In-Flight UV-A Exposure of Commercial Airline Pilots

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INTRODUCTION: Understanding UV exposure is essential for the assessment of its contribution to the occupational risk of pilots developing ocular and skin pathologies. The objective of this observational study was to measure the UV exposure of pilots flying between the United Kingdom and a range of destinations at three different seasons.

METHODS: The in-flight UV exposure of pilots was measured on 322 Monarch Airlines short-haul flights on the Airbus A321-231 and Airbus A320-214 to 31 destinations, mostly in Europe, from 4 UK airports in September 2016–August 2017. The erythema effective and UV-A doses were compared with the ICNIRP guidance and typical recreational weekend exposure of UK office workers.

RESULTS: The erythema effective radiant doses did not exceed 0.1 SED. For most of the flights, the UV-A exposure was also low. On 27 single sector flights, UV-A exposure could have exceeded the ICNIRP guidance if eye protection was not used.

DISCUSSION: The UV exposure in a cockpit is mostly governed by the presence of direct sunlight and the duration of a flight. The average monthly exposures were low and significantly below weekend recreational exposures of UK office workers over a similar period. To assess the contribution of occupational UV exposure to the risk of developing sun-related ocular and cutaneous pathologies, it is important to consider the accumulative flight time, destinations, and UV attenuation of aircraft windshields. Additionally, leisure and recreational outdoor time needs to be considered before meaningful overall risk analysis can be undertaken.

KEYWORDS: ultraviolet radiation, UV exposure, occupational exposure, skin cancers, ocular pathologies.

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Professional pilots are exposed to a combination of potentially harmful environmental hazards, including ionizing radiation from cosmic rays and solar radiation. Meta-analysis studies indicated that airline pilots are at twice the risk of melanoma and keratinocyte skin cancers than the general population,[13,19,25] and they have a raised mortality from melanoma. Analysis of correlation between levels of in-flight exposure to ionizing radiation or circadian rhythm disruption due to the pilots' shift working and skin cancers is inconclusive;[13,21] possible over-exposure to ultraviolet radiation (UVR) during flights may be implicated. The latter is known to cause considerable damage to the skin, increasing the risk of skin cancers and suppressing adaptive immunity.[16] There is also a body of evidence that long-term UV exposure is a risk factor for cortical cataracts in the general population;[11,17] to date, no conclusive evidence of the increased prevalence of cataracts was found for pilots.[6] Understanding UV exposure is essential for the assessment of its contribution to the occupational risk of pilots developing ocular and skin pathologies.

Pilots can be exposed to higher UVR levels at cruise altitude compared with ground terrestrial levels because atmosphere attenuation of UVR decreases with altitude.[2,18] In-flight measurements of solar radiation are challenging and published information is limited. The solar radiation in the cockpit depends on the position of the solar disk in relation to the aircraft; the highest levels are expected in the presence of direct sunlight, reflection from clouds or snow surfaces below the aircraft, and during episodes of low atmospheric ozone.

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Importantly, UVR exposure depends on the windshield and visor attenuation characteristics.

The previous studies concluded that even while the erythema effective irradiance was considered insignificant, the levels of UV-A may be relatively high.[5,9,26] Chorley et al.[5,9] reported that pilots' UV-A exposure may be in excess of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline limits[15] for aircraft windshields with poor UV-A attenuation if sunglasses or visors were not used. Estimation of UVR in cockpits using a radiative transfer model[18] concluded that it may be 10–20 times higher in the presence of direct sunlight.

The life-long UV exposure of pilots depends on an overall flight time governed by shift pattern, destinations, and UV attenuation of aircraft windshields, which may vary between aircraft of the same fleet.[5] The use of visors and sunglasses can also influence the outcomes of the risk assessment and needs to be included in the evaluation.

The objective of this observational study was to measure the UV exposure of pilots flying between the UK and a range of destinations at three different seasons. The erythema effective and UV-A doses were calculated for each outbound and inbound flight and compared with the ICNIRP guidance. The in-flight UVR doses were also compared with typical recreational weekend exposure of UK office workers over a similar period.

METHODS

Equipment and Subjects

The UV dosimetry was carried out by Monarch Airlines pilots in three seasons from August 2016 to August 2017. Monarch Airlines operated from UK airports from 5 April 1968 to 2 October 2017 and, during the period of data collection, flew to 43 destinations in the south of Europe, Israel, and the Canary Islands. For a few weeks, pilots wore a dosimeter that was clipped to the shirt at the chest level. Pilots were asked to fill in a diary that included date and time of outbound and inbound flights, departure and destination airports, aircraft type and registration, and use of visors or sunglasses during flight. Ethical approval for this study was granted by the Institute of Optometry's Research Ethics Committee. Pilots signed consent forms and they were free to withdraw at any time.

The measurements were carried out on a total of 312 flights on Airbus aircraft types A320-214 and A321-231, all manufactured after 1998 and flying from Manchester, London Gatwick, Leeds Bradford, and Birmingham airports:

- 4 pilots on 82 flights in August–September 2016 (summer);
- 7 pilots on 88 flights in December 2016–January 2017 (winter);
- 3 pilots on 22 flights in March–April 2017 (spring); and
- 4 pilots on 120 flights in June–August 2017 (summer).

The list of destinations and airport coordinates are given in **Table I**. The most easterly and westerly destinations were Tel Aviv (34°53' E) and Tenerife South (16°34' W); the most southern destination was Tenerife (28°2' N).

Table I. Airport IATA Codes, Names, and Coordinates.[14]

IATA AIRPORT CODE	AIRPORT	COORDINATES
ACE	Lanzarote, Spain	28° 56' N, 13° 36' W
AGP	Malaga, Spain	36° 40' N, 4° 30' W
ALC	Alicante, Spain	38° 17' N, 0° 33' W
AXD	Alexandroupolis, Greece	40° 51' N, 25° 57' E
BCN	Barcelona, Spain	41° 17' N, 2° 4' E
BHX	Birmingham, UK	52° 27' N, 1° 45' W
DBV	Dubrovnik, Croatia	42° 33' N, 18° 16' E
DLM	Dalaman, Turkey	36° 42' N, 28° 47' E
FAO	Faro, Portugal	37° 01' N, 7° 58' W
FNC	Madeira, Portugal	32° 42' N, 16° 46' W
FUE	Fuerteventura, Spain	28° 28' N, 13° 51' W
GIB	Gibraltar, UK	36° 9' N, 5° 21' W
GNB	Grenoble, France	45° 21' N, 5° 19' E
GVA	Geneva, Switzerland	46° 14' N, 6° 6' E
HER	Heraklion, Greece	35° 20' N, 25° 10' E
IBZ	Ibiza, Spain	38° 52' N, 1° 22' E
INN	Innsbruck, Austria	47° 15' N, 11° 20' E
LBA	Leeds-Bradford, UK	53° 52' N, 1° 39' W
LCA	Larnaca, Cyprus	34° 52' N, 33° 37' E
LEI	Almeria, Spain	36° 50' N, 2° 22' W
LGW	Gatwick, UK	51° 8' N, 0° 11' W
LIS	Lisbon, Portugal	38° 47' N, 9° 81' W
LPA	Gran Canaria, Spain	27° 56' N, 15° 23' W
MAH	Mahon, Spain	39° 51' N, 4° 14' E
MAN	Manchester, UK	53° 21' N, 2° 16' W
NAP	Naples, Italy	40° 54' N, 14° 17' E
OPO	Porto, Portugal	41° 15' N, 8° 41' W
PFO	Paphos, Greece	34° 43' N, 32° 30' E
PMI	Palma de Mallorca, Spain	39° 33' N, 2° 44' E
PVK	Aktion, Greece	38° 55' N, 20° 46' E
TFS	Tenerife South, Spain	28° 2' N, 16° 34' W
TLV	Tel Aviv, Israel	32° 0' N, 34° 53' E
VCE	Venice, Italy	45° 30' N, 12° 21'E
VRN	Verona, Italy	45° 23' N, 10° 53' E
ZAG	Zagreb, Croatia	45° 44' N, 16° 41' E

The GENESIS-UV (GENeration and Extraction System for Individual expoSure) system was used to collect UV radiation data; it was previously deployed in large studies of occupational solar exposure.[27,31] The electronic data logger X-2012-10 (Gigahertz, Türkenfeld, Germany) comprises sensors for measurements of UV-A and erythema effective irradiances. The 15-s sampling interval was chosen to enable long deployments.

The spectral sensitivity of the UV-A detector presented in **Fig. 1** has strong wavelength dependence; it peaks at 325 nm and decreases with increasing wavelengths. If this wavelength dependence is not taken into account, it could introduce substantial measurement errors for aircraft with different types of windshields. Fig. 1 shows short wavelength solar radiation spectra attenuated by two types of aircraft windshields taken from Chorley et al.[9] To account for spectral dependence of sensitivity, the UV-A sensors were calibrated with the sunlight filtered at 345, 360, and 385 nm to simulate transmission of UVR in the cockpits.[5,9] If windshield spectral properties are not considered, the UV-A dose in flights with high UV-A transmitting windshields (shown as in-flight spectrum 1 in Fig. 1)

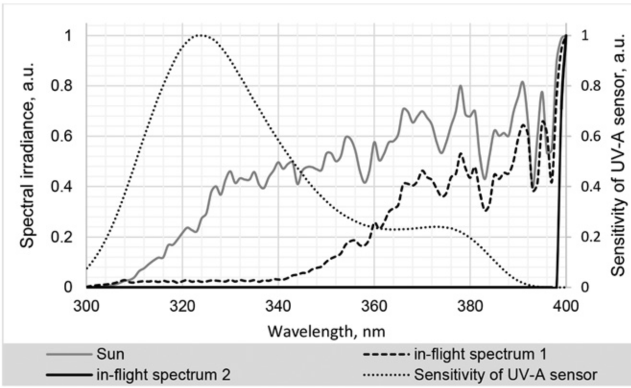

Fig. 1. Spectral sensitivity of the UV-A detector (dotted line) and examples of solar spectra measured outside and inside cockpits[5,9] shown as relative values (arbitrary units, a.u.).

may be underestimated by up to 6 times; for flights with high UV-A attenuating windshields (shown as in-flight spectrum 2), transmitted UV radiation is below the measurement threshold of the instrument used. The calibration was carried out before and after deployments. None of the aircraft involved in the current study had low UV-A windshield transmission.

Data Analysis

The erythema effective and UV-A doses were calculated for each outbound and inbound flight and compared with the ICNIRP guidance on exposure to the eyes and skin;[15] these limits represent levels which are not expected to result in adverse effects in healthy individuals. Erythema effective dose was expressed in standard erythema dose, SED of 100 $J \cdot m^{-1}$.[2,10] The in-flight doses were also compared with expected weekend recreational UV exposures of UK office workers over the same period. The Chi-squared test of independence[30] was used to test the null hypothesis for age of the aircraft and season.

On any given day, participants were flying two-sector flights. Data collection periods varied between 7 and 53 d. Participating pilots wore dosimeters and filled in diaries for all flights during the collection period. Diary records were accurately correlated with data measured by the dosimeters. Data from three return flights when a dosimeter was not worn by the pilot were excluded from the analysis.

The in-flight doses received by the pilot participants were compared with estimated sun exposure of an indoor worker during the same data collection period in three regions of the United Kingdom: Camborne (50°13'N, 5°19'W), Chilton (51°35'N, 1°19'W), and Glasgow (55°51'N, 4°20'W), based on environmental data from the Public Health England solar monitoring network.[22] This was used to aid the interpretation of the presented results of pilots' exposure.

RESULTS

The erythema effective doses were insignificant and did not exceed 0.1 SED in any flight, in agreement with published data.[5,12,26] UV-A exposure doses for morning outbound flights are given in **Table II**, split into seasons and, where applicable, grouped for similar destinations: south, southwest, and southeast of Europe and the Canary Islands. Flights to some destinations are seasonal; there were no flights southeast of Europe in August–September 2016 and March–April 2017. Where the recorded exposure dose was below 10% of the 10 $kJ \cdot m^{-2}$ ICNIRP guidance exposure limit, it is reported as $< 1\ kJ \cdot m^{-2}$. The times are in UTC; the time of the first flights was 04:49 in July–June 2017, 05:00 and 05:50 in March–April 2017 and August–September 2017, and 06:00 in December 2017–January 2018.

On 74 morning outbound and morning or early afternoon inbound flights, the UV-A exposures were under 1 $kJ \cdot m^{-2}$; on 33 flights it was higher than 1 $kJ \cdot m^{-2}$, but below 10 $kJ \cdot m^{-2}$. On four outbound and seven inbound flights, UV-A doses were above 10 $kJ \cdot m^{-2}$. The highest values were recorded at 20.1 $kJ \cdot m^{-2}$ on the 05:18 flight to Dubrovnik and 32.2 $kJ \cdot m^{-2}$ on the 09:50 flight from Naples. The highest cumulative dose of 29.6 $kJ \cdot m^{-2}$ was recorded on a return flight from Dalaman in July 2017. No correlation between time of the morning departures and UV-A doses were found for flights to the south and southwest of Europe ($P < 0.05$).

Flights departing from the UK in the afternoon are shown in **Table III** and they are split into seasons and grouped for similar destinations. For the afternoon outbound and afternoon or evening inbound flights (119 return flights), UV-A exposures were under 1 $kJ \cdot m^{-2}$; on 24 flights, they were higher than 1 $kJ \cdot m^{-2}$, but below 10 $kJ \cdot m^{-2}$ for the duration of the two-sector flight.

A total of 43 sector flights were not flown during daylight hours and none of the afternoon inbound flights contributed to overall exposure of pilots. In five outbound flights, UV-A doses were above 10 $kJ \cdot m^{-2}$; the highest was recorded at 63.5 $kJ \cdot m^{-2}$ on the 13:34 flight to Tenerife in summer 2016.

The results presented here show that UV-A exposure is mostly governed by the presence of direct sunlight in the cockpit and also the duration of the flight. The highest UV-A dose was recorded on afternoon outbound flights from southwesterly directions to Tenerife. These flights were the longest, up to 4 h, 45 min, and the UV-A dose was $\sim$12 $kJ \cdot m^{-2}$ per hour of flight.

In this study, 32 different Airbus aircraft were flown and they were manufactured in 1998 or later. The measured UV-A doses were independent of age of the aircraft ($P = 0.73$). Some flights to the same destinations at the same time of the day and season recorded significantly different doses, e.g., the 13:34 MAN–TFS with a UV-A dose of 63.5 $kJ \cdot m^{-2}$ and the 13:34 MAN-TFS flights with a UV-A dose of 8.5 $kJ \cdot m^{-2}$, both in summer 2016. This difference may be explained by using visors: the pilots reported that visors were not used on the flight with the higher UV-A dose. This explanation is supported by a previous study that showed that visors decrease the UV-A level to below 5% in the Airbus cockpits.[4] In some cases, the measured doses were relatively high despite records of visor use in the participant's diary. This may be due to the visors being used only for part of the flight or that the pilot shielded their eyes from the bright sunlight, leaving the chest-mounted dosimeter fully or partly exposed.

Table II. UV-A Exposure on Morning Outbound and Morning or Early Afternoon Inbound Flights.

	OUTBOUND FLIGHT		INBOUND FLIGHT	
DESTINATION	**DEPARTURE TIME, UTC**	**UV-A EXPOSURE, kJ · m^{-2}**	**DEPARTURE TIME, UTC**	**UV-A EXPOSURE, kJ · m^{-2}**
AUGUST–SEPTEMBER 2016				
MAN–PMI	05:00:00	<1	09:00:00	<1
MAN–PMI	05:15:00	<1	09:10:00	<1
MAN–PMI	05:27:00	<1	09:26:00	<1
MAN–PMI	05:28:00	5.4	09:09:00	11.3
MAN–PMI	05:35:00	<1	09:15:00	<1
MAN–ALC	06:00:00	<1	09:40:00	<1
MAN–NAP	06:00:00	4.5	09:50:00	32.2
MAN–AGP	06:05:00	<1	10:01:00	<1
MAN–ALC	06:11:00	<1	09:47:00	3.6
MAN–FAO	06:14:00	<1	10:19:00	<1
MAN–BNC	06:20:00	5.7	09:40:00	8.9
MAN–ALC	06:20:00	3.5	10:15:00	10.4
BWX–VCE	06:22:00	4.2	09:20:00	10.2
MAN–VCE	06:32:00	<1	09:59:00	<1
LBA–FAO	06:40:00	<1	10:30:00	<1
MAN–BCN	06:35:00	<1	09:58:00	<1
LBA–FAO	06:40:00	<1	10:30:00	<1
CANARY ISLANDS				
MAN–ACE	06:20:00	9.0	11:30:00	10.8
MAN–FNC	06:35:00	5.4	11:35:00	10.0
MAN–TFS	06:35:00	<1	12:25:00	<1
MAN–FNC	06:39:00	2.6	11:51:00	5.3
DECEMBER 2016–JANUARY 2017				
MAN–ALC	06:00:00	<1	12:00:00	<1
LBA–AGP	06:18:00	1.7	10:16:00	1.6
MAN–LIS	07:00:00	<1	11:00:00	<1
LBA–FAO	07:00:00	13.9	10:56:00	4.0
LBA–FAO	07:15:00	<1	10:50:00	<1
MAN–FAO	07:47:00	<1	11:07:00	1.3
CANARY ISLANDS				
MAN–TFS	06:00:00	<1	12:00:00	<1
LBA–TFS	06:10:00	<1	11:00:00	<1
LBA–TFS	06:15:00	15.8	11:33:00	5.6
MAN–TFS	08:56:00	<1	14:31:00	<1
MAN–TFS	09:00:00	<1	14:47:00	<1
SOUTHEAST				
MAN–LEI	07:35:00	<1	11:16:00	<1
MAN–TLV	08:42:00	<1	15:14:00	<1
MARCH–APRIL 2017				
LGW–GNB	05:50:00	<1	08:20:00	<1
LGW–GVA	06:10:00	<1	09:10:00	<1
LGW–GVA	06:30:00	<1	09:30:00	<1
LGW–ALC	07:23:00	1.8	11:00:00	<1
LGW–FAO	08:40:00	<1	12:00:00	<1
LGW–FAO	08:57:00	8.2	12:18:00	2.0
CANARY ISLANDS				
LGW–ACE	06:10:00	<1	11:15:00	<1
JUNE–JULY 2017				
MAN–BCN	04:49:00	<1	08:31:00	1.9
MAN–BCN	04:49:00	1.5	08:03:00	<1
MAN–PMI	05:25:00	2.6	09:30:00	6.1
MAN–PMI	05:32:00	<1	09:05:00	<1
MAN–VCE	05:40:00	<1	09:40:00	<1
MAN–MAH	06:00:00	<1	09:28:00	<1
BHX–ALC	06:05:00	2.0	09:35:00	3.2
MAN–FAO	06:08:00	<1	10:04:00	3.2
MAN–AGP	06:09:00	<1	10:03:00	3.0
MAN–ALC	06:12:00	3.0	09:50:00	<1
MAN–FAO	06:16:00	<1	10:13:00	3.0
MAN–AGP	06:18:00	<1	10:27:00	<1

Table II, *Continued.*

	OUTBOUND FLIGHT		INBOUND FLIGHT	
DESTINATION	DEPARTURE TIME, UTC	UV-A EXPOSURE, $kJ \cdot m^{-2}$	DEPARTURE TIME, UTC	UV-A EXPOSURE, $kJ \cdot m^{-2}$
MAN–FAO	06:24:00	<1	10:33:00	3.0
MAN–BCN	06:26:00	<1	09:43:00	<1
MAN–VCE	06:36:00	1.5	10:45:00	<1
MAN–PMI	06:38:00	<1	10:09:00	1.3
MAN–MAH	07:00:00	2.3	10:30:00	2.2
SOUTHEAST				
BHX–DBV	05:18:00	20.1	08:55:00	3.4
MAN–DLM	05:29:00	17.3	11:00:00	12.3

The UV-A doses strongly depended on season ($P < 0.05$). In winter, all recorded doses on the afternoon inbound flight were below 1 $kJ \cdot m^{-2}$ and/or took place when it was dark. Winter flight schedules resulted in less frequent flights to the southeast of Europe and the Canary Islands, which significantly reduced the overall monthly UV-A exposure. This seasonal effect is even clearer when mean daily doses on flight days in different seasons are considered for each participating pilot (**Table IV**). The average in-flight daily doses are below 8.8 $kJ \cdot m^{-2}$ and they strongly depend on the season. In winter, UV-A exposures were insignificant for the majority of participants and, for one pilot only, this exposure reached 21.4 $kJ \cdot m^{-2}$ on a return flight to Tenerife. This is a consequence of more flights outside of daylight hours or in low UVR levels; there are also less frequent flights with direct sunlight in the cockpit. Summer 2017 was the busiest period and pilots flew 13 to 20 flights a month compared to 6 to 11 flights in winter.

Table V lists a calculated sun exposure of an indoor worker in three different locations in the UK. The doses were calculated over 2.5 h of typical recreational time spent outdoors by office workers over the weekend in the United Kingdom[1] and under the assumption that vertically orientated surfaces receive 25% of radiation measured on the horizontal plane.[28]

DISCUSSION

Under the morning sun, the average daily 2.5-h long weekend UV-A exposures for the period of 17 June–16 July 2017 were in the range of 62–73 $kJ \cdot m^{-2}$ in all locations, comparable with the maximum in-flight UV-A dose of 63.5 $kJ \cdot m^{-2}$ received on an outbound flight to Tenerife in summer 2016; recreational weekend exposure to the afternoon sun was higher than the recorded in-flight values.

In-flight measurements of solar radiation are challenging and published information is limited. Very low erythema effective doses were recorded in all flights, consistent with the 1990 study by Diffey et al.[12] and the later studies of Nakagawara,[20] Chorley et al.,[5,9] Cadilhac et al.,[3] Schennetten et al.,[26] and Sanlorenzo et al.[24] In-flight measurements of UV-A radiation were not feasible in Diffey and Roscoe[12] because the spectral response of the polysulphone film used in that study is limited to wavelengths below 330 nm, which would have been effectively blocked by the aircraft windshields. Furthermore, their measurements showed that transmission from the acrylic side windshields of the Airbus A320 was below 1% for wavelengths shorter than 385 nm.

Post-2000 studies all reported substantially lower UV-A attenuation of newer aircraft. Thus, in 2006, the transmittance of eight disassembled windshields, including the laminated glass windshields of the Airbus A320 and Boeing 727 and 737 aircraft, were measured by Nakagawara et al.[20] and showed wide variations of UV-A attenuation, up to 53.5% UV-A for laminated glass windshields. Chorley et al.[5] carried out measurements of 15 windshields from Boeing 777, 757, and 747, Airbus A321 and A320, Concorde, Embraer 195, and Bombardier Dash8 manufactured between 1973 and 2011 and showed that UV-A attenuation was independent of the type of aircraft, but correlated with its age. Variation of UV transmission of aircraft windshields was confirmed by five in-flight spectral measurements by Schennetten et al. in 2019,[26] who reported two different types of windshield, with good and poor UV-A attenuation, but did not provide any information on aircraft age. Increased UV transmission of windshields in modern aircraft would suggest that the prevalence of good UV-A attenuation windshields on commercial passenger airplanes will decrease over time as all the newest aircraft had poor UV-A attenuating windshields. This circumstance raised a concern that accumulative occupational UV-A exposure of pilots may be increasing in recent years.

Variations of UV-A attenuation of windshields in the fleet employing aircraft of different ages may, in part, explain a difference of maximum in-flight UV-A doses reported in post-2010 studies such as, for example, flights to the same destination at the same time of the year by Chorley et al. [5] All the Monarch Airbus A320 and A321 flown in the current study were manufactured in or after 1998 and in-flight measurements confirmed low UV-A attenuation of the windshields.

Schennetten et al.[26] measured 6.5%/1000 m altitude dependence of UV-A above the cloud ceiling during the approach to Frankfurt on an Airbus A340-313 Narita–Frankfurt flight in December 2016. Measurements were carried out behind the high UV-A transmitting front left windshield, solar elevation angle was nearly constant at 10.5–11°, and there was a very small course correction of 3° in heading during these measurements. In this study, the direct sunlight in the cockpit and solar

Table III. UV-A Exposures on Afternoon Outbound and Evening Inbound Flights.

	OUTBOUND FLIGHT		INBOUND FLIGHT	
DESTINATION	DEPARTURE TIME, UTC	UV-A EXPOSURE $kJ \cdot m^{-2}$	DEPARTURE TIME, UTC	UV-A EXPOSURE $kJ \cdot m^{-2}$
AUGUST–SEPTEMBER 2016				
MAN-AGP	14:20:00	<1	18:15:00	<1
MAN-AGP	14:20:00	2.6	18:15:00	<1
MAN-AGP	14:21:00	16.9	18:22:00	<1
MAN-AGP	14:24:00	<1	18:12:00	<1
MAN-ALC	15:05:00	<1	18:50:00	<1
MAN-GIB	15:10:00	10.5	19:00:00	<1
MAN-BCN	15:14:00	<1	18:37:00	<1
LBA-BCN	15:20:00	<1	18:45:00	<1
MAN-PMI	15:24:00	<1	19:12:00	<1
MAN-PMI	15:25:00	3.3	19:00:00	<1
MAN-ALC	16:09:00	2.3	20:00:00	dark
MAN-ALC	16:20:00	<1	20:06:00	dark
MAN-ALC	16:35:00	<1	20:13:00	dark
MAN-IBZ	20:35:00	dark	00:17:00	dark
MAN-IBZ	22:24:00	dark	02:02:00	dark
CANARY ISLANDS				
MAN-TFS	13:34:00	8.5	19:31:00	<1
MAN-TFS	13:34:00	63.5	19:09:00	<1
MAN-ACE	14:05:00	<1	19:20:00	<1
MAN-TFS	14:35:00	<1	19:55:00	<1
MAN-TFS	15:13:00	1.7	21:07:00	dark
DECEMBER 2016–JANUARY 2017				
MAN-INN	13:54:00	<1	18:00:00	dark
MAN-GIB	14:00:00	<1	18:00:00	dark
MAN-FAO	14:28:00	<1	18:11:00	dark
LBA-AGP	14:28:00	<1	18:21:00	dark
MAN-FAO	14:29:00	<1	18:00:00	dark
MAN-ALC	15:00:00	<1	18:00:00	dark
MAN-ALC	15:00:00	<1	19:00:00	dark
MAN-GIB	15:08:00	<1	18:49:00	dark
MAN-LIS	15:15:00	<1	19:02:00	dark
MAN-LIS	15:16:00	<1	19:06:00	dark
MAN-GIB	15:20:00	<1	19:01:00	dark
MAN-GIB	15:20:00	<1	18:00:00	dark
MAN-LIS	16:00:00	<1	19:35:00	dark
MAN-ALC	15:34:00	<1	19:15:00	<1
MAN-VCE	16:30:00	<1	19:40:00	dark
MAN-AGP	16:35:00	dark	23:58:00	dark
MAN-PMI	16:49:00	dark	20:15:00	dark
MAN-VCE	16:50:00	dark	19:55:00	dark
MAN-BCN	16:53:00	dark	20:13:00	dark
MAN-LIS	17:06:00	dark	20:49:00	dark
MAN-VCE	17:43:00	dark	21:01:00	dark
CANARY ISLANDS				
MAN-TFS	12:00:00	<1	18:00:00	<1
MAN-TFS	12:05:00	<1	17:46:00	<1
MAN-FUE	13:00:00	1.6	18:00:00	<1
MAN-LPA	13:33:00	<1	18:00:00	<1
MAN-TFS	14:00:00	<1	18:00:00	<1
MAN-TFS	14:20:00	<1	18:00:00	<1
MAN-ACE	15:04:00	<1	20:24:00	<1
MAN-ACE	15:05:00	<1	20:11:00	<1
MAN-FUE	15:13:00	<1	20:43:00	<1
MAN-FUE	15:33:00	<1	20:37:00	<1
MARCH–APRIL 2017				
LGW-VCE	13:18:00	<1	16:00:00	<1
LGW-AGP	15:25:00	23.8	19:05:00	dark
CANARY ISLANDS				
LGW-TFS	12:20:00	2.5	17:50:00	<1
LGW-TFS	14:40:00	<1	20:30:00	dark

Table III, *Continued.*

DESTINATION	OUTBOUND FLIGHT DEPARTURE TIME, UTC	OUTBOUND FLIGHT UV-A EXPOSURE kJ · m^{-2}	INBOUND FLIGHT DEPARTURE TIME, UTC	INBOUND FLIGHT UV-A EXPOSURE kJ · m^{-2}
		JUNE–JULY 2017		
BHX-NCE	12:10:00	<1	15:10:00	<1
MAN-FAO	13:37:00	<1	18:03:00	<1
BHX-MAH	13:49:00	<1	17:00:00	<1
MAN-GIB	14:05:00	3.4	17:50:00	<1
MAN-OPO	14:06:00	<1	17:41:00	<1
MAN-GIB	14:11:00	3.2	17:55:00	<1
MAN-GIB	14:17:00	3.3	18:18:00	<1
MAN-AGP	14:20:00	<1	18:17:00	<1
MAN-LIS	14:22:00	1.4	18:30:00	<1
MAN-AGP	14:23:00	<1	17:57:00	<1
BHX-GIB	14:24:00	<1	18:08:00	<1
MAN-GIB	14:28:00	<1	18:15:00	<1
MAN-LIS	14:28:00	4.4	18:22:00	<1
MAN-AGP	14:30:00	4.7	18:13:00	<1
BHX-NAP	14:53:00	<1	18:33:00	<1
BHX-ALC	14:54:00	4.1	18:05:00	<1
MAN-AGP	15:06:00	3.9	19:01:00	<1
BHX-ALC	15:10:00	6.2	18:37:00	<1
BHX-OPO	15:31:00	4.6	19:05:00	<1
MAN-VRN	15:40:00	<1	18:35:00	<1
MAN-BCN	15:54:00	2.1	19:35:00	<1
MAN-ALC	16:15:00	<1	19:57:00	<1
MAN-ALC	17:10:00	<1	20:05:00	dark
BHX-VCE	17:31:00	<1	20:22:00	dark
MAN-PMI	17:35:00	1.8	21:09:00	dark
MAN-PMI	17:56:00	<1	21:16:00	dark
		CANARY ISLANDS		
MAN-ACE	13:35:00	3.0	20:05:00	<1
MAN-FUE	13:52:00	12.7	19:04:00	<1
BHX-FUE	13:57:00	<1	19:07:00	<1
MAN-FNC	14:09:00	<1	18:49:00	<1
MAN-ACE	14:47:00	8.3	20:15:00	<1
MAN-FUE	14:59:00	1.6	20:02:00	<1
		SOUTHEAST		
BHX-LCA	12:59:00	2.7	18:39:00	<1
BHX-PFO	13:17:00	<1	18:47:00	<1
MAN-DBV	14:12:00	2.2	17:52:00	<1
MAN-DBV	14:19:00	<1	18:24:00	<1
MAN-DLM	15:06:00	<1	20:00:00	dark
BHX-HER	15:46:00	<1	18:37:00	<1
MAN-AXD	16:44:00	<1	19:58:00	dark
MAN-ZAG	16:45:00	<1	20:00:00	dark
MAN-ZAG	17:00:00	<1	20:05:00	dark

elevation angles were attributed to the variation of UV-A irradiance. Comparison of the 02:28 UTC Nagoya–Frankfurt flight in December 2017 (more direct sunlight due to low solar elevation but low UV-A irradiance) and the 10:35 UTC Frankfurt–Faro–Frankfurt flight in June 2017 (less direct sunlight with high solar elevations but higher irradiance) showed that although low solar elevation angles resulted in more direct sunlight, e.g., blinding conditions, to the pilot's face, UV-A irradiance was higher with higher solar elevation, and their combination in these two particular flights resulted in very similar peak irradiance of 7 W · m^{-5}.

Sanlorenzo et al.[24] used two broadband Solartech, UV-A+UV-B and UV-B only UV index meters to measure UV radiation in the pilot seat at the 2500–30,000 ft (762–9144 m) range of altitude during turboprop Sokata TBM850 flights in California and Nevada in April 2014. Direction, departure times, and duration of flights are not reported in this publication. The study showed that UV-A irradiance approximately doubled at cruising altitude compared with ground level, peaking at 2.4 W · m^{-5} at 30,000 ft in California, and this increase is consistent with the findings of Schennetten et al.[26] The authors also concluded that 20 min on a tanning bed would result in an equivalent UV-A dose to a pilot during 56.6 min of flight. It should be noted that this publication did not provide information on whether the spectral sensitivity of the UV-A+UV-B sensor was corrected to account for attenuation of the aircraft windshields. Spectral

Table IV. Average UV-A Doses of Individual Pilots for Different Seasons.

PERIOD	PILOT ID	START DATE	END DATE	FLIGHT DAYS	AVG. DAILY UV-A DOSE ON FLIGHT DAYS, $kJ \cdot m^{-2}$	STDEV, $kJ \cdot m^{-2}$	UV-A DOSE RANGE, $kJ \cdot m^{-2}$	TOTAL UV-A DOSE PER PERIOD, $kJ \cdot m^{-2}$
Summer 2016	1	03/08/2016	01/09/2016	10	4.5	4.9	0–11.3	45.4
	2	04/08/2016	03/09/2016	10	4.2	4.7	0.1–32.1	42.4
	3	02/08/2016	29/08/2016	8	4.6	11.2	0–32.1	37.1
	4	03/08/2016	30/08/2016	12	8.1	18.2	0–65.7	97.0
Winter 2016-2017	1	02/12/2016	24/12/2016	11	0.4	1.0	0–2.8	4.8
	2	12/12/2016	25/12/2016	4	0.8	0.4	0.4–1.3	3.1
	3	12/12/2016	18/12/2016	4	0.5	0.8	0–1.6	1.9
	4	09/12/2016	02/01/2017	10	4.5	8.1	0–21.4	44.9
	5	10/12/2016	01/01/2017	5	0.2	0.2	0–0.5	1.2
	6	15/12/2016	26/12/2016	3	0.2	0.4	0–0.6	0.6
	7	09/12/2016	01/01/2017	4	0.0	0.0	0–0	0.2
Spring 2017	1	16/03/2017	02/04/2017	3	8.8	13.1	0.1–23.8	26.4
	2	18/03/2017	02/04/2017	5	1.0	0.8	0.2–2.1	4.9
	3	17/03/2017	24/03/2017	3	3.8	5.6	0.1–10.2	11.4
Summer 2017	1	17/06/2017	01/08/2017	15	1.8	3.4	0–13.3	26.6
	2	16/06/2017	17/07/2017	13	4.8	8.0	0.1–29.5	62.2
	3	18/06/2017	19/07/2017	16	2.7	1.2	0–1.6	43.8
	4	30/06/2017	26/07/2017	16	3.2	5.9	0.1–23.5	51.8

sensitivity of a sensor used in the study had a maximum at approximately 360–365 nm and dropped to less than 5% of peak value at 400 nm.[29] If wavelength dependence of sensor sensitivity is not considered, it may underestimate UV-A irradiance behind the windshield, as explained in the Methods section of this manuscript.

An RM12 (OPSYTEC) radiometer equipped with three UV-A, UV-B, and UV-C sensors was used by Cadilhac et al.[3] to measure UV radiation during daylight hours during 14 short and long-haul flights from July to October 2016; depending on the duration of the flight, three to seven measurements were taken at cruise altitude. UV-A irradiance varied between 0.1 $W \cdot m^{-5}$ and 12.2 $W \cdot m^{-5}$. It should be noted that ground UV-A radiation was in the range of 4.5–33.8 $W \cdot m^{-5}$. Comparison of measured maximum UV-A and UV-B irradiances in Boeing 777 cockpits (see Table III in this publication) suggest that aircraft flown on CDG–Vancouver and Vancouver–CDG flights were equipped with high UV attenuating windshields; aircraft flown to or from Beirut, Tokyo, Panama, and Lima were equipped with low UV attenuating windshields. No UV radiation was measured in flight on any of the flown Airbuses (A330, A319, and A380). Similarly to the Sanlorenzo study,[25] there is no information on whether spectral sensitivity to UV-A was corrected to account for attenuation of the aircraft windshields. Spectral sensitivity of a sensor used in the study also had a maximum at approximately 360–365 nm and dropped to less than 5% of the peak value at 400 nm.[23] Again, if wavelength dependence of sensor sensitivity is not considered, it may underestimate the UV-A irradiance behind the windshield, as previously described.

The Schennetten et al.[26] and Cadilhac et al.[3] studies also demonstrated significant attenuation of UVR by visors, by a factor of ~30 and ~10, respectively, consistent with the findings of the current study. Meerkotter et al.[18] suggested a numerical model to estimate UV radiation inside cockpits using the radiative transfer model and taking into account windshield transmission and cockpit geometry. Its application was illustrated for 10 single sector intercontinental flights from Europe on days around the solstices and equinox and also calculated as a function of the day of the year. The study concluded that UV radiation in the cockpit strongly depends on the presence of direct sunlight in the cockpit. The highest doses between 380 and 600 $kJ \cdot m^{-2}$ were on flights from East Asia on westward routes in March and September with direct sunlight contributing to the total dose for up to 70% of the flight time (~12 h long). If confirmed experimentally, such an approach would provide a very useful tool for the evaluation of in-flight UV exposures, including retrospective life-long flight history.

Table V. The Average Daily Weekend UV-A Doses from a 2.5-h Exposure in the Middle of the Day (11:00-13:30 BST) or Morning (9:00-11:30 BST) and Total UV-A Recreational Weekend Exposures Over Data Collection Period from 17 June to 16 July 2017 in Chilton, Camborne, and Glasgow.

TIME OF THE DAY	9:00-11:30 BST			11:00-13:30 BST		
SITE	UV-A WEEKEND DAILY DOSE, $kJ \cdot m-2$ (STDEV)	RANGE	TOTAL UV-A DOSE/ PERIOD, $kJ \cdot m-2$	UV-A WEEKEND DAILY DOSE, $kJ \cdot m-2$ (STDEV)	RANGE	TOTAL UV-A DOSE/ PERIOD, $kJ \cdot m-2$
Chilton	55.0 (19.5)	29.0–82.0	443	72.6 (23.5)	32.3–101.6	581
Camborne	47.4 (23.8)	20.5–79.5	379	62.5 (35.8)	25.2–104.4	500
Glasgow	51.8 (16.7)	26.2–79.7	414.4	66.2 (28.6)	21.4–98.9	529.7

BST = British Summer Time.

UV exposures were measured for a single airline with a specific portfolio of destinations, pilot shift patterns, and a fleet of Airbus A320 and A321 aircraft of similar ages. As such, the presented results cannot be used to generalize pilots' exposure for different airlines, destinations, or latitudes. For the northern hemisphere, the highest predicted doses during the short- and long-haul flights are expected to be in the easterly destinations in the morning and westerly destinations in the afternoon, but these are yet to be confirmed experimentally. The transmission of the windshield plays a very important role and all Monarch Airline fleet aircraft deployed in this study were manufactured in 1998 or later. Other airlines may have different fleet age profiles; however, as the older pre-1990 aircraft are being gradually replaced with newer planes, the results from this study will be more appropriate for the UV exposure of pilots in the foreseeable future.

The cumulative UV-A doses of pilots during their occupational life have not been quantified as they depend on the total flight time, specific destinations, and the UV-A transmission of aircraft windshields of aircraft flown and personal preference in using sun protection measures such as visors, sunglasses, sunscreens, etc. Finally, leisure and recreational sun exposure need to be considered before meaningful risk analysis can be undertaken.

For interpretation of in-flight ocular exposure to UVR, it is important to treat the results presented here with some caution. The position of the dosimeter (chest level) may not accurately represent exposure of pilots' eyes. Furthermore, Chorley et al.[5] measured UV exposure looking ahead and down and showed that ocular exposure decreased by 30–50% when looking down at the instrument dashboard; therefore, ocular dose should be integrated over possible eye movement. In addition, the use of sunglasses, aircraft visors covering a relatively small area of the windshield,[5] or nonstandard procedures to control sunlight brightness on the flight deck[7,8] would reduce the irradiance at the eye level, but may not affect the sunlight level recorded by the dosimeter on the chest.

The recent meta-analysis studies indicate that airline pilots are at twice the risk of developing melanoma and keratinocyte skin cancers than the general population and they have increased mortality from melanoma. Although to date there is no conclusive evidence of the increased prevalence of cataracts among pilots, in the future it is important to review this evidence considering gradual replacement of aircraft with high UV attenuating windshields with models equipped with high UV transmitting windshields. Analysis of correlation between in-flight exposure to ionizing radiation or circadian rhythm disruption caused by pilots' shift work and skin cancers is inconclusive; possible overexposure to UVR during flights may be implicated. In this study, in-flight measurements of UVR were conducted over three seasons from September 2016 to August 2017 by Monarch Airlines pilots. The UV-A and erythema effective doses were measured on the Airbus A320-214 and A321-231 type of aircraft on 312 short-haul flights to 31 destinations in Europe from 4 UK airports. The erythema (sunburn) doses were negligible and did not exceed 0.1 SED for all flights, in agreement with published data. For most of the flights, the UV-A exposures were low; on 13 flights out of 312, UV-A exposure could have exceeded the ICNIRP exposure guidance if sunglasses had not been worn or visors deployed. Analysis of results clearly demonstrated that the UV-A level in a cockpit is mostly governed by the presence of direct sunlight (direction and time of the flight dependent); exposure dose is further affected by duration of the flight. In the northern hemisphere, direct sunlight may be present in the cockpit in the morning in the easterly directions and in the afternoon in the westerly directions. The highest UV-A doses were on afternoon outbound flights in the southwesterly direction to Tenerife in the summer. The UV-A doses on winter flights to the same destinations were significantly lower; for one pilot only, it reached 21.4 $kJ \cdot m^{-2}$ on the return flight to Tenerife. Although some of the UV-A doses exceeded ICNIRP guidance, the average monthly doses were lower than the average UV-A recreational weekend exposures of UK office workers over a similar period. The maximum UV-A dose of 63.5 $kJ \cdot m^{-2}$ received by the pilot on the flight to Tenerife was comparable to the recreational weekend UV-A exposure in the morning sun, but lower than estimated for the middle of the day in summer.

The cumulative occupational UV exposure of pilots depends on the total flight time, the destination, and on the UV attenuation of the aircraft's windshield. Additionally, the leisure and recreational sun exposure of pilots needs to be considered before meaningful overall risk analysis can be undertaken.

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