

24 **Tables: 4, Figures: 5** (*Photochem Photobiol* no limit)

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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

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45 Exposure to solar ultraviolet radiation (UVR), and specifically ultraviolet-B (UVB) radiation, is
46 the primary risk factor for basal cell carcinoma (BCC), squamous cell carcinoma (SCC) (1, 2),
47 melanoma (2), and cataract (3, 4), but may be protective of other cancers (5-7). Ground-based
48 UVR estimates, in particular those using Robertson-Berger meters, have been used in studies of
49 melanoma (8) and other skin cancers (9). More recently, the AVerage daily total GLObal solar
50 radiation (AVGLO) estimates, interpolated by Tatalovich *et al* (10) using total solar radiation data
51 from the National Solar Radiation Database (NSRAD) of the Department of Energy (DOE), have
52 been used to assess risk of skin cancer in a large multi-center cohort of women (11) and melanoma
53 in US Surveillance, Epidemiology and End Results data (12). National Aeronautics Space
54 Administration (NASA) Total Ozone Mapping Spectrometer (TOMS) satellite-based UVR data
55 has been used to study breast, thyroid and skin cancer in the US Radiologic Technologists (USRT)
56 (13-15), and similar studies using this metric have been conducted of melanoma in residents of
57 Seattle-Puget Sound (16) and in the US Nurses Health Study (NHS) (17).

58 The two main assessment approaches used to estimate individual lifetime ambient ultraviolet
59 irradiance in epidemiologic studies, i.e., estimates derived from ground-based solar measurement
60 stations such as AVGLO and from satellite measurements such as NASA TOMS, have rarely been
61 compared. In the current study we compared findings using ground-based and satellite-based
62 assessments to estimate ambient lifetime UVR exposure in a single, nationwide population-based
63 US cohort using self-reported, questionnaire-derived lifetime residential history. We examined
64 correlations between these two types of ambient measurements of UVR, considering the metrics
65 of UVR irradiance and cumulative UVR radiant exposure, in the US Radiation Technologist
66 cohort. Because of the importance of early life exposure for cancer in relation to UVR exposure

67 (2), it is clearly highly desirable to estimate UVR at this age if possible. Nevertheless, if early-life
68 and later-life UVR exposures were found to be highly correlated then these later exposures might
69 prove acceptable surrogates. In the light of this, we assessed how well estimates of UV correlate
70 from birth over life, considering the residential mobility of the USRT population. Connected with
71 this we also determined the residential mobility of the population, in particular assessing the
72 average geodesic distance moved and mean latitude-difference from location of residence in
73 childhood over life.

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Materials and Methods

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Overview – UVR Exposure Metrics

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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).

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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.

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Exposure Assessment Methods

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Description of UVR Exposure Assessment Estimation Approaches

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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

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90 largest ground-based network in the US, containing statistical summaries computed from hourly
91 measurement data (with some infilling for missing data) for 239 US radiation stations for the
92 period 1961-1990 (see Figure 1), including monthly, yearly, and 30-year average global solar
93 radiation measures. Tatalovich *et al* (10) incorporated AVGLO measures, latitude, longitude, and
94 elevation from a 30 arc-second Digital Elevation Model into the ANUSPLIN spline-interpolation
95 algorithm to deliver estimates of potential solar ambient irradiance (~250-2700 nm) at 1 km²
96 resolution in the US. AVGLO used 30-year averages of ANUSPLIN spline-interpolated ground
97 solar ambient irradiance measurements after initial analysis of temporal variability that showed no
98 statistically significant difference in between the three 10-year periods embedded in the 1961-1990
99 data summaries for each radiation station (10). Prior to interpolation of UV estimates, AVGLO
100 measures of total solar ambient irradiance (~100-3000 nm, corresponding to the range ultraviolet
101 C - infrared B (19)) have been validated as a proxy for UV, because spatial distribution of AVGLO
102 data was larger and their quantity more complete than any UV database available at the time. The
103 UV measures used for comparison with AVGLO consisted of monthly-averaged UVB data (~280-
104 315 nm (2)) covering the period 1995-2004, collected from 7 Surface Radiation Budget Network
105 (SURFRAD) measurement stations of the National Oceanic and Atmospheric Administration
106 (NOAA) (near to certain of the AVGLO measurement sites) in 7 climatologically diverse states
107 (Montana, Colorado, Illinois, Mississippi, Pennsylvania, Nevada, and South Dakota) (10). The
108 UVB flux employed by Tatalovich *et al* for the SURFRAD data (10) was the total UVB convoluted
109 with the erythemal action spectrum (i.e., weighted to that part of the UVB spectrum responsible
110 for sun burns on human skin (erythema) and DNA damage). As shown by Tatalovich *et al* (10)
111 AVGLO was highly correlated with SURFRAD-based UVB irradiance (280-315 nm (2)) and was
112 therefore used as a proxy for UV in subsequent computational analysis, resulting in 1 km² estimates

113 of potential UV ambient irradiance across the Continental US. For the current study, these
114 estimates were aggregated to zip-codes of historical residences of persons in the USRT study
115 cohort.

116 **>Figure 1<**

117 The Total Ozone Mapping Spectrometer (TOMS) database, which is maintained by the US
118 National Aeronautics and Space Administration (NASA) (20), is a satellite based system that uses
119 measurements of atmospheric ozone and cloud reflectivity (21) to estimate average noontime
120 ambient UVR irradiance, measured as the irradiance (in $\text{mW m}^{-2} \text{nm}^{-1}$) (22), in a 1.25° longitude
121 $\times 1^\circ$ latitude grid (approximately 110 x 110km) or 69 x 69 miles) grid. Satellite-based annual
122 estimates of daily noon-time UVR per location have varied little since the start of measurements
123 in the late 1970s (23), thus, daily noon-time estimates were averaged over years 1978–1993 for
124 each location to construct stable estimates. We used the TOMS UVR irradiance estimates at the
125 wavelength of 305 nm, in the middle of the UVB band.

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

127 AVGLO is an estimate of total direct and diffuse solar daily radiation received on a horizontal
128 surface, in units of Wh m^{-2} (10). We scaled this to the CIE unit of average UVR irradiance (with
129 units of W m^{-2}) by dividing by 24 (number of hours in a day) and the ratio of total solar irradiance
130 (which includes infrared, visible and UVR radiation) to total UVR irradiance, which we took to be
131 about 25 (24). [As stated “In terms of energy, sunlight at Earth's surface is around ... 3 to 5 percent
132 ultraviolet (below 400 nm)” (24). The 25 was derived as $100/4$, where 4 is the midpoint of this
133 interval 3-5. A similar estimate, $100/5 = 20$ can be derived from figures given elsewhere (2).] From
134 the NASA TOMS UVR estimate of average noontime ambient UVR irradiance (in $\text{mW m}^{-2} \text{nm}^{-1}$)
135 in the middle of the UVB spectrum (305 nm) we estimated the average UVR irradiance (in W m^{-2})

136 ²), for the full width of the UVR spectrum (280-400 nm), by dividing by 1000, to convert from
137 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
138 frequency band (280-315 nm) (24)), the ratio of average UVR (280-400 nm) ambient irradiance to
139 average UVB (280-315 nm) ambient irradiance, which we assumed to be about 20 (2), the average
140 proportion of the day that is comprised of sunshine (7/24), and the ratio of average (over hours of
141 sunshine) to noontime peak UVR (assumed to be about 0.5, because it is approximately a triangular
142 distribution with peak at noon, decaying to near 0 (25)).

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

146 *Assessment of geodesic distance moved*

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

153 **Application of Exposure Assessment Measurement Approaches and Metrics for Assessing**

154 **Cumulative Exposure to a Nationwide U.S. Population-Based Cohort**

155 *Overview description of USRT cohort*

156 The USRT study population, cohort follow-up, and ionizing radiation dosimetry methods have
157 been described elsewhere (27-29) (see also www.radtechstudy.nci.nih.gov). Briefly, the US
158 National Cancer Institute, in collaboration with the University of Minnesota and the American

159 Registry of Radiologic Technologists (ARRT), has studied cancer incidence and mortality among
160 146,022 (106,953 women) US radiologic technologists who were certified for at least two years
161 during 1926-1982 (30, 31). Active follow-up was conducted through yearly review of ARRT
162 records on re-certification. Inactive registrants were linked with national and other databases,
163 including the Social Security Administration to determine vital status and the National Death Index
164 (NDI-Plus) to obtain cause of death for those known or presumed to be deceased. Four
165 questionnaires were administered during 1983–1989, 1994–1998, 2003–2005, and 2012-2014 to
166 collect information on health outcomes (including self-reports of cataract and cataract surgery in
167 all but the first questionnaire), work history, demographic and lifestyle characteristics, and medical
168 histories. The third and fourth questionnaires were sent only to cohort members who had responded
169 to the first and/or the second questionnaire.

170 *UVR exposure assessment for the USRT*

171 On the third questionnaire (administered during 2003-2005) questions were asked about the
172 lifetime residential history of the technologists. The technologists were asked to specify which city
173 they had lived in longest for various age groups (<13, 13-19, 20-39, 40-64, ≥65). These cities of
174 longest residence by age group were used in conjunction with independent databases of average
175 solar exposure and average noontime ultraviolet exposure to derive measures of total UVR (UVA
176 + UVB) ambient irradiance. The latitude and longitude of the respective cities were also assessed.
177 The USRT subcohort included in the current evaluation includes all those who answered the third
178 questionnaire with enough detail on residential history to ascertain location in a manner that
179 enabled linkage with NASA TOMS and AVGLO UVR/solar ambient irradiance data. There were
180 69,085 persons with available AVGLO solar ambient irradiance estimates, and of these 67,189
181 also had NASA TOMS UVR estimates.

182 **Statistical Methods**

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

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

196 **>Figure 2<**

197 Table 3 reports the Pearson (32) and Spearman-rank (33) correlation coefficients between
198 the NASA TOMS- and AVGLO-derived estimates of UVR irradiance and cumulative UVR
199 radiant exposure by age group. The Pearson (32) and Spearman-rank (33) correlation coefficients
200 are standard measures of association, the latter a non-parametric measure of association that is
201 favored when there are uncertainties as to the precise probabilistic form of the underlying
202 distribution. Figures 3 and 4 display this information in graphical form. Table 4 computes the
203 Pearson and Spearman-rank correlation coefficients between the NASA TOMS-derived UVR

204 irradiance at birth and at the time of the third questionnaire, also the analogous correlation using
205 AVGLO-derived UVR irradiance. Figure 5 displays this data in graphical form.

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

207 **Data accessibility statement**

208 All data used can be obtained from MPL on request.

209 **Results**

210 **>Table 1<**

211 Table 1 demonstrates that the mean distance moved from city of longest residence in childhood
212 (ages 0-12 years) progressively increased from 137.6 km at ages 13-19 years to 870.3 km at ages
213 of 65 years and older. However, the median geodesic distances moved were much less than the
214 mean, ranging from a mean of 57.7 km at ages 20-39 to 193.8 km at ages 65 and above. Table 1
215 shows that the mean difference in latitude moved from city of longest residence in childhood (ages
216 0-12 years) decreased from -0.03 degrees at ages 13-19 years to -0.76 degrees at ages 65 and older,
217 suggesting that with increasing age people moved nearer the equator. The mean absolute latitude
218 difference moved from city of longest residence in childhood (ages 0-12 years) increased from
219 0.48 degrees at ages 13-19 years to 1.21 degrees at ages of 65 years and older. However, the
220 median, and indeed 75%, latitude differences were always 0.

221 **>Table 2<**

222 Table 2 demonstrates that there were 67,189 persons with sufficient information on location
223 to derive both AVGLO-based average solar ambient irradiance and NASA TOMS-derived average
224 noontime UVR irradiance by year of age. However, the number of technologists who responded
225 to the third questionnaire, and so furnished information on lifetime exposure up to that point
226 diminished with age, so that by age 80 there were only 955 technologists contributing information.

227 Table 2 also demonstrates the range of UVR irradiance derived from NASA TOMS and from
228 AVGLO data. As can be seen the UVR irradiance was approximately constant by age within this
229 cohort of technologists, but cumulative UVR radiant exposure increased with age. The mean UVR
230 irradiance and cumulative UVR radiant exposure were generally about 14-15% less in the NASA
231 than in the AVGLO data, so for example at age 60 the mean cumulative UVR radiant exposure
232 was 1.134 MJ cm⁻² in the NASA data, compared with a mean estimate of 1.325 MJ cm⁻² in the
233 AVGLO series (Table 2). The ratio of NASA TOMS to AVGLO irradiance tended to be slightly
234 higher in the more southerly parts of US (Figure 2).

235 >Table 3<

236 >Figure 3<

237 >Figure 4<

238 Table 3 and Figures 3 and 4 demonstrate that at all ages (20, 40, 60 and 80 years of age)
239 Pearson and Spearman correlations of average UVR irradiance (mW m⁻²) and cumulative radiant
240 exposure (MJ cm⁻²) were uniformly high, between 0.894-0.915 for the UVR irradiance, and 0.872-
241 0.913 for the cumulative UVR radiant exposure. Spearman-rank correlation coefficients had very
242 similar, or slightly higher values than the Pearson correlation coefficients.

243 >Table 4<

244 >Figure 5<

245 Table 4 and Figure 5 demonstrate that there was still appreciable correlation between the
246 irradiance at birth and at the last known residential location, at the time of the third questionnaire,
247 0.512 for the NASA TOMS data, and 0.547 for the AVGLO data. The analogous Spearman
248 correlation coefficients were slightly higher, 0.587 and 0.600 respectively.

249

Discussion

250

251 This is one of the first studies to compare the two major UVR estimation methods, using ground-
252 based and satellite-based estimates in a large nationwide cohort of persons living at a wide range
253 of latitudes. We have shown that AVGLO and TOMS estimates of UVR were very highly
254 correlated, both for irradiance and cumulative radiant exposure. This is perhaps remarkable, given
255 that AVGLO estimates are fundamentally long-term daily averages of ground-based total ambient
256 solar irradiance measurements assessed for a 1 km x 1 km grid, whereas the NASA TOMS data
257 were long-term averages of noontime UV estimates using a rather coarser, approximately 110 km
258 x 110 km grid, although as we discuss later the solar radiation variation within even the 110 km x
259 110 km grid is not substantial. There was also reasonably high correlation between the irradiance
260 at birth and the last known irradiance, at the time of the third questionnaire, for both the AVGLO
261 and TOMS UVR measures. The NASA-derived satellite-based estimates were on average below
262 those in the AVGLO ground-based series, by between 14-15% (Table 2). The present study is also
263 one of the first that has attempted to quantify distance and absolute latitude difference between
264 birth and late-in-age addresses and thus determine whether the late-in-age address is a good proxy
265 for birth address. We found that in this cohort, the late-in-life address would not result in too much
266 loss of accuracy. Indeed, the correlation of UVR at birth and at time of third questionnaire may be
267 explained by the relatively moderate amount of movement from city of residence in childhood to
268 city of longest residence in adulthood, which on average was between 500-700 km, with somewhat
269 smaller movement, on average about 140 km, from childhood to late childhood/early adulthood
270 (ages 13-19) (Table 1). The latitude differences were similarly modest, with mean difference no
271 more than 1.2 degrees, and more than 75% of the cohort did not shift in latitude over the course of
272 life (Table 1). Another novel feature was use of newer metrics of UVR exposure based on CIE-

273 recommended quantities (18), specifically irradiance and cumulative radiant exposure, in contrast
274 to the metric of average lifetime exposure that has been employed in some epidemiological studies
275 (13, 14).

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

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

294 The relatively small geographic variation in residence over the course of childhood was
295 consistent with what has been observed in childhood in the UK (43). A review of mothers who

296 moved during pregnancy found generally low mobility rates, which declined with increasing age,
297 parity and socioeconomic status (44). In our study the median distance moved was very much
298 smaller than the mean (Table 1), indicating the disproportionate effect of those who moved long
299 distances. Indeed, until the oldest age group, the mean distance moved from location of residence
300 in early childhood was greater than or comparable with the third quartile distance moved.

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

307 Strengths of the cohort and our analysis is that ours is one of few studies that have life-course
308 residential history. In many cohorts where UVR has been assessed over the lifetime, a single
309 exposure metric, often average annual ambient UVR, is considered. In particular this is the case in
310 recent analyses of the USRT (13, 14), in a cohort of residents of Seattle-Puget Sound (16), and in
311 analysis of the NHS (17). Older analyses of the USRT used Robertson-Berger meter assessments
312 of UVR (47, 48), as also did an older analysis of the NHS (9). Robertson-Berger meters measure
313 erythemally-weighted UVR (49). In contrast the AVGLO measure employed here estimates
314 erythemally-unweighted total solar exposure (10). In none of these studies was there a comparison
315 of different UVR exposure metrics. The present study has evaluated two separate estimates of
316 UVR, derived from satellite and ground-based data and considered two different measures,
317 irradiance and cumulative radiant exposure, within each dataset, as recommended by the CIE (18).

318 It is not clear which of irradiance and cumulative radiant exposure is necessarily the better
319 measure; this will likely differ by the particular disease endpoint being considered.

320 A potential weakness of the data we used is that it relied on self-reported city of longest
321 residence by age group (0-12, 13-19, 20-39, 40-64, 65+). As such there will inevitably be some
322 misclassification of exposure, as people could move residence within these age groups. It is also
323 possible that they might have mis-recalled city of longest residence, although this is unlikely,
324 except perhaps for the youngest age groups. Supporting this, assessment of reliability of recall of
325 residential history in other studies suggests that short-duration moves may well be mis-
326 remembered, although longer duration moves are more reliably recorded (50, 51). In any case, this
327 will affect both sets of estimates used here, and is unlikely to substantially affect correlations
328 between them. The metrics all focused on ambient estimates. There is no account taken of
329 behavior, for example hours of sun exposure. This information was collected on the questionnaire
330 but we judged that it was probably less reliable than the location data, and so no use was made of
331 it here. A study of 6-month recall of time spent outdoors with a contemporary activity diary in the
332 USRT found reasonable agreement of weekday activity, but less good agreement with respect to
333 weekends, when UVR exposure would be expected to be greater (52). Our calculations of average
334 UVR derived from the NASA TOMS measurements were based on an assumed ratio of UVR to
335 UVB of about 20 (2), and assumed an approximately triangular diurnal distribution of UVR (25)
336 (see the Methods and Appendix A for more details). These approximations are likely to be
337 reasonable in aggregate, although there are known to be diurnal variations of the ratio of UVR to
338 UVB, in a manner that will also depend on latitude (53, 40). It is perhaps remarkable that, as can
339 be seen from Table 2, the mean estimates of total UVR that we derived from the NASA satellite-
340 based measurements are reasonably close to those derived from the AVGLO ground-based

341 measures of total solar ambient exposure, whether using UVR irradiance or cumulative UVR
342 radiant exposure. A possibly limiting feature of the USRT as an occupational cohort is that
343 residential mobility may not be as generalizable as in other occupational groups to the general US
344 population, because work authorization/certification is tied to state of residence.

345 In summary our study suggests that AVGLO-derived UVR data is highly correlated with
346 NASA TOMS data, although AVGLO was 14-15% higher. The modest difference between
347 satellite-based and ground-based measurements of UVR may result from the fact that the latter
348 incorporated daily fluctuations in cloud and ozone, which were incompletely incorporated in the
349 single noontime satellite overpass ultraviolet value. However, it is also possible that some of the
350 scaling factors we applied to both sets of measurement (see Appendix A and the Methods) may
351 have been slightly biased. Our study suggests that AVGLO-derived UVR measures, both of
352 irradiance and of cumulative radiant exposure should be considered as measurements of ambient
353 exposure to UVR. A commonly employed UVR measure derived from these CIE measures is the
354 average irradiance, which is given as the cumulative radiant exposure divided by the number of
355 year of age, and so the conclusions with respect to correlations will apply equally to this measure.
356 The potentially higher accuracy of AVGLO measurements will provide urgently needed input into
357 epidemiological research into UVR and diseases such as cancer. However, the nominally higher
358 resolution in the AVGLO data is largely irrelevant here, as linkage was made only by the zipcode
359 of city of longest residence in various age intervals. Also, in practice, there is only modest variation
360 in UV level locally; for example, at county level, there is a maximum coefficient of variation of
361 17% (10). Set against that, TOMS data are available worldwide, which ground-based measures
362 such as AVGLO are generally not in any uniformly measured way. The reasonable correlation
363 between UVR exposure in early childhood and later in life, and the relatively modest geodesic

364 distances and latitude moved, suggests that at least in this cohort later-life exposure could be used
365 as a surrogate for early life exposure. However, this is unlikely to be a general phenomenon, and
366 should be assessed in other cohorts with lifetime residential history and ambient UVR
367 measurements.

368

369

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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 $W \text{ hour}/m^2$ estimated by Tatalovich *et al* (10) is given by:

$$\begin{aligned} Z &= \frac{F_{tot/UVR}}{[T / (24 \cdot 3600)]} \frac{1}{3600} \int_0^T Cf(s)ds \\ &= 24WF_{tot/UVR} \end{aligned} \quad (A2)$$

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:

$$W[a, a + \delta] = \frac{Z[a, a + \delta]}{24F_{tot/UVR}} \quad (A4)$$

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

$$G = \frac{1000Z}{24F_{tot/UVR}} \quad (A5)$$

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:

$$\begin{aligned} E(a) &= 10^{-10} \int_0^{3600 \times 24 \times 365.2425a} Cf(s)ds \\ &= 10^{-10} (3600 \times 24 \times 365.2425) \left[\frac{1}{(3600 \times 24 \times 365.2425)} \int_0^{3600 \times 24 \times 365.2425a} Cf(s)ds \right] \\ &\approx 10^{-10} (3600 \times 24 \times 365.2425) \sum_{i=0}^{a-1} \frac{1}{(3600 \times 24 \times 365.2425)} \int_{3600 \times 24 \times 365.2425i}^{3600 \times 24 \times 365.2425[i+1]} Cf(s)ds \\ &\approx \frac{10^{-10} (3600 \times 24 \times 365.2425)}{24F_{tot/UVR}} \sum_{i=0}^{a-1} Z[i, i+1] \end{aligned} \quad (A6)$$

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

$$G'(t) = [315 - 280] I_{av/peak} F_{UVR/UVB} C' f'(t) [7/24] \quad (A7)$$

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) ≈ 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:

$$\begin{aligned}
 E'(a) &= 10^{-13} \int_0^{3600 \times 24 \times 365.2425a} G'(s) ds \\
 &= 10^{-13} \sum_{i=0}^{a-1} \int_{3600 \times 24 \times 365.2425i}^{3600 \times 24 \times 365.2425[i+1]} G'(s) ds \\
 &\approx 10^{-13} \sum_{i=0}^{a-1} 3600 \times 7 \times 365.2425 \times [315 - 280] I_{av/peak} F_{UVR/UVB} C' f'(3600 \times 24 \times 365.2425i)
 \end{aligned} \tag{A8}$$

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

Age group (years)	Mean / median geodesic (great circle) distance moved (km)	Minimum / 1st quartile / 3rd quartile / maximum geodesic (great circle) distance moved (km)
13-19	137.6 / 0.00	0.0 / 0.0 / 0.0 / 15,505.4
20-39	589.5 / 57.7	0.0 / 0.0 / 443.4 / 16,953.5
40-64	661.8 / 93.2	0.0 / 8.3 / 699.3 / 16,960.8
65+	870.3 / 193.8	0.0 / 17.9 / 1243.9 / 15,572.8
Age group (years)	Mean / median latitude difference moved [latitude at later age – latitude at birth](degrees)	Minimum / 1st quartile / 3rd quartile / maximum latitude difference moved [latitude at later age – latitude at birth] (degrees)
13-19	-0.03 / 0.00	0.00 / 0.00 / 75.67 / 1.00
20-39	-0.49 / 0.00	0.00 / 0.00 / 75.67 / 1.00
40-64	-0.51 / 0.00	0.00 / 0.00 / 75.67 / 1.00
65+	-0.76 / 0.00	0.00 / 0.00 / 75.67 / 1.00
Age group (years)	Mean / median absolute latitude difference moved (degrees)	Minimum / 1st quartile / 3rd quartile / maximum absolute latitude difference moved (degrees)
13-19	0.48 / 0.00	0.00 / 0.00 / 0.00 / 75.67
20-39	0.93 / 0.00	0.00 / 0.00 / 0.00 / 75.67
40-64	0.95 / 0.00	0.00 / 0.00 / 0.00 / 75.67
65+	1.21 / 0.00	0.00 / 0.00 / 0.00 / 75.67

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

Age	Persons	Mean	Minimum / 1st quartile / 3rd quartile / maximum	Mean	Minimum / 1st quartile / 3rd quartile / maximum	
Ambient UVR irradiance (mW m ⁻²)						
			NASA TOMS			
20	67,189	6012.35	340.28 / 5240.28 / 6737.50 / 11229.17	7011.22	5011.67 / 6443.33 / 7561.67 / 9565.00	
40	67,188	6059.02	1531.25 / 5240.28 / 6975.69 / 10548.61	7049.72	5186.67 / 6445.00 / 7593.33 / 9560.00	
60	20,032	6109.87	1871.53 / 5240.28 / 7043.75 / 10548.61	7088.60	5220.00 / 6453.33 / 7673.33 / 9560.00	
80	955	6263.46	2041.67 / 5240.28 / 7213.89 / 9459.72	7194.05	5328.33 / 6466.67 / 7835.00 / 9560.00	
Potential cumulative UVR radiant exposure (MJ cm ⁻²)						
			NASA TOMS			
20	67,189	0.369	0.010 / 0.331 / 0.397 / 0.650	0.434	0.318 / 0.405 / 0.461 / 0.603	
40	67,188	0.748	0.155 / 0.661 / 0.827 / 1.194	0.877	0.661 / 0.814 / 0.937 / 1.207	
60	20,032	1.134	0.485 / 0.999 / 1.254 / 1.791	1.325	1.003 / 1.223 / 1.419 / 1.810	
80	955	1.523	0.735 / 1.337 / 1.691 / 2.313	1.778	1.340 / 1.639 / 1.903 / 2.410	

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

Age	Persons	Correlation coefficients	
		NASA TOMS vs AVGLO ambient irradiance (mW m ⁻²)	NASA TOMS vs AVGLO potential cumulative radiant exposure (MJ cm ⁻²)
Pearson correlation			
20	67,189	0.894	0.889
40	67,188	0.910	0.909
60	20,032	0.912	0.909
80	955	0.904	0.906
Spearman correlation			
20	67,189	0.895	0.872
40	67,188	0.914	0.898
60	20,032	0.919	0.911
80	955	0.915	0.913

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

Pearson correlation coefficient	
NASA TOMS ambient irradiance (mW m ⁻²)	AVGLO ambient irradiance (mW m ⁻²)
0.512	0.547
Spearman correlation coefficient	
NASA TOMS irradiance (mW m ⁻²)	AVGLO irradiance (mW m ⁻²)
0.587	0.600

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.

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