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Higher ultraviolet light exposure is associated with lower mortality: An analysis of data from the UK biobank cohort study

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ABSTRACT

We aimed to examine associations between ultraviolet (UV) exposure and mortality among older adults in the United Kingdom (UK). We used data from UK Biobank participants with two UV exposures, validated with measured vitamin D levels: solarium use and annual average residential shortwave radiation. Associations between the UV exposures, all-cause and cause-specific mortality were examined as adjusted hazard ratios. The UV exposures were inversely associated with all-cause, cardiovascular disease (CVD) and cancer mortality. Solarium users were also at a lower risk of non-CVD/non-cancer mortality. The benefits of UV exposure may outweigh the risks in low-sunlight countries.

1. Introduction

Public health messaging in the United Kingdom (UK) and other countries with a large population of European descent has emphasised the risks of ultraviolet (UV) exposure. The known association between UV radiation and melanoma pathogenesis is of particular concern. However, in 2017–2019, melanoma mortality was relatively low, representing just 1% of all cancer deaths (Cancer Research UK, 2022). Recent evidence suggests that the benefits of UV exposure may outweigh risks, especially in low-sunlight environments. In a cohort of Swedish women, participants with higher levels of sun exposure lived longer than those who avoided the sun (Lindqvist et al., 2016). The mortality advantage was mainly attributed to lower cardiovascular disease (CVD) and non-CVD/non-cancer mortality. In a case-control study of Swedish women with low-to-moderate sun exposure habits, women with fair phenotypes had an 8% lower all-cause mortality rate than non-fair women (Lindqvist et al., 2020).

Several biologically plausible mechanisms exist for a relationship between ultraviolet A (UVA) and ultraviolet B (UVB) exposure and health. UVB synthesises vitamin D in exposed skin (Holick, 2016). Higher vitamin D levels are associated with lower cancer and CVD rates in observational studies (Chowdhury et al., 2014). However, recent randomised controlled trials of vitamin D supplementation and Mendelian randomisation studies do not support a causal role of vitamin D on a range of extra-skeletal health outcomes (Pilz et al., 2016; Manson et al., 2019). UVA photons have longer wavelengths and penetrate deeper into the skin (Holick, 2016). Dermal UVA exposure triggers nitric oxide (NO)-mediated vasodilatation, which lowers blood pressure (Liu et al., 2014). NO is also a negative regulator of the NLRP3 inflammasome, which is associated with a wide range of diseases, including type II diabetes and atherosclerosis (Mao et al., 2013). New evidence suggests that UVA protects against myocardial infarction (Mackay et al., 2019) and COVID-19 mortality, (Cherrie et al., 2021) independent of UVB.

The UK is a high latitude and low-sunlight country. The UV index, which measures the erythemal intensity of sunlight, rarely exceeds 6 (where 3–5 is classified as moderate and 6–7 high) in much of the UK. (UK Air, n.d.) Indeed, there is a high prevalence of low vitamin D, a biomarker for low UV exposure (Lips et al., 2019). Public health campaigns are perhaps influenced by those from extreme UV environments like Australia with pale skinned European populations. Residential

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location and behavioural factors are determinants of personal UV irradiation (Diffey, 2002; World Health Organization, 2016). This study aimed to determine to what extent UV exposure is associated with all-cause and cause-specific mortality using data from participants of the UK Biobank. We used two distinct estimates of exposures validated against serum vitamin D levels, a biomarker for UV exposure, and a negative control outcome to test this question.

2. Materials and methods

2.1. Cohort and sample

The UK Biobank is a prospective community-based cohort of over 500,000 participants aged 37 to 73 at recruitment (2006 and 2010), living close to 22 recruitment centres located throughout England, Wales and Scotland (Sudlow et al., 2015). Sociodemographic details, health, physical assessment with blood, urine and saliva samples were collected. UK Biobank's ethical approval was from the North West Centre for Research Ethics Committee (11/NW/0382). Genetic skin pigmentation plays an important role in biological responses to UV exposure (Brenner and Hearing, 2008). To limit the potential confounding effect of UV exposure, skin pigmentation and mortality, we restricted to participants of white European ancestry in the present analysis using a combination of self-reported ethnic background and genetic information.

2.2. Study design

To better assess causality we used; [i] two exposures estimated from independent processes, modelling them separately (allowing triangulation (Lawlor et al., 2017)), [ii] measured serum vitamin D levels, a biomarker for UV exposure, to validate the exposures and [iii] a negative control outcome to test for appropriate adjustment.

We developed estimates for UV exposures derived from different social and economic processes and we modelled these separately. By using different, independent, social processes we maximise the chance that there is not a single major 'omitted variable' biasing our results because it is unlikely to exist in both contexts. We chose an outcome that met the negative control criteria (that exposures of interest have no reported or plausible effect on but are subject to the same unobserved confounding as the outcomes of interest) that in particular could be affected by two confounders in our directed acyclic graphs (DAGs; **Supplementary File 1**): risky behaviours and socioeconomic factors. Any association observed between the exposure and a negative control outcome indicates that there may be confounding in the main models.

The UK Biobank has data from which behavioural and geographic UV exposures can be estimated. Firstly, participants were asked 'how many times a year would you use a solarium or sunlamp?' We recoded the responses to create a *solarium use* variable (solarium user or solarium non-user, defined as one or more times per year versus never or less than one time per year).

Secondly, we estimated an annual average *residential shortwave radiation* (SWR; kJ/m^2) over the follow-up period variable for each participant. Downward SWR is the total incoming solar energy over the Earth's surface in the shortwave spectrum and comprises both UVA and UVB radiation, (Yu et al., 2021) the components solar radiation that have effects on human health. The Japan Aerospace Exploration Agency (JAXA) calculates half-monthly average of daily downward SWR (250 nm–2500nm) measurements using daily data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Aqua and Terra satellites, considering cloud and aerosol thickness (Murakami, 2010). These measurements are available at a 0.05°x.0.05° spatial resolution.

We calculated the 2008 yearly average of SWR for each 0.05°x.0.05° grid point across the UK. We selected 2008 because it falls midway through the recruitment period for UK Biobank participants (2006–2010). The UK Biobank provides north and east co-ordinates of each participant's residential location at recruitment and any subsequent address changes, using the Ordnance Survey (OSGB) reference at a 1 km × 1 km resolution. We converted these OSGB co-ordinates into latitudes and longitudes and spatially joined them to the nearest SWR measurement using ArcMap (10.8.2).

To account for changes in residential location and SWR exposure, we calculated the annual average SWR for each participant based on their address history over the follow-up period, considering the duration spent at each address. We then converted the values measured in W/m^2 to kJ/m^2 (× 86,400 s in a day/1000) for consistency with previous studies (Mackay et al., 2019). Finally, we scaled the measure for the survival analyses so that the hazard ratio represents an increase of 2,000 kJ/m^2. This represents the approximate 2008 annual average difference in SWR between places like Glasgow (SWR = 8329 kJ/m^2) and Cornwall (SWR = 10,295 kJ/m^2).

We validated both exposure measures by comparing them to measured serum 25-Hydroxy Vitamin D (25(OH)D) levels at baseline. As negative controls outcomes we measured and assessed hospitalisations due to car or motorcycle accidents (ICD-10: V200-V499).

2.3. Outcomes of interest

All-cause and cause-specific mortality (CVD, cancer, and non-CVD/non-cancer) were the primary outcomes of interest in this study. Each participant from the UK Biobank was linked to a national death registry at the date of their recruitment into the study (Sudlow et al., 2015). A list of ICD-10 codes used for each mortality outcome is available in Supplementary File 2. Much attention has been devoted to the association between UV exposure and melanoma incidence; however, previous research has indicated a complex interplay between UV-linked melanoma incidence and mortality (Adamson et al., 2022; Maduka et al., 2023). To test this, we compared melanoma incidence and mortality in secondary analyses. We also compared non-skin cancer incidence and mortality.

2.4. Confounders

We identified several demographic, socioeconomic, and behavioural factors *a priori* (aided by our DAGs; **Supplementary File 1**), that we assume could influence both our measures of an individual's UV exposure and mortality risk and therefore could be confounding. For the *solarium use* variable, we considered age at recruitment (39–48, 49–54, 55–59, 60–63, 64–73), sex (female or male), employment status (employed or unemployed), age completed full-time education (≤15, 16 to 18, ≥19), area-level UK-adjusted Index of Multiple Deprivation (IMD) (a continuous variable), smoking status (never, former and current), number of days a week of vigorous physical activity lasting more than 10 min (none or one or more days), risk-taking behaviour (yes or no: 'Would you describe yourself as someone who takes risks?'), body mass index (BMI, kg/m^2) (<25, 25 to 30, 30+), history of mental health concerns (having seen a doctor for either nerves, anxiety, tension or depression), health at baseline (poor versus fair, good or excellent) and average residential SWR (a continuous variable). Health at baseline was included to account for possible reverse causation (i.e., the effect of poor health on solarium use). We considered age, sex, age completed full-time education, employment status, area-level UK-adjusted IMD, solarium use, smoking status, physical activity, and risk-taking behaviour for the average *residential SWR* variable.

The IMD measures relative deprivation at the small-area level across England, Wales, Northern Ireland and Scotland (Noble et al., 2006). The IMD is calculated in lower layer super output areas (LSOAs) in England and Wales (population approximately 1000 to 3000) (Office of National Statistics, 2021), data zones in Scotland (population approximately 500 to 1000) (Scottish Government, 2021) and super output areas (SOAs) in Northern Ireland (population approximately 400 to 5500) (Nothern

Ireland Assembly, 2018). These are comparable to census tracts in the United States, which have a population of approximately 1200 to 8000 (United States Census Bureau, 2022). Each country in the UK has a separate IMD encompassing material deprivation and other aspects such as health and crime. The indices are not directly comparable because the domains, data sources and scales differ; however, they all aim to measure the same multiple deprivation concept. We assessed the range and distribution for the raw scores of the income domain, which is the same across the UK, and found them to very similar (National Statistics, 2020; Scottish Government, 2020). Therefore, to create a UK-wide adjusted measure of IMD, we rescaled the Wales and Scotland IMDs to the distribution of the England IMD, described in Equation (1). Higher scores represent more deprived areas.

$$IMD_{adj} = \frac{(IMD_{Ci} - IMDmin_C)}{IMDrange_C} \; x \; (IMDmax_E - IMDmin_E) + IMDmin_E \qquad [1]$$

IMD_{Ci} is the IMD score for area i in country C; $IMDmin_C$ is the minimum IMD score in country C; $IMDrange_C$ is the difference between the minimum and maximum score in country C; $IMDmax_E$ is the maximum IMD score in England and $IMDmin_E$ is the minimum IMD score in England.

2.5. Statistical analyses

Statistical analyses were performed using Stata 16 (College Station, TX: StataCorp LLC.). We calculated proportions or means and 95% confidence intervals (CIs) for each variable included in the study. Multiple Imputation (MI) using chained equations was used to impute values for missing data. Fifteen imputations were run and models included the outcome and exposure variables as well as all covariates. All adjusted analyses were based on imputed data. A complete case analysis was also carried out (**Supplementary File 3**). Linear regression models were fitted for the UV exposures and vitamin D serum levels, adjusted for the same confounders for each UV exposure described above, plus vitamin D supplementation. The 'mimrgns' command was used to estimate adjusted mean vitamin D serum levels to validate our exposure measures. Person-time was calculated from the date that each participant enrolled in the study to the date of death from any cause and each cause-specific death, loss to follow-up or the end of the follow-up (November 12, 2021). Age-adjusted and multivariable Cox proportional hazard regression models were fitted to estimate hazard ratios (HRs) for the binary solarium use and the continuous average residential SWR variables on all-cause and cause-specific mortality, adjusting for confounders identified *a priori*. The Restricted Mean Survival Time (RMST) was calculated for each exposure group while controlling for the same confounders identified above, and the difference in RMSTs between the groups was considered as the estimate of the difference in survival time over the follow-up period (Han and Jung, 2022). Multivariate cox proportional hazard regression models were fitted to estimate HRs for solarium use and average residential SWR exposures on hospitalisations due to car or motorcycle accidents (the negative control outcome).

Multivariable cox proportional hazard regression models were also fitted to estimate HRs solarium use and average residential SWR exposures on melanoma and non-skin cancer incidence and mortality, the secondary outcomes of interest. We considered the first hospitalisation after follow-up to calculate incidence. The models were adjusted for the same confounders described above.

3. Results

There were 502,412 participants enrolled in the UK Biobank cohort, 49,386 of whom did not have white European ancestry. Of those eligible, 395,086 participants had complete information (Fig. 1). The total follow-up time was 4,912,032 person-years, with a median follow-up of 12.7 years. Complete case participant information and missing data is described in Table 1. The leading five underlying causes of cardiovascular, cancer and non-cardiovascular/non-cancer deaths among the participants are described in Supplementary File 4.

In fully adjusted models, solarium users had higher levels of vitamin D compared to non-solarium users (Table 2). Participants who resided in places with higher residential SWR also had higher levels of vitamin D. This suggests that our two exposure measures are capturing genuine differences in personal UV exposure.

Solarium users had a 15% lower risk of all-cause mortality, a 23% lower risk of CVD mortality, a 14% lower risk of cancer mortality, and a 12% lower risk of non-CVD/non-cancer mortality compared solarium non-users in fully adjusted models (Fig. 2A). Solarium non-users had approximately 48 days of life lost over the follow-up period (15.7 years). Participants whose annual average residential SWR was 2000 kJ/m^2 higher had a 12% lower risk of all-cause mortality, a 19% lower risk of CVD mortality, and a 12% lower risk of cancer mortality in fully adjusted models (Fig. 2B). Participants whose annual average residential SWR was 2000 kJ/m^2 lower had approximately 26 days of life lost over the follow-up period (15.7 years). There were only very slight differences in the results from the multiply imputed compared to complete case analysis (see **Supplementary File 3** for complete case results).

3.1. Negative control outcome

In fully adjusted models, solarium use was not associated hospitalisations due to car and motorcycle accidents (HR = 1.09; 95% CI 0.86 to 1.37). Similarly, in fully adjusted models, higher average residential SWR was not associated with hospitalisations due to car and motorcycle accidents (HR = 0.98; 95% CI 0.82 to 1.17 for a 2000 kJ/m^2 increase). This suggests that behavioural (particularly risk taking) and socioeconomic confounding is not present in the adjusted models.

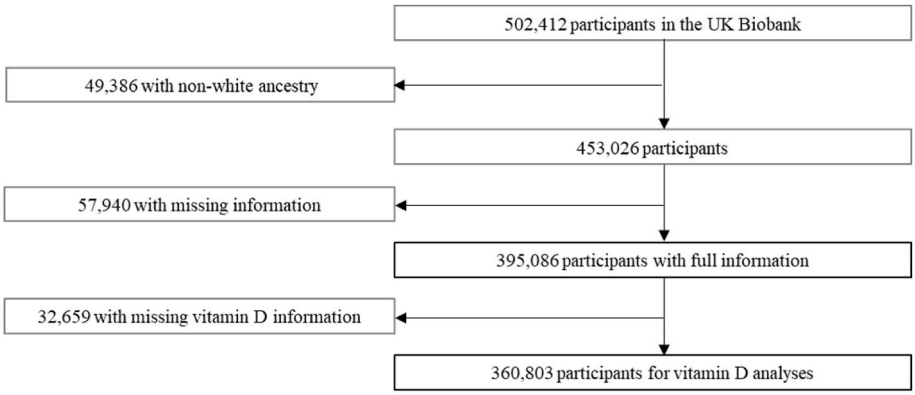

Fig. 1. Flowchart of participant information.

Table 1
Complete case participant information.

Participant characteristics	All participants (n = 395,086)	Missing (%)	Solarium non-users (n = 376,909)	Solarium users (n = 18,177)	Shortwave radiation, Q1 lowest (n = 131,429)	Shortwave radiation, Q2 (n = 131,702)	Shortwave radiation, Q3 highest (n = 131,955)
Median follow-up time, years	12.7	NA	12.7	12.9	13.3	12.3	12.6
All deaths, n	28,378	0 (0.0)	27,624	754	10,753	9284	8341
Cardiovascular disease deaths, n (% of deaths)	5663 (20.0)	0 (0.0)	5535 (20.0)	128 (17.0)	2217 (20.6)	1871 (20.2)	1575 (18.9)
Cancer deaths, n (% of deaths)	14,741 (52.0)	0 (0.0)	14,326 (51.9)	415 (55.0)	5458 (50.8)	4827 (52.0)	4456 (53.4)
Non-CVD/non-cancer deaths, n (% of deaths)	7974 (28.1)	0 (0.0)	7763 (28.1)	211 (28.0)	3078 (28.6)	2586 (27.9)	2310 (27.7)
Solarium user, %	4.6	3290 (0.7)	0.0	100.0	6.0	5.0	2.8
Average residential shortwave radiation (kJ/m^2), mean (95% CI)	9233.1 (9231.2, 9234.9)	6 (0.0)	9240.9 (9239.0, 9242.8)	9070.6 (9062.9, 9078.4)	8566.1 (8564.6, 8567.6)	9259.9 (9258.9, 9260.9)	9870.6 (9868.9, 9872.4)
Home latitude (°N), mean (95% CI)	53.1 (53.1, 53.1)	6 (0.0)	53.1 (53.0, 53.1)	53.5 (53.5, 53.5)	54.4 (54.4, 54.4)	53.1 (53.1, 53.1)	51.7 (51.7, 51.7)
Age at recruitment, %		0 (0.0)					
39 to 48	19.9	NA	19.1	37.6	20.1	18.8	20.8
49 to 54	17.9	NA	17.6	25.5	18.2	17.4	18.1
55 to 59	18.3	NA	18.4	16.9	18.5	18.1	18.3
60 to 63	20.3	NA	20.7	11.7	20.0	20.9	19.9
64 to 73	23.6	NA	24.4	8.4	23.2	24.7	22.9
Female, %	53.8	0 (0.0)	53.1	68.7	53.8	52.8	54.9
Health at baseline (fair, good or excellent)	96.1	1715 (0.4)	96.1	96.6	95.9	95.5	96.9
BMI (kg/m^2), %		1368 (0.3)					
<25	33.7	NA	33.6	35.9	32.1	31.4	37.5
25 to 30	42.8	NA	42.8	42.2	43.6	43.5	41.3
30+	23.6	NA	23.6	21.9	24.4	25.2	21.2
Adjusted IMD (Higher more deprived), mean (95% CI)	16.2 (16.1, 16.2)	11,165 (2.5)	16.0 (16.0, 16.1)	19.6 (19.4, 19.8)	17.0 (16.9, 17.1)	18.2 (18.1, 18.2)	13.4 (13.3, 13.5)
Smoking status, %		1611 (0.4)					
Never	54.5	NA	54.8	49.0	54.9	54.7	53.9
Former	35.6	NA	35.6	35.4	34.7	35.7	36.5
Current	9.9	NA	9.6	15.7	10.4	9.6	9.6
One or more days/week of vigorous physical activity (10+ minutes), %	62.5	21,605 (4.8)	62.2	69.4	60.8	61.9	64.9
Employed, %	58.5	3489 (0.8)	57.6	78.0	57.8	56.0	61.7
Age completed education, %		3688 (0.8)					
≤15	20.2	NA	20.2	19.1	23.4	23.4	13.7
16 to 18	37.8	NA	37.2	50.3	36.9	38.9	37.7
≥19	42.0	NA	42.6	30.7	39.7	37.7	48.6
History of mental health concerns, %	34.0	2947 (0.7)	33.6	43.7	34.9	34.9	32.4
Risk taking behaviour, %	26.2	15,781 (3.5)	25.8	35.0	25.4	25.4	27.8

[a]CVD = cardiovascular disease; BMI = body mass index; IMD = index of multiple deprivation; Q1 = first quartile (lowest quartile of shortwave radiation); Q2 = second quartile; Q3 = third quartile (highest quartile of shortwave radiation).

3.2. Melanoma and non-skin cancer incidence and mortality

In fully adjusted models, there was some evidence of a higher melanoma incidence for solarium users and those who resided at locations with higher average residential SWR (HR = 1.17; 95% CI 0.97 to 1.41 and HR = 1.10; 95% CI 0.96 to 1.25 for a 2000 kJ/m^2 increase). However, the associations were not statistically significant. In addition, solarium use and average residential SWR were not associated with melanoma mortality (HR = 0.84; 95% CI 0.43 to 1.64 and HR = 1.02; 95% CI 0.71 to 1.49 for a 2000 kJ/m^2 increase).

In fully adjusted models, solarium use was not associated with non-skin cancer incidence (HR = 1.02; 95% CI 0.97 to 1.07) but solarium use was associated with lower risk of non-skin cancer mortality (HR = 0.86; 95% CI 0.78 to 0.94). Higher average residential SWR was associated with lower non-skin cancer incidence (HR = 0.96; 95% CI 0.93 to 0.99) and lower non-skin cancer mortality (HR = 0.88; 95% CI 0.83 to 0.93). Results are displayed in Fig. 3.

4. Discussion

We find that UK Biobank participants who use solariums and who live at locations with higher annual average SWR have a lower risk of all-cause, CVD and cancer mortality. Solarium users also have a lower risk of non-CVD/non-cancer mortality. These results are consistent for two very different types of exposure, with adjustment and confirmation of appropriate adjustment through testing of a negative control outcome.

These results add to the growing literature suggesting that UV exposure is associated with lower mortality. Results from prospective cohort studies in Sweden, at a similar latitude to the UK, find an inverse relationship between more active sun-seeking behaviours and all-cause mortality (Lindqvist et al., 2014; Yang et al., 2011) and inverse dose-dependent relationships between CVD, non-CVD/non-cancer and cancer mortality (Lindqvist et al., 2016). Several studies have also suggested an association between latitude and mortality, whereby living closer to the equator was associated with higher life expectancy, lower

Table 2
Predicted serum 25(OH)D levels by ultraviolet exposure. Adjusted solarium use models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, body mass index, smoking status, physical activity, average residential shortwave radiation, history of mental health concerns, health at baseline, risk-taking behaviour, and vitamin D supplementation. Adjusted average residential shortwave radiation models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, smoking status, physical activity, sun-seeking behaviour, risk-taking behaviour and vitamin D supplementation. N = 453,026. Multiply imputed results.

Ultraviolet exposure	Example location (latitude, longitude)	Vitamin D serum, nmol/L (95% CI)	
		Age-adjusted	Fully adjusted
Solarium use			
Solarium non-user	NA	48.8 (48.7, 48.8)	48.8 (48.7, 48.8)
Solarium user	NA	66.4 (66.1, 67.0)	66.9 (66.6, 67.2)
Average residential shortwave radiation (kJ/m^2)			
8328	Glasgow (−4.25°, 55.85°)	47.1 (47.0, 47.2)	47.1 (47.0, 47.2)
9516	Nottingham (−1.15°, 52.95°)	50.4 (50.3, 50.4)	50.4 (50.3, 50.4)
10,295	Cornwall (−5.03°, 50.25°)	52.5 (52.4, 52.6)	52.5 (52.4, 52.6)

CVD mortality and lower mortality from several cancers (Grant, 2010; Borisenkov, 2011; Müller-Nordhorn et al., 2008).

Solarium use was not associated with non-skin cancer incidence but solarium use was associated with lower non-skin cancer mortality. Higher annual average SWR was associated with lower non-skin cancer incidence and mortality, with a larger effect on mortality than on incidence. One possible explanation for the difference between non-skin cancer incidence and mortality is that for participants with UV exposure and who develop cancer, cancer prognosis is better. Another possible explanation is that UV-linked incidence from specific cancer types (with different survival rates) vary. Previous observational research found inverse relationships between solar UV exposure and cancer mortality in multiple sites, including the bladder, colon, Hodgkin lymphoma, prostate, stomach, and breast (Boscoe and Schymura, 2006). In a large randomised controlled trial (the VITAL study), vitamin D supplementation was not associated with cancer incidence but there was reduced cancer mortality in models that accounted for latency, by excluding the first two years (HR = 0.75; 95% CI 0.59 to 0.96) (Manson et al., 2020).

There was some evidence that participants who were solarium users and who resided at locations with higher annual average SWR had higher melanoma incidence (the associations were not statistically significant). However, there was no evidence that the UV exposures were associated with melanoma mortality. The links between sun exposure and melanoma development and melanoma mortality are complex. Over-diagnosis of melanoma may be important, with incidence previously linked to scrutiny but not environmental UV (Adamson et al.,

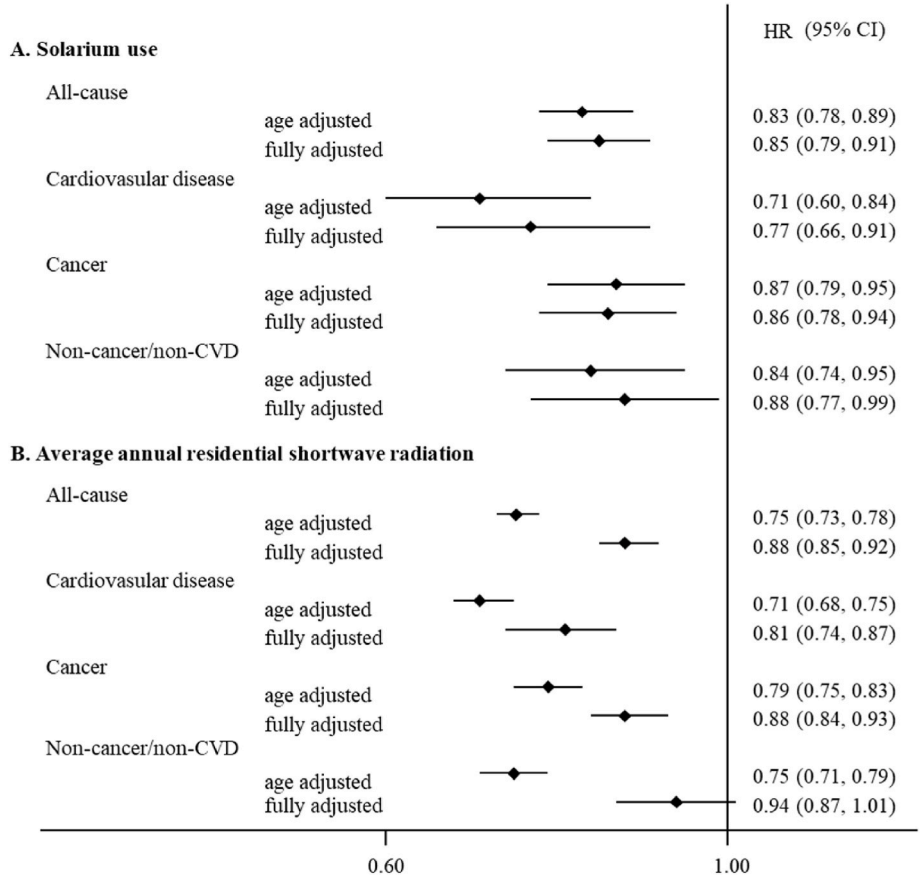

Fig. 2. A. Associations between solarium use and mortality. Fully adjusted models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, body mass index, smoking status, physical activity, average residential shortwave radiation, history of mental health concerns, health at baseline and risk-taking behaviour. **B.** Associations between average residential shortwave radiation and mortality. The hazard ratio represents a 2000 kJ/m^2 increase in shortwave radiation. Fully adjusted models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, smoking status, physical activity, sun-seeking behaviour, and risk-taking behaviour. N = 453,026. Multiply imputed results.
[a]CVD = cardiovascular disease.

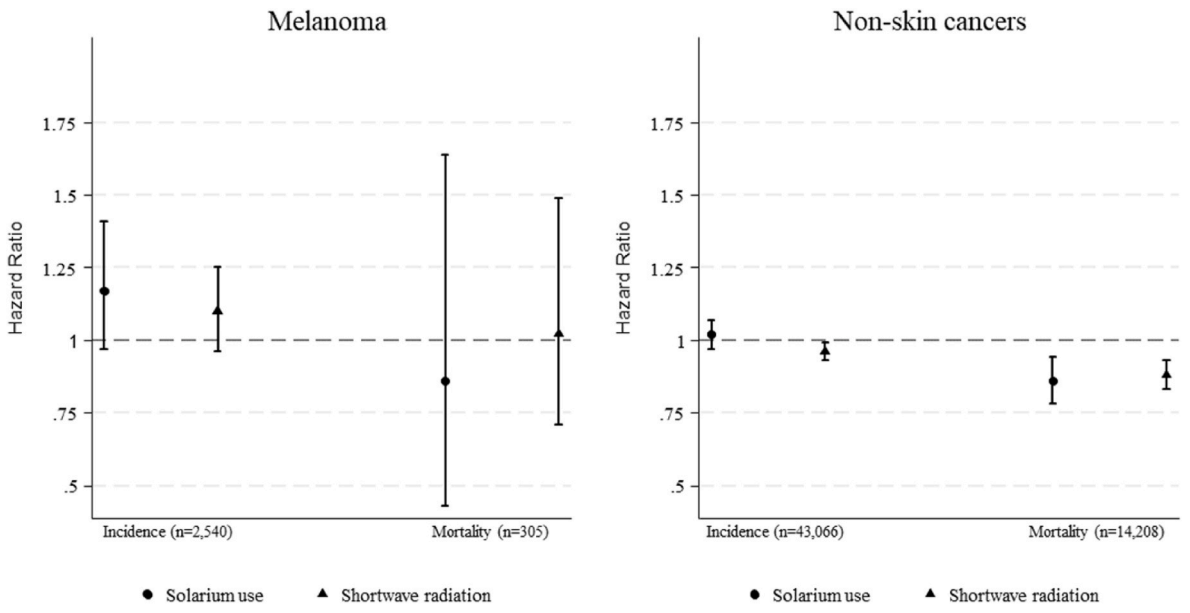

Fig. 3. Associations between ultraviolet exposures, non-skin cancer and melanoma incidence and mortality. Adjusted solarium use models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, body mass index, smoking status, physical activity, average residential shortwave radiation, history of mental health concerns, health at baseline, and risk-taking behaviour. Adjusted average residential shortwave radiation models included age, sex, employment status, age completed education, adjusted Index of Multiple Deprivation, smoking status, physical activity, sun-seeking behaviour, and risk-taking behaviour. N = 453,026. Multiply imputed results.

2022). In the most recent WHO classification of melanoma, the most common form of melanoma is the Low Cumulative Sun Exposure melanoma (Elder et al., 2020). These melanomas are typified by the absence of signs of chronic sun exposure and predominantly occur on intermittently sun exposed body sites. Most melanoma is a disease of intermittent burning sun exposure, particularly in childhood. Outdoor workers have no increase in melanoma incidence compared to indoor workers (Maduka et al., 2023). Multiple studies have correlated higher vitamin D levels -a biomarker for chronic sun exposure-with reduced melanoma mortality (Tsai et al., 2020). Evidence suggests that patients with in-situ melanoma have an increased but low risk of melanoma mortality and live longer than people in the general population (Patel et al., 2023). Studying the relationship between UV exposure and observed melanoma incidence may not be a good indicator of the relationship between UV exposure and melanoma mortality.

In this study we provide evidence that the risk of cancer deaths is reduced with UV exposure but in Table 1, the higher UV exposed groups also have a greater concentration of cancer deaths. This is the result of a competing risk situation, where life expectancy has been increased for the higher UV exposed groups, due to a reduction in CVD deaths, but death is of course just postponed and the most common cause of death, cancer, becomes more frequent.

It is commonly hypothesised that UVB-mediated vitamin D production is the causal mechanism between exposure to sunlight and better health outcomes. However, several Mendelian randomisation studies and clinical trials do not support the beneficial role of vitamin D and vitamin D supplementation on several extra-skeletal health outcomes (Pilz et al., 2016; Manson et al., 2019). A recent review of several clinical trials found that providing vitamin D supplementation to vitamin D-replete adults did not prevent cancer, CVD events, or the progression of type 2 diabetes (Bouillon et al., 2022). In the recent Australian D-Health trial, which was not included in the review, administering vitamin D did not reduce mortality compared to the placebo group (Neale et al., 2022). After excluding the first two years of follow-up in an exploratory analysis, participants in the vitamin D group had a higher hazard of cancer mortality. Vitamin D supplementation showed some promise in reducing the incidence of major CVD events, but the absolute risk difference was small and the association did not reach statistical significance (Thompson et al., 2023). Solar UVB may provide different health benefits from vitamin D supplements. UVB radiation has been shown to activate the central neuroendocrine system to regulate global homeostasis independent of vitamin D synthesis (Slominski et al., 2018).

Other pathways may be important. UVA exposure mobilises NO reserves in the skin and causes vasodilatation, which reduces blood pressure (Liu et al., 2014). Research has demonstrated that sun exposure is associated with reduced risk of hypertension in a dose-dependent manner (Lindqvist et al., 2021). High blood pressure and hypertension are risk factors for CVD and mortality (Brunström and Carlberg, 2018). NO also regulates the NLRP3 inflammasome, which plays a key role in the inflammatory response (Mao et al., 2013). Dysfunction of the NLRP3 inflammasome can contribute to chronic inflammation, which is a key feature for the development and progression of many cancers and is associated with cardiovascular disease, metabolic disorders and infections (Sharma and Kanneganti, 2021).

The solarium use variable may capture other sun-seeking behaviours. Studies suggest that indoor tanners engage in more active sun-seeking behaviours, such as intentional sun exposure (especially at peak hours), opting for less protective clothing, participating in more outdoor hobbies and accumulating more intensive lifetime sun exposure (Suppa et al., 2019). Measured vitamin D levels support this behavioural finding in our cohort. Therefore, the protective effect of solarium use on mortality may not be an effect of solely solarium use but of active sun-seeking behaviours more broadly. SWR is highly correlated with UVA ($r^2 = 0.99$) and UVB ($r^2 = 0.92$) radiation in a linear manner, (Deng et al., 2023) so the average residential SWR variable captures residential exposure to both UVA and UVB radiation. The protective effect of SWR may come from either UVA or UVB radiation, or a combination of the two.

A strength of our study is that it used a large sample of individuals followed up over time. Participants were linked to mortality registry data, which minimises the potential for measurement error and enhances the accuracy of mortality outcomes. We used multiple UV exposures with different confounding structures and found similar patterns of protection from mortality, suggesting that the relationships are not spurious. We also used a negative control outcome (hospitalisations due to car or motorcycle accidents) that the UV exposures have no reported

or plausible effect on but are subject to the same unobserved confounding as the mortality outcomes. There was no association between the solarium use or average residential SWR and the negative control outcome, suggesting that unmeasured confounding is not biasing the results.

There are several limitations to our study. The results are based on observational data, which may suffer from residual confounding. Additionally, UK Biobank participants are not representative of the UK population and there is evidence of a healthy volunteer selection bias (Fry et al., 2016). However, representativeness is not necessary for causal inference (Rothman et al., 2013). Selection can induce collider bias in cohort studies, whereby participation is influenced by the exposure and the outcome, leading to biased estimates of associations. However, solarium use and average residential SWR are not likely to influence participation or retention in the cohort to a large degree, especially compared to other exposures such as reduced cognitive ability. The follow-up time was relatively short, reducing the number of deaths and therefore the power of the study. Solarium use was collected through a questionnaire, which asked respondents how many times a year they use a solarium or sun lamp. Reporting bias and social desirability bias are a concern. The average residential SWR variable does not capture travel beyond their residential location, which could lead to variation in UV exposure. Despite this, there was a dose-response relationship between higher average residential SWR and vitamin D, indicating that higher average residential SWR is a determinant of higher UV exposure at UK latitudes. Another limitation is that information was collected from participants during their baseline assessment visits and participants' behaviour may have changed throughout the study. We used estimates of SWR from 2008 which may be different from other years. However, surface shortwave radiation over Europe was relatively stable between 2000 and 2012 (Sanchez-Lorenzo et al., 2015). Additionally, the annual average of SWR measurements between years are highly correlated (e.g., SWR measures in 2008 and in 2014 around the residential location of UK Biobank participants, $r_p = 0.92$). illustrating the relative temporal stability of this UV exposure.

Current public health messaging emphasises the hazards of UV exposure for skin cancer development. However, our study adds to growing evidence that the benefits of UV exposure on mortality outweigh the risks in low sunlight environments. Tailoring public health advice to weigh both hazards and benefits of UV exposure may reduce disease burden and increase life expectancy in the population countries with low sunlight. Notably, the Australian Skin and Skin Cancer Research Centre released a position statement that recommends balancing the risks and benefits of sun exposure (Australian Skin and Skin Cancer Research Centre, 2023). Policy agendas focusing on designing neighbourhoods to promote active living may synergistically benefit population health through increased physical activity and higher UV exposure. Future studies that investigate the independent effects of UVA and UVB exposure on health outcomes, the optimal amount of UV exposure to achieve health benefits and clinical trials of personal UV lamp use are warranted.

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Appendix A. Supplementary data

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