Improving Assessment of Lifetime Solar Ultraviolet Radiation Exposure in Epidemiologic Studies: Comparison of Ultraviolet Exposure Assessment Methods in a Nationwide United States Occupational Cohort

Mark P. Little¹ *, Zaria Tatalovich², Martha S. Linet¹, Michelle Fang¹, Gerald M. Kendall³, Michael G. Kimlin⁴

¹Radiation Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, NIH, DHHS, Bethesda, MD 20892-9778, USA
²Surveillance Research Program, Division of Cancer Control and Population Sciences, National Cancer Institute, NIH, DHHS, Bethesda, MD 20892-9778, USA
³Cancer Epidemiology Unit, University of Oxford, Richard Doll Building, Old Road Campus, Headington, Oxford OX3 7LF, UK
⁴NHMRC Centre for Research Excellence in Sun and Health, University of the Sunshine Coast, Queensland 4556, Australia

*Address for correspondence: Mark P. Little, D.Phil., Radiation Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, NIH, DHHS, 9609 Medical Center Drive, Bethesda, MD 20892-9778

E-mail: mark.little@nih.gov

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Abstract

Solar ultraviolet radiation is the primary risk factor for skin cancers and sun-related eye disorders. Estimates of individual ambient ultraviolet irradiance derived from ground-based solar measurements and from satellite measurements have rarely been compared. Using self-reported residential history from 67,189 persons in a nationwide occupational US radiologic technologists cohort, we estimated ambient solar irradiance using data from ground-based meters and noontime satellite measurements. The mean distance-moved from city of longest residence in childhood increased from 137.6 km at ages 13-19 to 870.3 km at ages ≥65, with corresponding increases in absolute latitude-difference moved. At ages 20/40/60/80, the Pearson/Spearman correlation coefficients of ground-based and satellite-derived solar potential ultraviolet exposure, using irradiance and cumulative radiant-exposure metrics, were high (=0.87-0.92). There was also moderate correlation (Pearson/Spearman correlation coefficients=0.51-0.60) between irradiance at birth and at last-known address, for ground-based and satellite data. Satellite-based lifetime estimates of ultraviolet radiation were generally 14-15% lower than ground-based estimates, albeit with substantial uncertainties, possibly because ground-based estimates incorporate fluctuations in cloud and ozone, which are incompletely incorporated in the single noontime satellite-overpass ultraviolet value. If confirmed elsewhere, the findings suggest that ground-based estimates may improve exposure-assessment accuracy and potentially provide new insights into ultraviolet-radiation-disease relationships in epidemiologic studies.
Introduction

Exposure to solar ultraviolet radiation (UVR), and specifically ultraviolet-B (UVB) radiation, is the primary risk factor for basal cell carcinoma (BCC), squamous cell carcinoma (SCC) (1, 2), melanoma (2), and cataract (3, 4), but may be protective of other cancers (5-7). Ground-based UVR estimates, in particular those using Robertson-Berger meters, have been used in studies of melanoma (8) and other skin cancers (9). More recently, the AVerage daily total GLObal solar radiation (AVGLO) estimates, interpolated by Tatalovich et al (10) using total solar radiation data from the National Solar Radiation Database (NSRAD) of the Department of Energy (DOE), have been used to assess risk of skin cancer in a large multi-center cohort of women (11) and melanoma in US Surveillance, Epidemiology and End Results data (12). National Aeronautics Space Administration (NASA) Total Ozone Mapping Spectrometer (TOMS) satellite-based UVR data has been used to study breast, thyroid and skin cancer in the US Radiologic Technologists (USRT) (13-15), and similar studies using this metric have been conducted of melanoma in residents of Seattle-Puget Sound (16) and in the US Nurses Health Study (NHS) (17).

The two main assessment approaches used to estimate individual lifetime ambient ultraviolet irradiance in epidemiologic studies, i.e., estimates derived from ground-based solar measurement stations such as AVGLO and from satellite measurements such as NASA TOMS, have rarely been compared. In the current study we compared findings using ground-based and satellite-based assessments to estimate ambient lifetime UVR exposure in a single, nationwide population-based US cohort using self-reported, questionnaire-derived lifetime residential history. We examined correlations between these two types of ambient measurements of UVR, considering the metrics of UVR irradiance and cumulative UVR radiant exposure, in the US Radiation Technologist cohort. Because of the importance of early life exposure for cancer in relation to UVR exposure
(2), it is clearly highly desirable to estimate UVR at this age if possible. Nevertheless, if early-life and later-life UVR exposures were found to be highly correlated then these later exposures might prove acceptable surrogates. In the light of this, we assessed how well estimates of UV correlate from birth over life, considering the residential mobility of the USRT population. Connected with this we also determined the residential mobility of the population, in particular assessing the average geodesic distance moved and mean latitude-difference from location of residence in childhood over life.

**Materials and Methods**

**Overview – UVR Exposure Metrics**

Two candidate exposure metrics are suggested *a priori*, namely UVR irradiance (in units of W m\(^{-2}\)), a measure of UVR power density on a surface, or cumulative UVR radiant exposure (in units of J m\(^{-2}\)), which is proportional to cumulative solar UVR energy deposition on a surface over a period of time. These are standard measures of ambient UVR exposure recommended by the Commission Internationale de l’Eclairage (CIE) (International Commission on Illumination) (18). Both measures are derived from two separate solar radiation datasets, one ground based, AVGLO, the other satellite-based, TOMS. As part of the analysis we also assessed the average geodesic distance moved from location of residence in childhood over life as many studies use location of residence as a proxy for lifetime sun exposure. We provide more details below.

**Exposure Assessment Methods**

**Description of UVR Exposure Assessment Estimation Approaches**

The National Solar Radiation Database (NSRAD) produced by the National Renewable Energy Laboratory (NREL) under the US Department of Energy’s Resource Assessment Program the
largest ground-based network in the US, containing statistical summaries computed from hourly measurement data (with some infilling for missing data) for 239 US radiation stations for the period 1961-1990 (see Figure 1), including monthly, yearly, and 30-year average global solar radiation measures. Tatalovich et al (10) incorporated AVGLO measures, latitude, longitude, and elevation from a 30 arc-second Digital Elevation Model into the ANUSPLIN spline-interpolation algorithm to deliver estimates of potential solar ambient irradiance (~250-2700 nm) at 1 km² resolution in the US. AVGLO used 30-year averages of ANUSPLIN spline-interpolated ground solar ambient irradiance measurements after initial analysis of temporal variability that showed no statistically significant difference in between the three 10-year periods embedded in the 1961-1990 data summaries for each radiation station (10). Prior to interpolation of UV estimates, AVGLO measures of total solar ambient irradiance (~100-3000 nm, corresponding to the range ultraviolet C - infrared B (19)) have been validated as a proxy for UV, because spatial distribution of AVGLO data was larger and their quantity more complete than any UV database available at the time. The UV measures used for comparison with AVGLO consisted of monthly-averaged UVB data (~280-315 nm (2)) covering the period 1995-2004, collected from 7 Surface Radiation Budget Network (SURFRAD) measurement stations of the National Oceanic and Atmospheric Administration (NOAA) (near to certain of the AVGLO measurement sites) in 7 climatologically diverse states (Montana, Colorado, Illinois, Mississippi, Pennsylvania, Nevada, and South Dakota) (10). The UVB flux employed by Tatalovich et al for the SURFRAD data (10) was the total UVB convoluted with the erythemal action spectrum (i.e., weighted to that part of the UVB spectrum responsible for sun burns on human skin (erythema) and DNA damage). As shown by Tatalovich et al (10) AVGLO was highly correlated with SURFRAD-based UVB irradiance (280-315 nm (2)) and was therefore used as a proxy for UV in subsequent computational analysis, resulting in 1 km² estimates
of potential UV ambient irradiance across the Continental US. For the current study, these estimates were aggregated to zip-codes of historical residences of persons in the USRT study cohort.

>Figure 1<

The Total Ozone Mapping Spectrometer (TOMS) database, which is maintained by the US National Aeronautics and Space Administration (NASA) (20), is a satellite based system that uses measurements of atmospheric ozone and cloud reflectivity (21) to estimate average noontime ambient UVR irradiance, measured as the irradiance (in mW m$^{-2}$ nm$^{-1}$) (22), in a 1.25º longitude x 1º latitude grid (approximately 110 x 110km) or 69 x 69 miles) grid. Satellite-based annual estimates of daily noon-time UVR per location have varied little since the start of measurements in the late 1970s (23), thus, daily noon-time estimates were averaged over years 1978–1993 for each location to construct stable estimates. We used the TOMS UVR irradiance estimates at the wavelength of 305 nm, in the middle of the UVB band.

**Scaling exposure metrics to estimate cumulative ambient UVRs**

AVGLO is an estimate of total direct and diffuse solar daily radiation received on a horizontal surface, in units of Wh m$^{-2}$ (10). We scaled this to the CIE unit of average UVR irradiance (with units of W m$^{-2}$) by dividing by 24 (number of hours in a day) and the ratio of total solar irradiance (which includes infrared, visible and UVR radiation) to total UVR irradiance, which we took to be about 25 (24). [As stated “In terms of energy, sunlight at Earth's surface is around ... 3 to 5 percent ultraviolet (below 400 nm)” (24). The 25 was derived as 100/4, where 4 is the midpoint of this interval 3-5. A similar estimate, 100/5 = 20 can be derived from figures given elsewhere (2).] From the NASA TOMS UVR estimate of average noontime ambient UVR irradiance (in mW m$^{-2}$ nm$^{-1}$) in the middle of the UVB spectrum (305 nm) we estimated the average UVR irradiance (in W m$^{-2}$).
2), for the full width of the UVR spectrum (280-400 nm), by dividing by 1000, to convert from mW m\(^{-2}\) nm\(^{-1}\) to W m\(^{-2}\) nm\(^{-1}\), and multiplying by the product of 35 (the width in nm of the UVB frequency band (280-315 nm) (24)), the ratio of average UVR (280-400 nm) ambient irradiance to average UVB (280-315 nm) ambient irradiance, which we assumed to be about 20 (2), the average proportion of the day that is comprised of sunshine (7/24), and the ratio of average (over hours of sunshine) to noontime peak UVR (assumed to be about 0.5, because it is approximately a triangular distribution with peak at noon, decaying to near 0 (25)).

For both measures, cumulative radiant exposure (in units of J m\(^{-2}\)) up to a given age was obtained by summing the average irradiance at a given calendar year of age multiplied by the length of the year in seconds (3600 x 24 x 365.2425). Further details are given in Appendix A.

Assessment of geodesic distance moved

The shortest distance between two points on the Earth’s surface is given by the geodesic (great circle) distance between the locations. If the shape of the Earth is ellipsoidal, which it is to high degree of accuracy (indeed there is only a very slight departure, as suggested by the 0.3% difference in major and minor axes, from a perfectly spherical shape), this can be derived using the Vincenty algorithm (26). The latitude and longitude and longitude of the two locations are specified.

Application of Exposure Assessment Measurement Approaches and Metrics for Assessing Cumulative Exposure to a Nationwide U.S. Population-Based Cohort

Overview description of USRT cohort

The USRT study population, cohort follow-up, and ionizing radiation dosimetry methods have been described elsewhere (27-29) (see also www.radtechstudy.nci.nih.gov). Briefly, the US National Cancer Institute, in collaboration with the University of Minnesota and the American
Registry of Radiologic Technologists (ARRT), has studied cancer incidence and mortality among 146,022 (106,953 women) US radiologic technologists who were certified for at least two years during 1926-1982 (30, 31). Active follow-up was conducted through yearly review of ARRT records on re-certification. Inactive registrants were linked with national and other databases, including the Social Security Administration to determine vital status and the National Death Index (NDI-Plus) to obtain cause of death for those known or presumed to be deceased. Four questionnaires were administered during 1983–1989, 1994–1998, 2003–2005, and 2012-2014 to collect information on health outcomes (including self-reports of cataract and cataract surgery in all but the first questionnaire), work history, demographic and lifestyle characteristics, and medical histories. The third and fourth questionnaires were sent only to cohort members who had responded to the first and/or the second questionnaire.

**UVR exposure assessment for the USRT**

On the third questionnaire (administered during 2003-2005) questions were asked about the lifetime residential history of the technologists. The technologists were asked to specify which city they had lived in longest for various age groups (<13, 13-19, 20-39, 40-64, ≥65). These cities of longest residence by age group were used in conjunction with independent databases of average solar exposure and average noontime ultraviolet exposure to derive measures of total UVR (UVA + UVB) ambient irradiance. The latitude and longitude of the respective cities were also assessed.

The USRT subcohort included in the current evaluation includes all those who answered the third questionnaire with enough detail on residential history to ascertain location in a manner that enabled linkage with NASA TOMS and AVGLO UVR/solar ambient irradiance data. There were 69,085 persons with available AVGLO solar ambient irradiance estimates, and of these 67,189 also had NASA TOMS UVR estimates.
Statistical Methods

Table 1 summarizes the mean, minimum, maximum, 1st and 3rd quartiles of the geodesic (great circle) distance between the centroid of the city of longest residence at ages 0-12 and the centroid of the city of longest residence at subsequent ages (13-19, 20-39, 40-64, 65+) (the age intervals determined by the corresponding intervals of city of longest residence by age groups specified in the USRT third questionnaire), also the mean absolute latitude difference between these locations in degrees. For each subsequent age group we only give the distance Moved and absolute latitude difference statistics for the subsample where the latitude and longitude are known for this age group and for ages 0-12 years.

Table 2 reports the mean, minimum, maximum, 1st and 3rd quartiles of the UVR irradiance and cumulative UVR radiant exposure corresponding to the ages 20, 40, 60 and 80. Again, we only calculate these quantities for the eligible technologists, so for age 80 only those who are older than this age at the time of answering the third questionnaire, and similarly for the other age groups. Figure 2 shows the geographical variation in the ratio of NASA TOMS to AVGLO irradiance.

Table 3 reports the Pearson (32) and Spearman-rank (33) correlation coefficients between the NASA TOMS- and AVGLO-derived estimates of UVR irradiance and cumulative UVR radiant exposure by age group. The Pearson (32) and Spearman-rank (33) correlation coefficients are standard measures of association, the latter a non-parametric measure of association that is favored when there are uncertainties as to the precise probabilistic form of the underlying distribution. Figures 3 and 4 display this information in graphical form. Table 4 computes the Pearson and Spearman-rank correlation coefficients between the NASA TOMS-derived UVR
irradiance at birth and at the time of the third questionnaire, also the analogous correlation using AVGLO-derived UVR irradiance. Figure 5 displays this data in graphical form.

All statistics and graphs were produced using R (34) and Excel (35).

Data accessibility statement

All data used can be obtained from MPL on request.

Results

Table 1 demonstrates that the mean distance moved from city of longest residence in childhood (ages 0-12 years) progressively increased from 137.6 km at ages 13-19 years to 870.3 km at ages of 65 years and older. However, the median geodesic distances moved were much less than the mean, ranging from a mean of 57.7 km at ages 20-39 to 193.8 km at ages 65 and above. Table 1 shows that the mean difference in latitude moved from city of longest residence in childhood (ages 0-12 years) decreased from -0.03 degrees at ages 13-19 years to -0.76 degrees at ages 65 and older, suggesting that with increasing age people moved nearer the equator. The mean absolute latitude difference moved from city of longest residence in childhood (ages 0-12 years) increased from 0.48 degrees at ages 13-19 years to 1.21 degrees at ages of 65 years and older. However, the median, and indeed 75%, latitude differences were always 0.

Table 2 demonstrates that there were 67,189 persons with sufficient information on location to derive both AVGLO-based average solar ambient irradiance and NASA TOMS-derived average noontime UVR irradiance by year of age. However, the number of technologists who responded to the third questionnaire, and so furnished information on lifetime exposure up to that point diminished with age, so that by age 80 there were only 955 technologists contributing information.
Table 2 also demonstrates the range of UVR irradiance derived from NASA TOMS and from AVGLO data. As can be seen the UVR irradiance was approximately constant by age within this cohort of technologists, but cumulative UVR radiant exposure increased with age. The mean UVR irradiance and cumulative UVR radiant exposure were generally about 14-15% less in the NASA than in the AVGLO data, so for example at age 60 the mean cumulative UVR radiant exposure was 1.134 MJ cm\(^{-2}\) in the NASA data, compared with a mean estimate of 1.325 MJ cm\(^{-2}\) in the AVGLO series (Table 2). The ratio of NASA TOMS to AVGLO irradiance tended to be slightly higher in the more southerly parts of US (Figure 2).

Table 3 and Figures 3 and 4 demonstrate that at all ages (20, 40, 60 and 80 years of age) Pearson and Spearman correlations of average UVR irradiance (mW m\(^{-2}\)) and cumulative radiant exposure (MJ cm\(^{-2}\)) were uniformly high, between 0.894-0.915 for the UVR irradiance, and 0.872-0.913 for the cumulative UVR radiant exposure. Spearman-rank correlation coefficients had very similar, or slightly higher values than the Pearson correlation coefficients.

Table 4 and Figure 5 demonstrate that there was still appreciable correlation between the irradiance at birth and at the last known residential location, at the time of the third questionnaire, 0.512 for the NASA TOMS data, and 0.547 for the AVGLO data. The analogous Spearman correlation coefficients were slightly higher, 0.587 and 0.600 respectively.
Discussion

This is one of the first studies to compare the two major UVR estimation methods, using ground-based and satellite-based estimates in a large nationwide cohort of persons living at a wide range of latitudes. We have shown that AVGLO and TOMS estimates of UVR were very highly correlated, both for irradiance and cumulative radiant exposure. This is perhaps remarkable, given that AVGLO estimates are fundamentally long-term daily averages of ground-based total ambient solar irradiance measurements assessed for a 1 km x 1 km grid, whereas the NASA TOMS data were long-term averages of noontime UV estimates using a rather coarser, approximately 110 km x 110 km grid, although as we discuss later the solar radiation variation within even the 110 km x 110 km grid is not substantial. There was also reasonably high correlation between the irradiance at birth and the last known irradiance, at the time of the third questionnaire, for both the AVGLO and TOMS UVR measures. The NASA-derived satellite-based estimates were on average below those in the AVGLO ground-based series, by between 14-15% (Table 2). The present study is also one of the first that has attempted to quantify distance and absolute latitude difference between birth and late-in-age addresses and thus determine whether the late-in-age address is a good proxy for birth address. We found that in this cohort, the late-in-life address would not result in too much loss of accuracy. Indeed, the correlation of UVR at birth and at time of third questionnaire may be explained by the relatively moderate amount of movement from city of residence in childhood to city of longest residence in adulthood, which on average was between 500-700 km, with somewhat smaller movement, on average about 140 km, from childhood to late childhood/early adulthood (ages 13-19) (Table 1). The latitude differences were similarly modest, with mean difference no more than 1.2 degrees, and more than 75% of the cohort did not shift in latitude over the course of life (Table 1). Another novel feature was use of newer metrics of UVR exposure based on CIE-
recommended quantities (18), specifically irradiance and cumulative radiant exposure, in contrast to the metric of average lifetime exposure that has been employed in some epidemiological studies (13, 14).

The correlations that we found between AVGLO and TOMS estimates of UVR very likely reflect the large degree of correlation that there is between various parts of the solar spectrum. In particular the ratio of total solar exposure irradiance to total UVR irradiance has been estimated to lie in the range 11 (36) to 20-30 (24). At a fixed geographic location there is little variation in the percentage of total solar ambient irradiance accounted for by UVR over the course of a year (37, 38). There is only slight variation in the proportion of solar ambient irradiance that is accounted for by UVR with latitude, so the that lower the latitude (i.e., the nearer the equator) the lower the proportion of total solar ambient irradiance that is UVR (37). However, the ratio of UVA/UVB is known to vary slightly with latitude (39), and more substantially over the course of a day, although not by much in the middle part of the day, when most potential exposure occurs (40).

The still appreciable correlation between UVR ambient irradiance at the last point known, at the third questionnaire, and location in early childhood (Table 4, Figure 5), suggests that, at least in this occupational cohort, that there would not be too much loss in using current location for the purposes of estimating UVR at earlier points of life. Nevertheless, in general the early-life UVR exposures are sufficiently different from later-life UVR exposures in many groups that the differential effects of UVR exposure can be clearly delineated as risk factors for melanoma, BCC and SCC (2, 41, 42). However, the changes in personal sun exposure with age may result in weaker correlations of personal (rather than ambient) exposure.

The relatively small geographic variation in residence over the course of childhood was consistent with what has been observed in childhood in the UK (43). A review of mothers who
moved during pregnancy found generally low mobility rates, which declined with increasing age, parity and socioeconomic status (44). In our study the median distance moved was very much smaller than the mean (Table 1), indicating the disproportionate effect of those who moved long distances. Indeed, until the oldest age group, the mean distance moved from location of residence in early childhood was greater than or comparable with the third quartile distance moved.

The NASA TOMS data used here uses a spectral weighting function $W$ that approximates the wavelength-dependent sensitivity of Caucasian skin to erythema-causing radiation (45), using the model proposed by McKinlay and Difffey (46). The AVGLO solar ambient irradiance data employed here is unweighted by any erythemal action spectrum (10). The erythemal weighting model used for the TOMS data is to some extent arbitrary and to this extent so must also be the TOMS UVR estimates.

Strengths of the cohort and our analysis is that ours is one of few studies that have life-course residential history. In many cohorts where UVR has been assessed over the lifetime, a single exposure metric, often average annual ambient UVR, is considered. In particular this is the case in recent analyses of the USRT (13, 14), in a cohort of residents of Seattle-Puget Sound (16), and in analysis of the NHS (17). Older analyses of the USRT used Robertson-Berger meter assessments of UVR (47, 48), as also did an older analysis of the NHS (9). Robertson-Berger meters measure erythemally-weighted UVR (49). In contrast the AVGLO measure employed here estimates erythemally-unweighted total solar exposure (10). In none of these studies was there a comparison of different UVR exposure metrics. The present study has evaluated two separate estimates of UVR, derived from satellite and ground-based data and considered two different measures, irradiance and cumulative radiant exposure, within each dataset, as recommended by the CIE (18).
It is not clear which of irradiance and cumulative radiant exposure is necessarily the better measure; this will likely differ by the particular disease endpoint being considered.

A potential weakness of the data we used is that it relied on self-reported city of longest residence by age group (0-12, 13-19, 20-39, 40-64, 65+). As such there will inevitably be some misclassification of exposure, as people could move residence within these age groups. It is also possible that they might have mis-recalled city of longest residence, although this is unlikely, except perhaps for the youngest age groups. Supporting this, assessment of reliability of recall of residential history in other studies suggests that short-duration moves may well be mis-remembered, although longer duration moves are more reliably recorded (50, 51). In any case, this will affect both sets of estimates used here, and is unlikely to substantially affect correlations between them. The metrics all focused on ambient estimates. There is no account taken of behavior, for example hours of sun exposure. This information was collected on the questionnaire but we judged that it was probably less reliable than the location data, and so no use was made of it here. A study of 6-month recall of time spent outdoors with a contemporary activity diary in the USRT found reasonable agreement of weekday activity, but less good agreement with respect to weekends, when UVR exposure would be expected to be greater (52). Our calculations of average UVR derived from the NASA TOMS measurements were based on an assumed ratio of UVR to UVB of about 20 (2), and assumed an approximately triangular diurnal distribution of UVR (25) (see the Methods and Appendix A for more details). These approximations are likely to be reasonable in aggregate, although there are known to be diurnal variations of the ratio of UVR to UVB, in a manner that will also depend on latitude (53, 40). It is perhaps remarkable that, as can be seen from Table 2, the mean estimates of total UVR that we derived from the NASA satellite-based measurements are reasonably close to those derived from the AVGLO ground-based
measures of total solar ambient exposure, whether using UVR irradiance or cumulative UVR radiant exposure. A possibly limiting feature of the USRT as an occupational cohort is that residential mobility may not be as generalizable as in other occupational groups to the general US population, because work authorization/certification is tied to state of residence.

In summary our study suggests that AVGLO-derived UVR data is highly correlated with NASA TOMS data, although AVGLO was 14-15% higher. The modest difference between satellite-based and ground-based measurements of UVR may result from the fact that the latter incorporated daily fluctuations in cloud and ozone, which were incompletely incorporated in the single noontime satellite overpass ultraviolet value. However, it is also possible that some of the scaling factors we applied to both sets of measurement (see Appendix A and the Methods) may have been slightly biased. Our study suggests that AVGLO-derived UVR measures, both of irradiance and of cumulative radiant exposure should be considered as measurements of ambient exposure to UVR. A commonly employed UVR measure derived from these CIE measures is the average irradiance, which is given as the cumulative radiant exposure divided by the number of year of age, and so the conclusions with respect to correlations will apply equally to this measure. The potentially higher accuracy of AVGLO measurements will provide urgently needed input into epidemiological research into UVR and diseases such as cancer. However, the nominally higher resolution in the AVGLO data is largely irrelevant here, as linkage was made only by the zipcode of city of longest residence in various age intervals. Also, in practice, there is only modest variation in UV level locally; for example, at county level, there is a maximum coefficient of variation of 17% (10). Set against that, TOMS data are available worldwide, which ground-based measures such as AVGLO are generally not in any uniformly measured way. The reasonable correlation between UVR exposure in early childhood and later in life, and the relatively modest geodesic
distances and latitude moved, suggests that at least in this cohort later-life exposure could be used as a surrogate for early life exposure. However, this is unlikely to be a general phenomenon, and should be assessed in other cohorts with lifetime residential history and ambient UVR measurements.

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Appendix A Measures of UVR exposure

Using the standard Commission Internationale de l’Eclairage (CIE) (International Commission on Illumination) terminology (18) we assumed that the daily UVR (=UVA+UVB) irradiance in a specified area at time $t$ (in seconds after some arbitrary origin) of UV in W/m$^2$ was given by a function $Cf(t)$, where for identifiability we imposed the condition $1 = \max [f(t)]$, so that $C$ is the maximum UVR irradiance in W/m$^2$. This means that the average UVR irradiance (in W m$^2$) over a 30 year period, with total number of seconds $T = 3600 \times 24 \times 365.2425 \times 30$ is given by:

$$W = \frac{1}{T} \int_{0}^{T} Cf(s) ds \quad (A1)$$

Therefore the AVGLO measure of average solar daily radiant exposure in W hour/m$^2$ estimated by Tatalovich et al (10) is given by:

$$Z = \frac{F_{tot/UVR}}{[T / (24 \cdot 3600)]} \frac{1}{3600} \int_{0}^{T} Cf(s) ds \quad (A2)$$

where $F_{tot/UVR}$ is the ratio of total (ground-level) solar output to UVR (=UVA+UVB). We estimated $F_{tot/UVR} \approx 1/0.04 = 25$, using the central estimate from the range given (3-5%), with range $F_{tot/UVR} \approx 1/0.05 = 20$ to $F_{tot/UVR} \approx 1/0.03 = 33.3$ (24). A similar estimate, 100/5 = 20 can be derived from figures given by the International Agency for Research on Cancer (IARC) (2). However, data given by Fligge and Solanki (36) suggest a slightly smaller value, $F_{tot/UVR} \approx 4.3 / 0.4 = 10.75$. Rearranging this we get:

$$W = \frac{Z}{24F_{tot/UVR}} \quad (A3)$$
Likewise, if we denote by $W[a,a+\delta]$ and $Z[a,a+\delta]$ the averages of these measures over the age interval (in years) $[a,a+\delta)$ then:

$$W[a,a+\delta] = \frac{Z[a,a+\delta]}{24F_{\text{tot/UVR}}}$$

(A4)

In particular, the average daily exposure rate, $G$, in mW m$^{-2}$ is given by:

$$G = \frac{1000Z}{24F_{\text{tot/UVR}}}$$

(A5)

It will also be of interest to estimate the total radiant exposure (in MJ cm$^{-2}$) up to a certain age $a$ (in years), given by:

$$E(a) = 10^{-10} \int_{0}^{3600 \times 24 \times 365.2425 a} C_f(s)ds$$

$$= 10^{-10} (3600 \times 24 \times 365.2425) \left[ \frac{1}{(3600 \times 24 \times 365.2425)} \int_{0}^{3600 \times 24 \times 365.2425 a} C_f(s)ds \right]$$

(A6)

$$\approx 10^{-10} (3600 \times 24 \times 365.2425) \sum_{i=0}^{a-1} \frac{1}{(3600 \times 24 \times 365.2425)} \int_{3600 \times 24 \times 365.2425 i}^{3600 \times 24 \times 365.2425 (i+1)} C_f(s)ds$$

$$\approx \frac{10^{-10} (3600 \times 24 \times 365.2425)}{24F_{\text{tot/UVR}}} \sum_{i=0}^{a-1} Z[i,i+1]$$

The TOMS database, which is maintained by NASA (20), provides average noontime estimate of ambient UVR irradiance, in units of mW m$^{-2}$ nm$^{-1}$ (22), in a 1.25º longitude x 1º latitude grid, $C_f'(t)$. The average daily UVR ambient irradiance (in mW m$^{-2}$) is therefore given by:

$$G'(t) = [315 - 280] I_{\text{av/peak}} F_{\text{UVB/UVBR}} C_f'(t)[7 / 24]$$

(A7)

The factor 7/24 scales the noontime ambient irradiance to the average UVR ambient irradiance over the full day, making use of the fact that at the latitude of Baltimore (about the average latitude in US) there are on average (over the course of a year) $\approx 7$ hours of sunshine per day (54). The factor [315-280] refers to the total width (in nm) of the UVB spectrum at ground level (2), and the
factor $F_{UVR/UVB}$ is the ratio of total UVR (=UVA + UVB) to UVB at ground level. We estimated $F_{UVR/UVB} \approx 20$ (2). The factor $I_{av/peak}$ measures the ratio of the average daily UVR exposure over daylight hours to the noontime peak UVR exposure. There is evidence that the diurnal variation of UVR is approximately triangular, with peak at noon, decaying to near 0 (25), so that to a good approximation it may be assumed that $I_{av/peak} \approx 0.5$. Expression (A7) ignores the small contribution from shorter wavelengths of UV (<280 nm), largely absorbed in the upper atmosphere (2). Average irradiance at a given time, $t$ (seconds), $G'(t)$, is related to the potential cumulative radiant exposure (irradiance) to UVR, $E'(t)$, via:

\[
E'(a) = 10^{-13} \int_{0}^{3600 \times 24 \times 365.2425 a} G'(s)ds
\]

\[
= 10^{-13} \sum_{i=0}^{a-1} \int_{3600 \times 24 \times 365.2425(i+1)}^{3600 \times 24 \times 365.2425i} G'(s)ds
\]

\[
\approx 10^{-13} \sum_{i=0}^{a-1} 3600 \times 7 \times 365.2425 \times [315 - 280] I_{av/peak} F_{UVR/UVB} C' f'(3600 \times 24 \times 365.2425i)
\]

in units of MJ cm$^{-2}$ (22).

It is likely that UVA, UVB and UVC can all induce all major types of skin cancer, specifically melanoma, basal cell carcinoma and squamous cell carcinoma (2). The mechanism is likely cumulative mutational DNA damage to cells in the basal cell layer, the higher lying melanocytes and the squamous cells positioned above both of these in the epidermis of the skin (2). There is hardly any human exposure to UVC in sunlight, and it is thought that UVA is markedly less efficient than UVB at causing DNA damage (2). Cataract is thought to result from cumulative oxidative stress in the eye lens (55), one component of which is associated with cumulative UVA exposure, as UVA is thought more directly capable of penetrating to the eye lens than UVB (56). The ratio of solar UVA to UVB varies slightly with latitude (39), and there is more
substantial variation over the course of a day, although not by much in the middle part of the day, when most exposure occurs (40). Therefore cumulative UVR (=UVA+UVB) radiant exposure will be highly correlated with UVA and UVB, and so will be a natural measure to use in assessing the effects of UVR on skin cancer and cataract. Other measures of UVR exposure include the minimal erythemal dose (MED), and the standard erythemal dose (SED) (22). The annual average irradiance at 305 nm UV [the approximate midpoint of the wavelength interval ascribed to UVB] was used to estimate $E(t)$ for each location for the period 1978–1993 to provide stability to the estimates, as previously described (57).

Using city and state of residence reported on the USRT third questionnaire for the five age periods reported (0-12, 13-19, 20-39, 40-64, 65+ years of age), ambient UVB irradiance was calculated at each age over the lifetime of the individual from AVGLO- or TOMS-estimated ambient irradiance.
Table 1. Distribution of geodesic (great circle) distance moved (km), latitude difference and absolute latitude difference moved (degrees) from city of longest residence in early childhood (age 0-12) to city of longest residence at later ages, as determined from responses to the third questionnaire

<table>
<thead>
<tr>
<th>Age group (years)</th>
<th>Mean / median geodesic (great circle) distance moved (km)</th>
<th>Minimum / 1st quartile / 3rd quartile / maximum geodesic (great circle) distance moved (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-19</td>
<td>137.6 / 0.00</td>
<td>0.0 / 0.0 / 0.0 / 15,505.4</td>
</tr>
<tr>
<td>20-39</td>
<td>589.5 / 57.7</td>
<td>0.0 / 0.0 / 443.4 / 16,953.5</td>
</tr>
<tr>
<td>40-64</td>
<td>661.8 / 93.2</td>
<td>0.0 / 8.3 / 699.3 / 16,960.8</td>
</tr>
<tr>
<td>65+</td>
<td>870.3 / 193.8</td>
<td>0.0 / 17.9 / 1243.9 / 15,572.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age group (years)</th>
<th>Mean / median latitude difference moved <a href="degrees">latitude at later age – latitude at birth</a></th>
<th>Minimum / 1st quartile / 3rd quartile / maximum latitude difference moved [latitude at later age – latitude at birth] (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-19</td>
<td>-0.03 / 0.00</td>
<td>0.00 / 0.00 / 75.67 / 1.00</td>
</tr>
<tr>
<td>20-39</td>
<td>-0.49 / 0.00</td>
<td>0.00 / 0.00 / 75.67 / 1.00</td>
</tr>
<tr>
<td>40-64</td>
<td>-0.51 / 0.00</td>
<td>0.00 / 0.00 / 75.67 / 1.00</td>
</tr>
<tr>
<td>65+</td>
<td>-0.76 / 0.00</td>
<td>0.00 / 0.00 / 75.67 / 1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age group (years)</th>
<th>Mean / median absolute latitude difference moved (degrees)</th>
<th>Minimum / 1st quartile / 3rd quartile / maximum absolute latitude difference moved (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-19</td>
<td>0.48 / 0.00</td>
<td>0.00 / 0.00 / 0.00 / 75.67</td>
</tr>
<tr>
<td>20-39</td>
<td>0.93 / 0.00</td>
<td>0.00 / 0.00 / 0.00 / 75.67</td>
</tr>
<tr>
<td>40-64</td>
<td>0.95 / 0.00</td>
<td>0.00 / 0.00 / 0.00 / 75.67</td>
</tr>
<tr>
<td>65+</td>
<td>1.21 / 0.00</td>
<td>0.00 / 0.00 / 0.00 / 75.67</td>
</tr>
</tbody>
</table>
Table 2. Mean, median and range of UVR (=UVA+UVB) ambient irradiance and potential cumulative radiant exposure, derived from AVGLO and from NASA TOMS data, by age

<table>
<thead>
<tr>
<th>Age</th>
<th>Persons</th>
<th>Mean</th>
<th>Minimum / 1st quartile / 3rd quartile / maximum</th>
<th>Mean</th>
<th>Minimum / 1st quartile / 3rd quartile / maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ambient UVR irradiance (mW m⁻²)</td>
<td></td>
<td>Ambient UVR irradiance (mW m⁻²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NASA TOMS</td>
<td>AVGLO</td>
<td>NASA TOMS</td>
</tr>
<tr>
<td>20</td>
<td>67,189</td>
<td>6012.35</td>
<td>340.28 / 5240.28 / 6737.50 / 11229.17</td>
<td>7011.22</td>
<td>5011.67 / 6443.33 / 7561.67 / 9565.00</td>
</tr>
<tr>
<td>40</td>
<td>67,188</td>
<td>6059.02</td>
<td>1531.25 / 5240.28 / 6975.69 / 10548.61</td>
<td>7049.72</td>
<td>5186.67 / 6445.00 / 7593.33 / 9560.00</td>
</tr>
<tr>
<td>60</td>
<td>20,032</td>
<td>6109.87</td>
<td>1871.53 / 5240.28 / 7043.75 / 10548.61</td>
<td>7088.60</td>
<td>5220.00 / 6453.33 / 7673.33 / 9560.00</td>
</tr>
<tr>
<td>80</td>
<td>955</td>
<td>6263.46</td>
<td>2041.67 / 5240.28 / 7213.89 / 9459.72</td>
<td>7194.05</td>
<td>5328.33 / 6466.67 / 7835.00 / 9560.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential cumulative UVR radiant exposure (MJ cm⁻²)</td>
<td></td>
<td>Potential cumulative UVR radiant exposure (MJ cm⁻²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NASA TOMS</td>
<td>AVGLO</td>
<td>NASA TOMS</td>
</tr>
<tr>
<td>20</td>
<td>67,189</td>
<td>0.369</td>
<td>0.010 / 0.331 / 0.397 / 0.650</td>
<td>0.434</td>
<td>0.318 / 0.405 / 0.461 / 0.603</td>
</tr>
<tr>
<td>40</td>
<td>67,188</td>
<td>0.748</td>
<td>0.155 / 0.661 / 0.827 / 1.194</td>
<td>0.877</td>
<td>0.661 / 0.814 / 0.937 / 1.207</td>
</tr>
<tr>
<td>60</td>
<td>20,032</td>
<td>1.134</td>
<td>0.485 / 0.999 / 1.254 / 1.791</td>
<td>1.325</td>
<td>1.003 / 1.223 / 1.419 / 1.810</td>
</tr>
<tr>
<td>80</td>
<td>955</td>
<td>1.523</td>
<td>0.735 / 1.337 / 1.691 / 2.313</td>
<td>1.778</td>
<td>1.340 / 1.639 / 1.903 / 2.410</td>
</tr>
</tbody>
</table>
Table 3. Pearson and Spearman correlation coefficients of ambient irradiance and potential cumulative radiant exposure of UVR (=UVA+UVB), derived from AVGLO and from NASA TOMS data, by age

<table>
<thead>
<tr>
<th>Age</th>
<th>Persons</th>
<th>NASA TOMS vs AVGLO ambient irradiance (mW m(^{-2}))</th>
<th>Pearson correlation</th>
<th>NASA TOMS vs AVGLO potential cumulative radiant exposure (MJ cm(^{-2}))</th>
<th>Spearman correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>67,189</td>
<td>0.894</td>
<td>0.889</td>
<td></td>
<td>0.872</td>
</tr>
<tr>
<td>40</td>
<td>67,188</td>
<td>0.910</td>
<td>0.909</td>
<td></td>
<td>0.898</td>
</tr>
<tr>
<td>60</td>
<td>20,032</td>
<td>0.912</td>
<td>0.909</td>
<td></td>
<td>0.911</td>
</tr>
<tr>
<td>80</td>
<td>955</td>
<td>0.904</td>
<td>0.906</td>
<td></td>
<td>0.913</td>
</tr>
</tbody>
</table>
Table 4. Pearson and Spearman correlation coefficients of UVR (=UVA+UVB) ambient irradiance at birth and at time of third questionnaire, derived from AVGLO and from NASA TOMS data

<table>
<thead>
<tr>
<th></th>
<th>Pearson correlation coefficient</th>
<th>Spearman correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA TOMS ambient irradiance (mW m⁻²)</td>
<td>AVGLO ambient irradiance (mW m⁻²)</td>
<td>NASA TOMS irradiance (mW m⁻²)</td>
</tr>
<tr>
<td>0.512</td>
<td>0.547</td>
<td>0.587</td>
</tr>
</tbody>
</table>
Figure legends

Figure 1. Distribution of NSRAD/AVGLO measurement sites in the US.

Figure 2. Ratio of TOMS / AVGLO UVR mean ambient irradiance estimates (both measured in mW m\(^{-2}\)) at ages 0-12 in relation to location of city of longest residence at ages 0-12.

Figure 3. UVR (UVA+UVB) irradiance, derived from AVGLO and from NASA TOMS data, by age: (a) age 20 years, (b) age 40 years, (c) age 60 years, and (d) age 80 years.

Figure 4. Cumulative potential UVR (UVA+UVB) radiant exposure, derived from AVGLO and from NASA TOMS data, by age: (a) age 20 years, (b) age 40 years, (c) age 60 years, and (d) age 80 years.

Figure 5. UVR (UVA+UVB) ambient irradiance at birth and at time of third questionnaire, derived from (a) NASA TOMS and (b) AVGLO data.
References


