5.1–5.8). The African Region, the Region of the Americas and the Western Pacific Region had DALY rates higher than the global rate, whereas the European and South-East Asian Regions had DALY rates lower than the global rate (Figure S7A in the Supplementary Material). These absolute inequalities in the rates by WHO Region, compared with the global rate, ranged from 5.3 DALYs per 100,000 working-age population in the African Region to −3.2 DALYs per 100,000 working-age population in the South-East Asian Region (Figure S7B in the Supplementary Material). For age groups up to and including 45–49 years, DALY rates were below the global DALY rate; after this age group, DALY rates were above the global DALY rate (Figure S8A in the Supplementary Material). These rate differences by age group (compared with the global rate) ranged from 41.9 DALYs per 100,000 working-age population in the age group of ≥95 years to –8.0 DALYs per 100,000 working-age population in those aged 15–19 and 20–24 years (Figure S8B in the Supplementary Material).

These patterns were also reflected in the relative inequalities, again measured as rate ratios with global DALY rate as the reference. The rate ratios were higher for males (1.3) than females (0.7). They were highest for the African Region (1.7) and lowest for the Eastern Mediterranean Region (0.6) (Figure S7C in the Supplementary Material). For age groups, the highest ratio was for people aged ≥95 years (6.2) (Figure S8C in the Supplementary Material).

3.4. Sensitivity analyses

Results from sensitivity analyses showed that, despite some variation in estimates, the numbers of deaths and of DALYs remained substantial and similar when the assumed lag time was reduced to 10 years and increased to 30 years, the time window of exposure was reduced to 10

Table 5
WHO/ILO Joint Estimates of the population occupationally exposed to UVR (195 countries/areas) and of the PAFs and of the numbers of deaths and of DALYs from NMSC attributable to occupational exposure to UVR (183 countries), 2000, 2010 and 2019, and mean percentage change for 2000–2010, 2010–2019 and 2000–2019, by sex.

Estimate type	Both sexes						Females		
	Point estimate (UR)			Percentage change (UR)			Point estimate (UR)		
	2000	2010	2019	2000–2010	2010–2019	2000–2019	2000	2010	2019
Proportion of the population occupationally exposed to UVR (%)	41.9 (40.9–43.0)	34.7 (34.1–35.3)	28.4 (27.9–28.8)	−17.3 (−19.6–−14.8)	−18.3 (−20.2–−16.3)	−32.4 (−34.3–−30.3)	33.3 (31.9–34.8)	24.5 (23.7–25.2)	16.9 (16.2–17.6)
PAF for deaths from NMSC attributable to occupational exposure to UVR (%)	28.8 (21.6–42.5)	29.4 (24.2–37.2)	29.0 (24.7–35.0)	2.1 (−31.0–64.4)	−1.3 (−24.9–32.0)	0.8 (−30.4–59.6)	24.0 (16.3–45.2)	25.1 (19.2–35.3)	24.2 (19.7–31.0)
PAF for DALYs from NMSC attributable to occupational exposure to UVR (%)	30.2 (29.1–31.4)	30.5 (29.3–31.7)	30.4 (29.0–31.7)	0.9 (−4.2–6.5)	−0.4 (−6.2–5.7)	0.6 (−5.3–6.8)	26.2 (24.6–27.8)	26.5 (24.7–28.3)	25.9 (24.0–27.9)
Number of deaths from NMSC attributable to occupational exposure to UVR	10,089 (9732–10,446)	14,655 (14,077–15,233)	18,960 (18,180–19,740)	45.3 (37.7–53.2)	29.4 (22.3–37.0)	87.9 (78.0–98.5)	3682 (3475–3889)	5399 (5039–5759)	6614 (6146–7082)
Number of DALYs (in '000) from NMSC attributable to occupational exposure to UVR	258.6 (249.7–267.5)	365.2 (351.3–379.0)	458.0 (439.4–476.6)	41.2 (34.2–48.7)	25.4 (18.6–32.6)	77.1 (67.8–86.9)	93.7 (88.5–98.9)	130.8 (122.4–139.1)	154.9 (144.3–165.4)

Footnotes: DALYs disability-adjusted life years; NMSC non-melanoma skin cancer; PAF population-attributable fraction; UR 95% uncertainty range; UVR solar ultraviolet radiation. Estimates of the PAFs and the numbers of deaths and of DALYs were not produced for the following countries/areas because of a lack of disease burden envelope in the Global Health Estimates: Andorra; Cook Islands; Dominica; Marshall Islands; Monaco; Nauru; Niue; occupied Palestinian territory, including east Jerusalem; Palau; Saint Kitts and Nevis; San Marino; and Tuvalu (World Health Organization, 2020).

years and increased to 30 years and people in occupations classified as *occasionally* exposed were added to the exposed group (Table S64 in the Supplementary Material).

4. Discussion

This article presents the first official estimates of the population occupationally exposed to UVR and of the burden of NMSC attributable to occupational exposure to UVR worldwide, regionally and nationally. In summary, in 2019, 28.4 % (UR 27.9–28.8) of the global working-age population were occupationally exposed to UVR. An estimated 18,960 deaths (UR 18,180–19,740) and 0.5 million (UR 0.4–0.5) DALYs from NMSC were attributable to this occupational risk factor (29.0 % of all deaths, UR 24.7–35.0, and 30.4 % of all DALYs, UR 29.0–31.7, from NMSC in 2019). This cancer burden was higher among people in the African Region, the Region of the Americas, the Western Pacific Region, and among men and people of middle to older working age. Between 2000 and 2019 in relative terms, the proportion of the population exposed decreased by 32.4 % (UR −34.3–−30.3) while the attributable burden of deaths from NMSC increased by 87.9 % (UR 78.0–98.5) due to the increase in the total burden of NMSC deaths. Action taken now to reduce hazardous occupational exposure to UVR would be expected to prevent NMSC burden in the future.

4.1. Comparison with previous findings and interpretations

Our study estimates that 1.6 billion workers (UR 1.6–1.6) were occupationally exposed to UVR in 2019 globally. This is more than three times higher than the only other previous estimate (>500 million people) (Wittlich et al., 2016); however, this previous estimate was produced by applying exposure data from one country (Germany) to data on all workers globally. We estimate a comparable number of NMSC deaths attributable to occupational exposure to UVR for Finland (2, UR 1–3, in 2000, compared with 2, UR unclear, in 1996 in Nurminen and Karjalainen (2001)); a much higher number of attributable NMSC DALYs for the Islamic Republic of Iran (2,613,000 DALYs, UR 2,303,000–2,923,000, in 2019, compared with 2907 DALYs, UR unclear, in 2019 in Saeedi et al. (2022)); and a higher number for attributable deaths for the United Kingdom of Great Britain and Northern Ireland (87, UR 72–102, in 2000, compared with 13, UR unclear, in 2005 in Young, Rushton and British Occupational Cancer Burden Study Group, (2012)). Differences may be due to different data sources and methods. Comparisons with the other studies that have estimated this burden of disease (Fritschi and Driscoll, 2006; Peters et al., 2019b) are not possible as these estimated incident cases of NMSC, rather than deaths or DALYs from NMSC.

Our estimates demonstrate that the cancer burden attributable to occupational exposure to UVR is the third largest of the occupational carcinogens included in the global WHO/ILO Comparative Risk Assessment (in terms of the number of deaths in 2016, 17,936, UR 17,226–18,646), only behind occupational exposures to asbestos (209,481 deaths, UR 205,856–213,106) and to silica (42,258 deaths, UR 40,632–43,884) (World Health Organization and International Labour Organization, 2021).

4.2. Strengths and limitations

WHO and the ILO have produced a first and detailed set of estimates of the global, regional, national and subnational populations occupationally exposed to UVR and of the global, regional and national attributable burdens of NMSC, disaggregated by sex and 5-year age group. UVR is an established carcinogen for NMSC in humans (Group 1) (International Agency for Research on Cancer, 1992; International Agency for Research on Cancer, 2012). These new official WHO/ILO

Females			Males					
Percentage change (UR)			Point estimate (UR)			Percentage change (UR)		
2000–2010	2010–2019	2000–2019	2000	2010	2019	2000–2010	2010–2019	2000–2019
−26.6 (−30.4–−22.6)	−31.0 (−34.4–−27.4)	−49.4 (−52.3–−46.3)	50.6 (49.1–52.0)	44.9 (44.1–45.8)	39.8 (39.2–40.5)	−11.1 (−14.1–−8.1)	−11.4 (−13.6–−9.2)	−21.2 (−23.8–−18.6)
4.4 (−43.7–181.7)	−3.5 (−34.4–48.6)	0.7 (−41.6–147.9)	32.4 (22.5–58.3)	32.6 (24.8–47.0)	32.4 (25.9–43.0)	0.6 (−44.4–130.6)	−0.6 (−34.1–57.0)	−0.1 (−41.5–129.1)
1.3 (−7.5–11.1)	−2.3 (−11.8–8.0)	−1.0 (−10.2–8.9)	33.1 (31.6–34.7)	33.3 (31.6–35.0)	33.4 (31.5–35.3)	0.5 (−6.4–7.9)	0.2 (−7.3–8.0)	0.6 (−6.4–8.4)
46.6 (34.3–60.0)	22.5 (11.0–34.9)	79.6 (63.9–96.6)	6407 (6117–6697)	9256 (8803–9709)	12,346 (11,722–12,970)	44.5 (35.1–54.6)	33.4 (24.3–43.1)	92.7 (80.0–106.0)
39.6 (28.0–51.7)	18.4 (8.1–30.2)	65.3 (50.8–80.5)	164.9 (157.7–172.1)	234.4 (223.3–245.5)	303.1 (287.8–318.5)	42.1 (33.3–51.7)	29.3 (20.5–38.3)	83.8 (71.9–96.1)

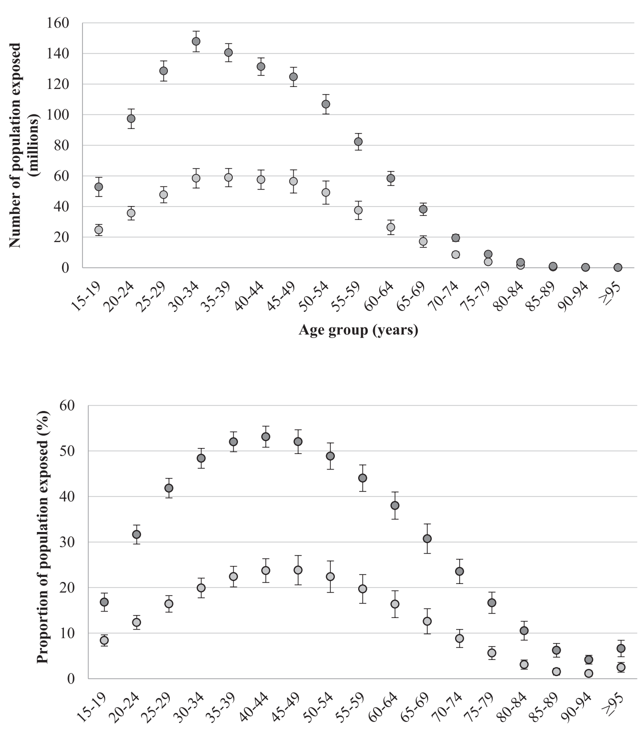

Fig. 2. WHO/ILO Joint Estimates of the number of and the proportion of the working-age population occupationally exposed to UVR, by sex (males indicated by dark points and females indicated by light points) and age group, 195 countries/areas, 2019.
Footnote: The points indicate the point estimates, and the bars indicate the UR.

estimates were based on 166 million observations from 763 official LFSs covering 96 countries and all WHO Regions. They were also based on a dedicated WHO/ILO systematic review and *meta*-analysis of the latest body of evidence produced specifically for this estimation (World Health Organization, 2021). Exposure over time was estimated with a comprehensive and novel microflow simulation model populated with official empirical longitudinal data on occupational transitions over time from 31 countries across all regions.

The study has several limitations. First, the estimates are produced based on exposure assigned via proxy of occupation that experts judged to always work outdoors. Assignment was carried out by ILO labour statisticians and occupational hygienists, who were not involved in the estimation, and subsequently independently reviewed by WHO occupational epidemiologists and a technical advisory group of individual experts (i.e., the Technical Advisory Group on Occupational Burden of Disease Estimation). Exposure assignment could, in addition to occupation with outdoor work, theoretically be based on direct personal exposure measurements (e.g., using dosimeters and/or questionnaires), but availability of these data is currently too limited to permit this. Moreover, all studies in the main WHO/ILO *meta*-analysis (World Health Organization, 2021) that produced the risk ratio used in our estimation and all previous burden of disease studies on the topic (Fritschi and Driscoll, 2006; Nurminen and Karjalainen, 2001; Peters et al., 2019b; Saeedi et al., 2022; Young, Rushton and British Occupational Cancer Burden Study Group, 2012) were also based on exposure assignment via proxy of occupation or outdoor work. We nevertheless acknowledge the risk of exposure misclassification bias in our estimation, which could have led to under- or overestimation of the exposure or burden of disease, or could have not impacted these.

Second, the quality of input data varies. Most LFSs collected self-reported data on occupation. Most data regarding deaths were obtained from national statistics offices with established, official data collection protocols (e.g., statistical standards). Variation in reporting can be expected and could lead to under- or overestimations of the exposure or burden of NMSC, depending on the direction of the error

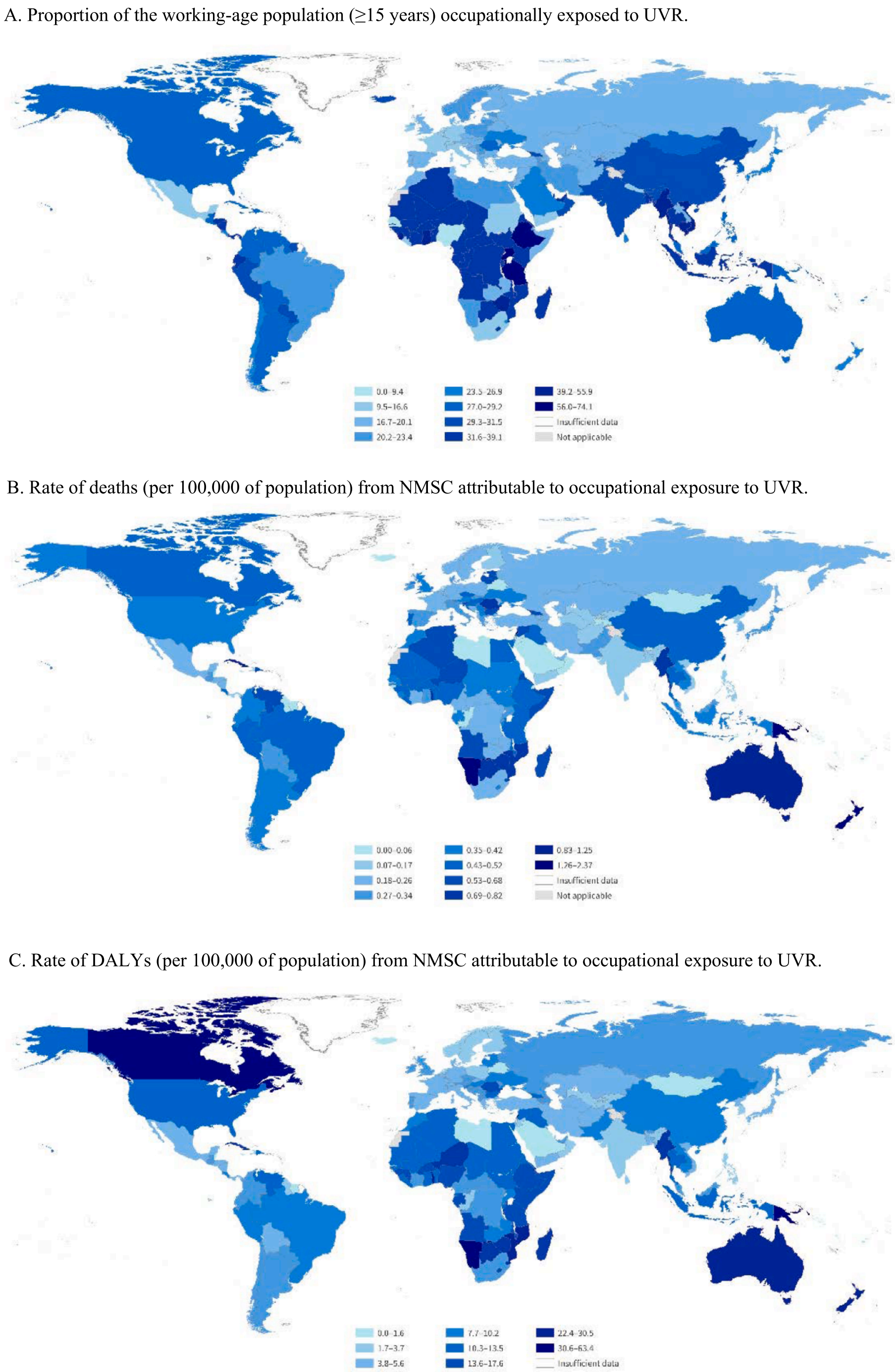

Fig. 3. WHO/ILO Joint Estimates of occupational exposure to UVR, 195 countries/areas, and of the rates of deaths and of DALYs from NMSC attributable to occupational exposure to UVR, 183 countries, 2019.
Footnote: Burden of disease estimates were not produced for the following countries/areas because of a lack of disease burden envelope in the Global Health Estimates: Andorra; Cook Islands; Dominica; Marshall Islands; Monaco; Nauru; Niue; occupied Palestinian territory, including east Jerusalem; Palau; Saint Kitts and Nevis; San Marino; and Tuvalu (World Health Organization, 2020).

and bias. Although cross-sectional LFS data were available for 49 % of countries globally, confidence would be further increased with data from more countries. Furthermore, some LFSs do not capture workers in the informal economy. Data from the European Union LFSs were disaggregated by 10-year age group, rather than by 5-year age group.

Third, we made several assumptions during the modelling. These were based on the latest evidence and transparently described (Table 4), but may require review as the body of evidence develops. Assignment of people exposed for at least one year during the time window of exposure as exposed, although standard practice across occupational burden of disease studies, may have resulted in overestimation of the health loss.

Fourth, the risk ratio used as an input relates to incidence (World Health Organization, 2021), but is applied to produce estimates of the burdens of deaths and of DALYs. As NMSC has a relatively high survival rate, this may not be ideal and could lead to under- or overestimation, or no change, of the burden of cancer. However, this was the pooled effect

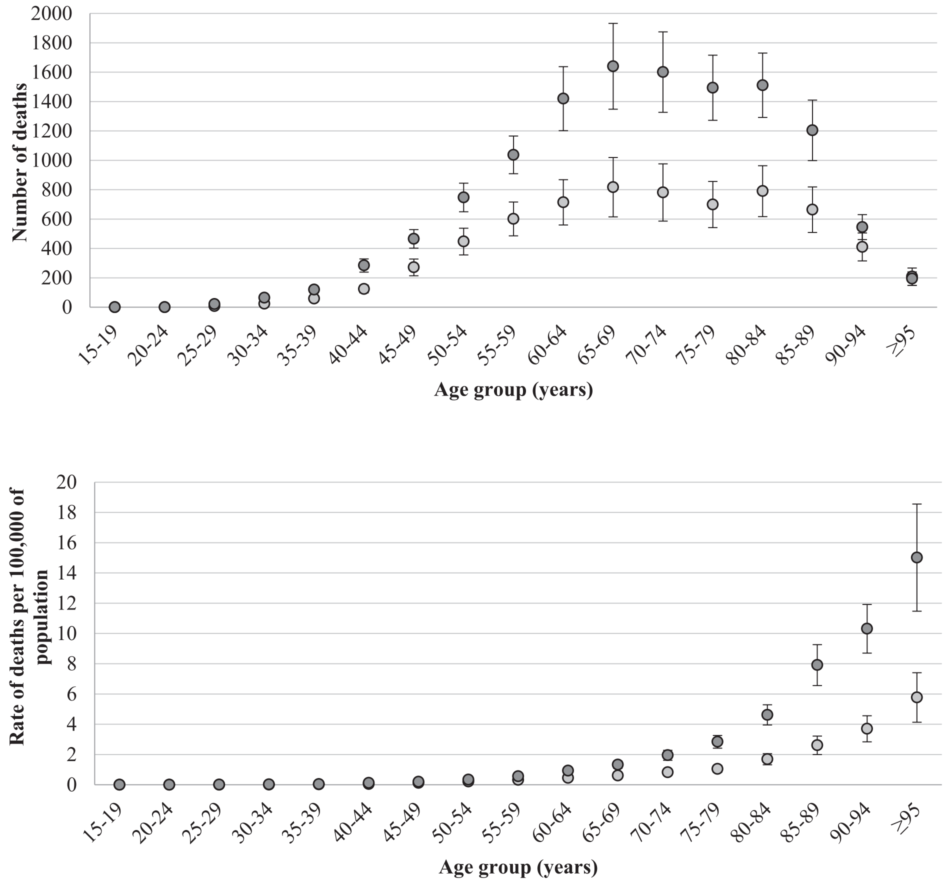

Fig. 4. WHO/ILO Joint Estimates of the number and the rate of death from NMSC attributable to occupational exposure to UVR, by sex (males indicated by dark points and females indicated by light points) and age group, 183 countries, 2019.
Footnotes: Estimates were not produced for the following countries/areas because of a lack of disease burden envelope in the Global Health Estimates: Andorra; Cook Islands; Dominica; Marshall Islands; Monaco; Nauru; Niue; occupied Palestinian territory, including east Jerusalem; Palau; Saint Kitts and Nevis; San Marino; and Tuvalu (World Health Organization, 2020). The points indicate the point estimates, and the bars indicate the UR.

estimate from the only body of evidence judged to be of "sufficient strength of evidence". Additionally, this effect estimate was statistically heterogenous (I^2 = 91 %) (World Health Organization, 2021), which could be the result of heterogeneity in exposure assessment, outcome assessment and/or study populations. More primary research studies are needed on NMSC incidence and mortality, from a wider range of countries and providing risk ratios by socioeconomic status, skin phototype, human immunodeficiency virus status, use of personal protective equipment and presence and implementation of preventive interventions (e.g., government regulations of outdoor work), as well as according to level of exposure. We were unable to estimate NMSC burden attributable to occupational exposure to UVR by subtype of BCC versus subtype of SCC, as there are no WHO Global Health Estimates for these subtypes. However, BCC is more prevalent than SCC (Hannuksela-Svahn et al., 1999; Koh et al., 2003; Guo et al., 2023), and the WHO/ILO systematic review reported effect estimates for BCC (1.50, 95 % CI 1.10–2.04) and for SCC (2.43, 95 % CI 1.64–3.62) in subgroup analyses (p for test for subgroup differences = 0.06); this provides impetus for future estimates of the burdens by NMSC subtype if and once feasible.

4.3. Preventive actions

Governments must protect outdoor workers from NMSC disease and death by reducing hazardous occupational exposure to UVR, including by introducing and enforcing regulations that limit such occupational exposure and that provide shade and shift working hours away from solar noon (World Health Organization, 2022; Vecchia et al., 2007; WHO, 2022). Workers could be provided with training, as well as personal protective clothing (e.g., broad-brimmed hat, long-sleeved shirts, long trousers) and sunscreen, for working outdoors. Occupational health services could provide regular screening for skin cancer, with a focus on the workers at highest risk. Messages should consider a risk–benefit balance as some UVR exposure may also have beneficial effects.

5. Conclusions

WHO and the ILO estimate that occupational exposure to UVR is common and leads to substantial numbers of deaths and of DALYs from NMSC. Men and older age groups carried larger burden. In the global WHO/ILO Comparative Risk Assessment, this occupational risk factor is currently the occupational carcinogen with the third-largest attributable burden of cancer. The number of NMSC deaths attributable to occupational exposure to UVR almost doubled between 2000 and 2019. The WHO/ILO Joint Estimates highlight the importance of and provide the evidence base for continuing research and action to prevent occupational exposure to UVR and, thereby, the attributable burden of NMSC, and for improving workers' health equity.

Disclaimers

The authors alone are responsible for the views expressed in this article, and they do not necessarily represent the views, decisions or policies of the institutions with which they are affiliated. The views expressed herein can in no way be taken to reflect the official opinion of

the European Union.

Funding sources

This modelling study was prepared with financial support to WHO from: the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention of the United States of America (Grant 1E11OH0010676-02, Grant 6NE11OH010461-02-01 and Grant 5NE11OH010461-03-00); the German Federal Ministry of Health (BMG Germany) under the BMG-WHO Collaboration Programme 2020–2023 (WHO specified award ref. 70672); and the Spanish Agency for International Cooperation (AECID) (WHO specified award ref. 71208). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

CRediT authorship contribution statement

Frank Pega: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft, Supervision, Writing – review & editing, Project administration, Funding acquisition. **Natalie C. Momen:** Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Project administration. **Kai N. Streicher:** Data curation, Methodology, Formal analysis, Visualization, Writing – review & editing. **Maria Leon-Roux:** Methodology, Writing – review & editing. **Subas Neupane:** Methodology, Writing – original draft, Writing – review & editing. **Mary K. Schubauer-Berigan:** Methodology, Writing – review & editing. **Joachim Schüz:** Methodology, Writing – review & editing. **Marissa Baker:** Methodology, Writing – review & editing. **Tim Driscoll:** Methodology, Writing – review & editing. **Irina Guseva Canu:** Methodology, Writing – review & editing. **Hannah M. Kiiver:** Data curation, Methodology, Formal analysis, Writing – review & editing. **Jian Li:** Methodology, Writing – review & editing. **Jamaji C. Nwanaji-Enwerem:** Methodology, Writing – review & editing. **Michelle C. Turner:** Methodology, Writing – review & editing. **Susana Viegas:** Methodology, Writing – review & editing. **Paul J. Villeneuve:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Several data used are already publicly available. Other data used that the authors are able to share are shared in the Supplementary File 1. The remaining data used are confidential, and the authors are therefore not able to share these data. The code is shared in Supplementary File 2.

Acknowledgements

Countries provided feedback on the estimates through WHO's consultation of its 194 Member States. We specially acknowledge the ILO for its strategic contributions, as well as its sharing of data and contributions to the production of the estimates. Eurostat produced and shared the transition probabilities for exposure to UVR assigned via proxy of occupation for 27 countries in the European Region. Dr Yuka Ujita (ILO) and then Dr Halim Hamzaoui (ILO) were the ILO focal point for the WHO/ILO Joint Estimates. Marion McFeedy (consultant to the ILO) contributed to initial database development, and Dr Bochen Cao (WHO) shared WHO Global Health Estimates. Dr Claudine Backes (WHO) and Dr Emilie van Deventer (WHO) contributed to the early development of the estimation approach. Jessica CY Ho (WHO), Wahyu R Mahanani (WHO), Dr Bálint Náfrádi (ILO), Dr Annette M Prüss (WHO) and Dr Yuka Ujita provided feedback on an earlier version of the manuscript. Dr Ivan D Ivanov (WHO), Nancy Leppink (ILO), Franklin Muchiri (ILO), Dr Maria P Neira (WHO), Vera L Isaac Paquete-Perdigão (ILO) and Joaquim P Pintado Nunes (ILO) contributed to the WHO/ILO Joint Estimates of the Work-related Burden of Disease and Injury. Dr Maria P Neira and Vera L Isaac Paquete-Perdigão provided overall guidance.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108226.

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