Ann. Occup. Hyg., Vol. 55, No. 5, pp. 465–475, 2011
Published by Oxford University Press
on behalf of the British Occupational Hygiene Society
doi:10.1093/annhyg/mer024

Airline Pilot Cosmic Radiation and Circadian Disruption Exposure Assessment from Logbooks and Company Records

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Received 8 April 2010; in final form 23 March 2011; published online 24 May 2011

Objectives: US commercial airline pilots, like all flight crew, are at increased risk for specific cancers, but the relation of these outcomes to specific air cabin exposures is unclear. Flight time or block (airborne plus taxi) time often substitutes for assessment of exposure to cosmic radiation. Our objectives were to develop methods to estimate exposures to cosmic radiation and circadian disruption for a study of chromosome aberrations in pilots and to describe workplace exposures for these pilots.

Methods: Exposures were estimated for cosmic ionizing radiation and circadian disruption between August 1963 and March 2003 for 83 male pilots from a major US airline. Estimates were based on 523 387 individual flight segments in company records and pilot logbooks as well as summary records of hours flown from other sources. Exposure was estimated by calculation or imputation for all but 0.02% of the individual flight segments' block time. Exposures were estimated from questionnaire data for a comparison group of 51 male university faculty.

Results: Pilots flew a median of 7126 flight segments and 14 959 block hours for 27.8 years. In the final study year, a hypothetical pilot incurred an estimated median effective dose of 1.92 mSv (absorbed dose, 0.85 mGy) from cosmic radiation and crossed 362 time zones. This study pilot was possibly exposed to a moderate or large solar particle event a median of 6 times or once every 3.7 years of work. Work at the study airline and military flying were the two highest sources of pilot exposure for all metrics. An index of work during the standard sleep interval (SSI travel) also suggested potential chronic sleep disturbance in some pilots. For study airline flights, median segment radiation doses, time zones crossed, and SSI travel increased markedly from the 1990s to 2003 ($P_{trend} < 0.0001$). Dose metrics were moderately correlated with records-based duration metrics (Spearman's $r = 0.61–0.69$).

Conclusions: The methods developed provided an exposure profile of this group of US airline pilots, many of whom have been exposed to increasing cosmic radiation and circadian disruption from the 1990s through 2003. This assessment is likely to decrease exposure misclassification in health studies.

Keywords: circadian disruption; cosmic radiation; exposure assessment; flight crew; pilots

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is examining the relation between workplace exposures and health effects, including cancer, in flight crew. Reviews (Hammer *et al.*, 2009) and meta-analyses (Buja *et al.*, 2005, 2006) of cancer studies among flight crew agree on excesses of breast cancer and melanoma and possible excesses for other sites. However, corroborative findings (e.g. increasing risk trends with surrogates of cabin exposures) have not

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been consistently identified. This may be due, at least in part, to the limitations of the exposure metrics used (Whelan, 2003).

Cosmic radiation exposure at aircraft altitudes and circadian rhythm disruption due to travel through multiple time zones are two primary exposures hypothesized as cancer risk factors (IARC, 2000; Straif *et al.*, 2007; El Ghissassi *et al.*, 2009). In addition to their biological plausibility, these two exposures are judged to have sufficient variability in the air cabin environment to independently assess and analyze in regard to health outcomes. Other aircraft exposures (e.g. aspects of cabin air quality) have been described (Waters *et al.*, 2002) but lack the variability necessary for analytic separation in health outcomes analyses.

Primary cosmic radiation interacts with molecules of the atmosphere and generates secondary and tertiary radiation at aircraft altitudes. These include neutrons, which the International Agency for Research on Cancer (IARC) has determined to be a Group I (known human) carcinogen (IARC, 2000; El Ghissassi *et al.*, 2009), as well as charged particles with high relative biological effectiveness (Heinrich *et al.*, 1999; Goldhagen, 2000). The International Commission on Radiological Protection (ICRP, 1991, 2008) recommends effective dose (ED) limits of 20 mSv year^{-1} averaged over 5 years (100 mSv in 5 year) for radiation workers and 1 mSv year^{-1} for the public. The ICRP considers flight crew to be occupationally exposed to cosmic radiation. European Union member states implemented regulations for flight crew requiring assessment of exposure when exposure is likely to be >1 mSv year^{-1} [and adjustment of work schedules so that no individual exceeds 6 mSv year^{-1} (EURADOS, 1996)]. Although the US Federal Aviation Administration (FAA), which has jurisdiction over the health and safety of US flight crew, formally recognized in a 1994 Advisory Circular that aircrew members are occupationally exposed to cosmic radiation (FAA, 1994), this circular was canceled and replaced by a 2006 Advisory Circular (FAA, 2006) which states 'provided air carriers respond to solar radiation alerts, ionizing radiation from the sun should not contribute enough additional radiation to exceed recommended exposure limits' and 'the likelihood of developing cancer because of occupational exposure to galactic cosmic radiation is a small addition to health risks experienced by the general population'. There are no official dose limits for aircrew members in the USA.

Flight crew also experience chronic circadian rhythm disruption when their typical work schedule requires flying across multiple time zones or working during their normal sleep hours, a form of shiftwork (Grajewski *et al.*, 2003). Recent research indicates that the molecular circadian clock, which sets rates and periodicity for many biochemical functions, also modulates cellular response to DNA repair (Sancar *et al.*, 2010). IARC classified shiftwork that involves circadian disruption as Group IIA (probably carcinogenic to humans) based, in part, on studies of female flight attendants (Straif *et al.*, 2007).

Occupational exposure for most flight attendant cancer studies has been estimated using duration of employment. In contrast, many pilot cancer studies have estimated cosmic radiation exposure from additional information often available for pilots (aircraft equipment flown, typical routes flown, block time, or flight hours). However, the extent to which these estimates or surrogate metrics represents exposures of interest in the air cabin environment is not fully understood. These estimates do not directly address cosmic radiation exposures incurred from solar particle events (SPEs; also referred to as solar energetic particle events). SPEs are transient (several hours to days) sources of energetic ionizing radiation associated with eruptions of varying intensity on the Sun's surface.

There are ∼614 000 active non-military pilots in the USA, including 147 000 active airline transport pilots (FAA, 2009), and these totals may not include some pilots who fly as first officers. For a NIOSH study of chromosome aberrations among commercial airline pilots and a comparison group of university faculty, the adjusted translocation frequency was significantly associated with flight years ($P = 0.01$) with rate ratios of 1.06 [95% confidence interval (CI) 1.01–1.11] and 1.81 (95% CI 1.16–2.82) for a 1- and 10-year incremental increase in flight years, respectively (Yong *et al.*, 2009).

The first objective of this study was to develop methods to provide detailed cosmic radiation and circadian disruption exposure data for additional analyses of this study's chromosome aberration data. The second objective was to describe the workplace exposures of this group of US pilots in detail.

METHODS

A summary of methods is provided below. A full description of methods is located in Supplementary data available at *Annals of Occupational Hygiene* online.

The study population consisted of 83 full-time male pilots working for a major US airline at a domicile (hub) with international service and a comparison group of 51 male university faculty from the same city

(Yong *et al.*, 2009). For each individual flight segment flown (a single flight between two cities without intermediate stops), the following data were extracted, calculated, or imputed: date flight began, origin, and destination cities (city pairs); block time (airborne time plus taxi time); and local departure and arrival times. Methods were also developed to assess non-segment (summary) flight, commuter, recreational, and pass travel (non-work-related passenger flying, usually on the study airline) and to impute exposure metrics based on partial data.

CARI6P, screen version 9/17/2005, and CARI6PM, screen version 5/1/2007 (Friedberg and Copeland, 2003) were used to estimate background galactic cosmic radiation effective, absorbed, and particle-specific doses for each flight segment. Dose rates for seven distinct aircraft clusters were used for summary data or when origin and destination airports were unknown. Number of SPEs was assessed separately with reference to satellite data for 23 moderate or large events during the study period. To assess circadian disruption, non-directional cumulative time zones crossed and standard sleep interval (SSI) travel, a separate measure of sleep disturbance, were calculated (Grajewski *et al.*, 2003).

The calculated exposure metrics were compared to a questionnaire-derived edited metric for years of flight at the study airline and other commercial employment (questionnaire-edited flight experience; Yong *et al.*, 2009). This metric is not equivalent to duration of employment as typically calculated in flight crew studies.

SAS v9.2 (SAS; SAS Institute, Inc., Cary, NC, USA) was used for analyses. Medians and ranges were used to describe most data.

RESULTS

A summary assessment of the study pilots and their work histories is provided in Table 1, including records quality and levels of some uncertainties in the data. After all efforts to obtain missing work history data, 10% of pilots retained one or more unverified work history time gaps (median 7 months) which could not be evaluated.

Our evaluation included records not always considered in pilot exposure assessment. In addition to their personal logbooks, 45% of study pilots provided summary flight hours records from military service, flight school, or other training. These figures usually were not reflected in logbook records but contributed a median of 628 block hours to exposure estimates (4.2% of a median pilot's cumulative block time, where present). For comparison, the median block hours flown by pilots in the last study year was ~650.

The logbook and company electronic records combined allowed assessment of exposures from 523 387 individual flight segments, which incurred over a million hours of block time. The second half of Table 1 provides information on the impact of the methods developed to minimize the number of segments that could not be analyzed. After these methods were applied, only ~0.5% of all segments representing 0.02% of block time had block times of <5 min or sufficient missing data to make the calculation of radiation dose in CARI6P impossible.

Radiation and circadian disruption metrics for pilots and faculty are found in Table S1 (Supplementary data are available at *Annals of Occupational Hygiene* online). Cumulative exposures by flight type and study time periods are provided for effective and absorbed dose (total and by particle type) and time zones crossed. Combining this information with the summary data from Table 1, a hypothetical (median) pilot in this study had ~26 occupational years of flying and 28 years of flying from all sources. He incurred a cumulative ED of 34.4 mSv (range 10.18–85.25 mSv), with 1.92 mSv (range 0.55–3.83 mSv) in the year preceding the study end date. Median total absorbed dose was 14.85 (range 4.54–37.8) mGy cumulative and 0.85 (0.25–1.69) mGy in the year preceding the study end date. The median pilot worked for the study airline almost 15 years, which was the largest source of exposure; for 70% of study pilots, military flights accounted for the next largest source of exposure (median 8.1 years). Almost half of the study pilots flew with commercial entities other than the study airline (median of 4.9 years). Fifty-seven percent of study pilots commuted to work by flying at some time, but commuting generally contributed relatively little (median 0.18 mSv, 0.5%) to a median pilot's cumulative ED. Private and pass travel flight categories were also relatively minor contributors to exposure. Thus, the exclusion of pass travel prior to age 18 years was not likely to modify these results. Each pilot's work history was different, however, and there were wide ranges of values for the contribution of flights from these categories. For example, half of the pilots who commuted incurred a cumulative ED of 1.73–51.92 mSv from their commuting alone, and commuting represented 17–48% of the cumulative block time for the four pilots with unusually high (>1000) block hours per year. In contrast to the study pilots, the study faculty's median cumulative ED (0.83 mSv) was ~2.4% of the study pilots', although the faculty flew for about the same number of years as the pilots.

Table 1. Characteristics of the work histories of the 83 study pilots[a]

Summary metrics		
Years of flying (all) [median (range)]	27.8 (19.1–38.9)	
Years of occupational flying [median (range)]	26.3 (13.4–38.9)	
Years at study airline [median (range)]	14.8 (0.9–29.1)	
Pilots with military flight experience [n (%)]	58 (70)	
Years of military flying [median (range)]	8.1 (1.7–22.5)	
Pilots with other commercial flight experience [n (%)]	41 (49)	
Years of other commercial flying [median (range)][b]	4.9 (0.2–12.3)	
Pilots who commuted by flying at any time [n (%)]	47 (57)	
Pilots with summary flight hours in work history [n (%)]	37 (45)	
Flight hours [median (range)]	628 (12–4512)	
Unverified[c] gaps present in work history [n (%)]	8 (10)	
Years [median (range)]	0.6 (0.2–5.3)	
Individual flight segments from pilot logbooks and company records		
	N (% of total)	Block time, h (% of total)
Total individual flight segments assessed	523 387 (100)	1 063 754 (100)
No dose calculable	2724 (0.5)	227[d] (0.02)
Dose imputed from equipment dose rate	35 207 (6.7)	23 331 (2.2)
Based on actual equipment	35 026 (6.7)	22 950 (2.2)
Based on pilot equipment cluster mode	181 (0.03)	381 (0.04)
Deadhead imputed segments	2142 (0.4)	3753 (0.4)
Segments derived from multiple landings	95 959 (18.3)	41 549 (3.9)
Imputed block time	87 678 (16.8)	130 715 (12.3)
Outliers replaced	13 151 (2.5)	41 647 (3.9)
Prorated[e]	67 969 (13.0)	74 631 (7.0)
Missing/in error	6558 (1.3)	14 437 (1.4)
Imputed origin and/or destination cities	22 359 (4.3)	18 089 (1.7)

[a]Table data, with the exception of commuter flight, are derived from pilot logbooks and summary hours and company records. Denominators: for summary metrics, the 83 study pilots; for individual flight segments, the total number of flight segments or total block hours from individual study flight segments. Totals may differ from 100 due to rounding. See Methods in Supplementary data available at *Annals of Occupational Hygiene* online, for details.
[b]Among pilots with other commercial experience not at the study airline.
[c]Time during which pilot's occupational activities could not be determined. Median and range are among pilots with unverified gaps.
[d]Estimated based on 5 min of block time per segment.
[e]Individual segment block time assigned to each of a series of segments from a single logged block time.

Variation was also present in the circadian disruption metrics time zones crossed and SSI travel. Median values for pilot cumulative time zones crossed were 362 (40–729) in the last study year and a cumulative total of 5161 (1367–11 062). Although the group median for SSI travel per segment was 0 min, 33% of the individual pilots had non-zero median values of up to 233 min per flight segment (data not shown).

Figure 1 shows the relative contributions of flight categories to estimated cumulative ED. Figure 2 shows the particle components of the pilots' cumulative absorbed dose. Neutrons represented ~58% of the median cumulative ED and 22% of median cumulative absorbed dose, while electromagnetic showers (EMSs) represented the largest proportion (55%) of median cumulative absorbed dose.

Exposure metrics per flight segment by type of flight and decade (Figure 3) indicate, especially for study airline flights, that median doses, time zones crossed, and SSI travel per segment rose markedly from the 1990s to 2003 ($P_{trend} < 0.0001$). This same trend of increasing metric values per segment was seen, to a lesser extent, in other commercial flights during this period as well. The relation of this trend to pilot seniority at the time of flight was also examined. A surrogate for seniority, time in service, was calculated as time from date of first record of work

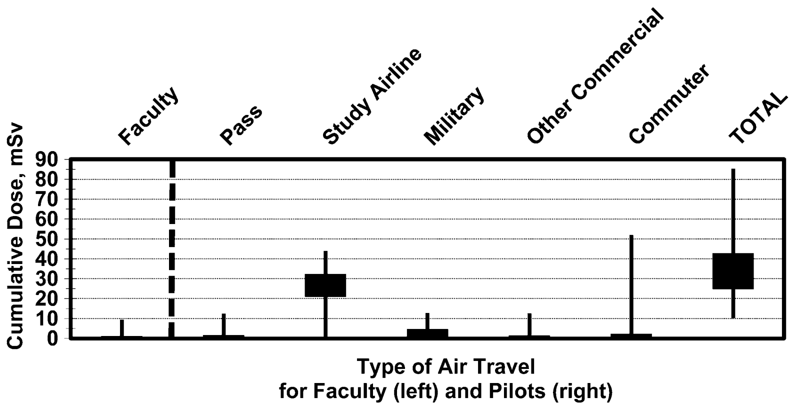

Fig. 1. Components of cumulative effective galactic cosmic radiation dose for 83 pilots. The cumulative ED for 51 faculty (comparison group; recreational travel only) is included for comparison. Black boxes indicate interquartile range and lines indicate data range. Private flight is not shown since values were too low to visualize.

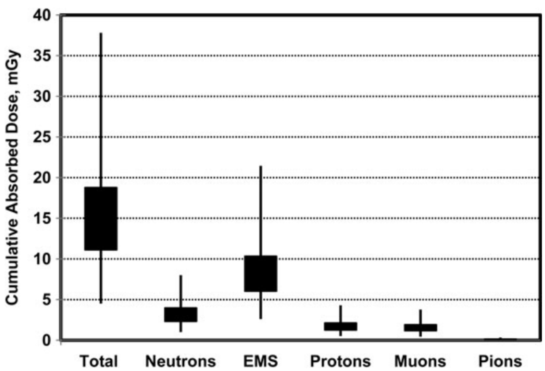

Fig. 2. Cumulative total and particle absorbed galactic cosmic radiation doses for pilots. Black boxes indicate interquartile ranges and lines indicate data ranges.

at the study airline to the date of the flight. In our data, the date of flight and time in service were correlated (0.60 Pearson and 0.59 Spearman; $P <$ 0.0001) because of the voluntary recruitment methods for our study; many of the study pilots volunteered in the later stages of their career. However, by stratifying the data by time in service level, the metric increases from the 1990s forward can be visualized to some degree within all time in service levels for each of the exposure metrics.

The tables and figures describe exposure to background galactic cosmic radiation and do not include our assessment of additional potential exposure to SPEs. SPEs were evaluated in 80% (N = 419 155) of the flight segment data after exclusion of 85 989 (16.4%) segments flown prior to the available SPE data and 18 243 (3.5%) segments missing origin and destination cities (data not shown). Within the 419 155 evaluated flight segments, 14.7% (61 616) were considered to have no significant SPE exposure due to low-altitude equipment. We were able to compare departure and arrival times to the beginning and ending times of the SPE for 72% (256 704) of the remaining segments; 28% (100 775) could only be compared by departure date to the dates of the SPE. Of the evaluated flight segments, a total of 1389 (0.3%) were considered possibly exposed to an SPE by date/time match and an origin or destination city at a geomagnetic latitude of 45° (North or South) or greater.

At least one study pilot was exposed to 22 of the 23 moderate and large SPEs by meeting our exposure criteria for one or more flight segments they flew. The number of pilots possibly exposed to any single SPE was between 3 and 59 (4–71% of all study pilots). Pilots incurred this possible exposure a median of 6 times (range 1–14 times) or once every 3.7 years of work (range 1.6–16.8 years).

Analysis of aircraft equipment flown by study pilots was essential to development of dose rates for imputation and assessment of the relative contribution of neutrons to total radiation dose from flight with each type of equipment. Table S2 (see Supplementary Data available at *Annals of Occupational Hygiene* online) describes the seven clusters formed by study equipment data based on median cruise speed and altitude. Two-thirds of the study's flight segments used equipment from Clusters D and F, which described commercial single- to multi-engine jets. These two clusters, along with the single engine jet fighters of Cluster B (0.1% of study segments), had the highest dose rates in our data. The remaining clusters (A, C, E, and G) described different groups of single- to twin-engine propeller aircraft and helicopters, which generally operated at lower dose rates.

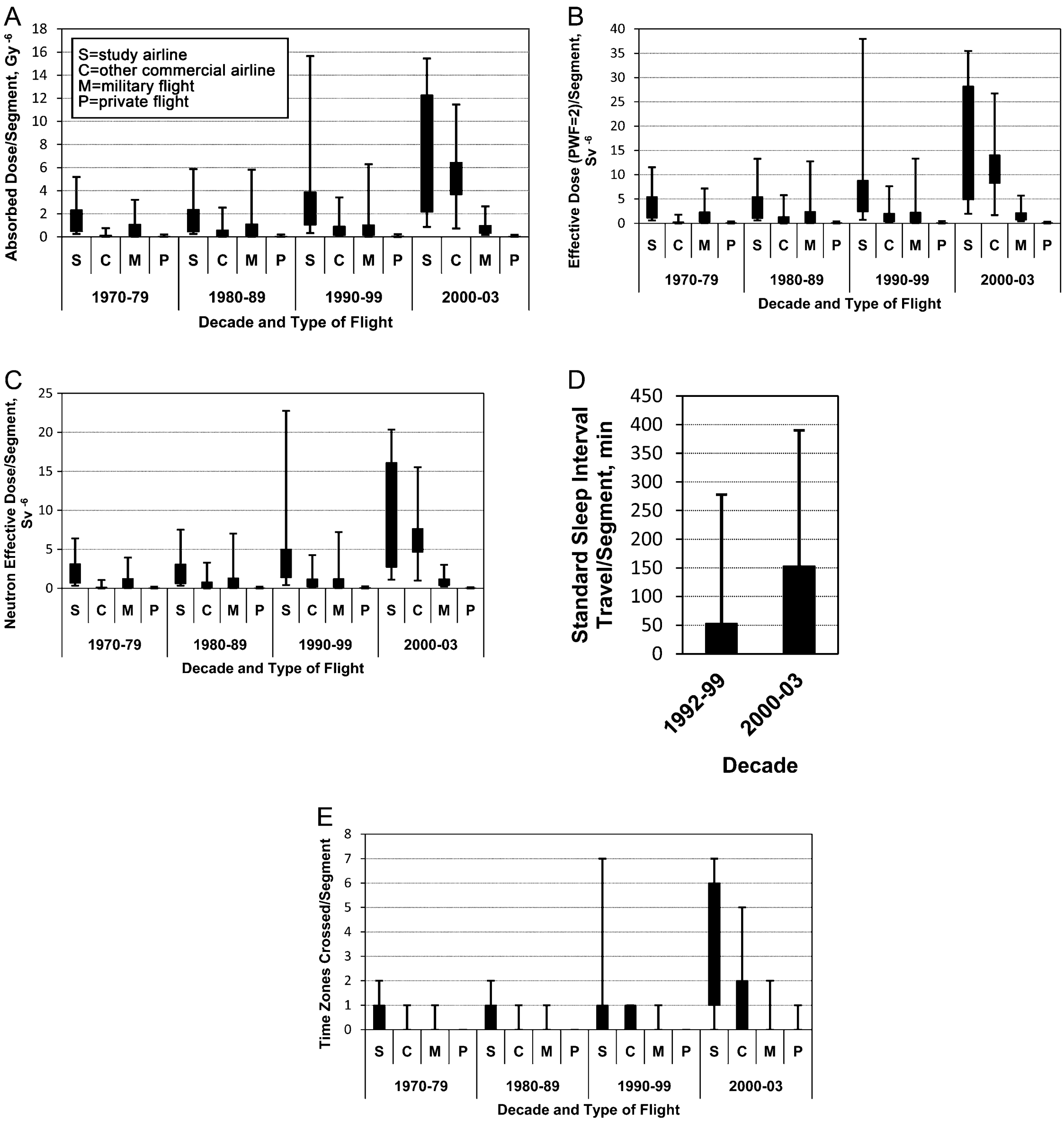

Fig. 3. Exposure metrics per pilot flight segment by type of flight and decade. Galactic cosmic radiation absorbed dose (in microGray), total ED (proton weighting factor = 2) and neutron ED (in microSieverts), SSI travel, and time zones crossed are presented. Black boxes indicate interquartile ranges and lines indicate 5th–95th percentiles of data. Metrics were calculated from individual segment data, which does not include commuter travel, pass travel, or summary flight hours. For SSI travel, segment data were only available from the study airline from 1992 to 2003. The 611 flight segments from the 1960s (0.1% of all flights) were incorporated into the 1970–1979 group since these flights represent four pilots and 99% of these segments were private flights.

Figure S1 (see Supplementary data available at *Annals of Occupational Hygiene* online) shows the contribution from each component of cosmic radiation to ED rate for each equipment cluster. For each equipment cluster except low-altitude propeller aircraft and helicopters (G), neutrons contributed the most to ED rate due to the relatively high radiation weighting factor for neutrons compared to the other particles. Absorbed neutron dose rates followed a similar pattern, with Cluster B jet fighters at a maximum of 24.4% neutrons followed by commercial aircraft (Clusters D and F) at 21–22% (data not shown).

Correlations between the cumulative exposure metrics and questionnaire-edited flight experience are given in Tables 2 and 3. A separate set of correlations is provided for military flights. Questionnaire-edited flight experience was closely correlated to block time (0.84 Spearman and 0.81 Pearson) and occupational years of flying (0.77 Spearman and 0.80 Pearson). Questionnaire-edited flight experience as well as the years of flying metrics (from all sources or occupational) were less closely correlated with effective and absorbed dose metrics (0.61–0.69 Spearman and 0.58–0.66 Pearson). Questionnaire-edited flight experience was estimated based on study airline and other commercial flight only. When questionnaire-edited flight experience was compared only to metrics based on study airline and other commercial flights, correlation coefficients increased by 0.05–0.14 (data not shown).

For military flights, questionnaire self-reported duration of military employment was also correlated to cumulative military block time (0.91, Spearman and 0.88 Pearson) and less closely correlated with cumulative military effective or absorbed dose (0.75 Spearman and 0.63 Pearson). However, correlations between military time zones, block times, and dose were not as strong as those found between these metrics for non-military flights.

DISCUSSION

This is the first published flight crew career exposure assessment from individual flight segments. The moderate correlation of this study's dose data with questionnaire-edited flight experience data or years of flying (occupational or from all sources) indicates that this more detailed level of assessment from individual flight segments is likely to reduce exposure misclassification and increase etiologic clarity for flight crew studies in general.

This assessment is an improvement over self-reported flight attendant questionnaire responses, which have been found to overreport exposures (Grajewski *et al.*, 2004; Kojo *et al.*, 2004). Flights are generally logged by pilots in real time, which reduces recall bias compared to retrospective questionnaire responses. It is professional custom for

Table 2. Correlations between questionnaire-edited flight experience and records-based exposure metrics. Pearson correlations are above the identity diagonal and Spearman correlations below. Metrics are cumulative unless otherwise specified. All P-values are ≤0.1 unless italicized. See Methods in Supplementary Data available at *Annals of Occupational Hygiene* online, for details

	Questionnaire-based	Records-based (pilot logbooks, summary hours, company records, and questionnaire self-report[a])								
	Questionnaire-edited flight experience	Block time	Flight segments	Time zones	SSI travel/ segment, median[b]	ED (pwf = 2)[c]	Absorbed dose	Neutron absorbed dose	Years of flying (all)	Years of flying (occupational)
Questionnaire-based										
Questionnaire-edited flight experience	1	0.81	0.65	0.65	*−0.01*	0.65	0.66	0.65	0.72	0.80
Records-based										
Block time	0.84	1	0.68	0.84	*0.11*	0.89	0.90	0.89	0.66	0.73
Flight segments	0.68	0.68	1	0.44	*−0.12*	0.41	0.42	0.4	0.43	0.51
Time zones	0.67	0.82	0.42	1	0.38	0.90	0.89	0.91	0.56	0.64
SSI travel/ segment, median	*−0.03*	*0.06*	*−0.09*	0.32	1	0.25	0.24	0.26	*−0.06*	*−0.01*
ED (pwf = 2)	0.67	0.86	0.37	0.92	0.26	1	0.99	0.99	0.58	0.65
Absorbed dose	0.69	0.87	0.38	0.91	0.25	0.99	1	0.99	0.59	0.66
Neutron absorbed dose	0.66	0.85	0.36	0.92	0.27	0.99	0.99	1	0.58	0.64
Years of flying (all)	0.71	0.69	0.44	0.55	*−0.14*	0.63	0.64	0.61	1	0.91
Years of flying (Occupational)	0.77	0.73	0.51	0.60	*−0.07*	0.66	0.67	0.65	0.90	1

[a]Questionnaire self-report is included only as incorporated into pass and commuter travel estimates.
[b]Minutes of flight segment block time flown between 2200 and 0800 home base time. SSI travel data were only available from the study airline for flight segments from 1992 to the end of the work history (2001–2003), and are calculated as a median value per segment for each pilot.
[c]ED weightings from ICRP 60 (ICRP, 1991; updated in ICRP 103, 2008). Pwf, Proton weighting factor.

Table 3. Correlations between questionnaire-based duration of military employment and records-based exposure metrics. Pearson correlations are above the identity diagonal and Spearman correlations below. Metrics are cumulative unless otherwise specified. All *P*-values are <0.003. See Methods in Supplementary Data available at *Annals of Occupational Hygiene* online, for details

	Questionnaire-based	Records-based (military flight recorded in logbook and summary hours)					
	Duration of military employment	Block time	Flight segments	Time zones	ED (pwf = 2)	Absorbed dose	Neutron absorbed dose
Questionnaire-based							
Duration of military employment	1	0.88	0.76	0.38	0.63	0.63	0.63
Records-based							
Block time	0.91	1	0.75	0.60	0.63	0.63	0.62
Flight segments	0.82	0.86	1	0.37	0.33	0.34	0.32
Time zones	0.60	0.69	0.69	1	0.35	0.38	0.34
ED (pwf = 2)	0.75	0.75	0.59	0.55	1	0.99	0.99
Absorbed dose	0.75	0.75	0.60	0.56	0.99	1	0.99
Neutron absorbed dose	0.75	0.75	0.59	0.54	0.99	0.99	1

pilots to log flight time for several reasons throughout their career, including student equipment rental, FAA licensure and regulatory requirements, flight time-based pay, and operational needs (e.g. fuel requirements). Preliminary comparison of pilot logs to company flight records (data not shown) suggested that despite individual variation in format, pilots logged their flights fairly accurately.

In the literature, several flight crew studies have implemented intermediate assessment approaches, including aircraft-based exposure matrices rather than relying on duration of employment. A domicile-based retrospective assessment may enhance the ongoing NIOSH retrospective mortality and cancer incidence studies of former PanAm workers (Waters *et al.*, 2009). Oksanen (1998) estimated radiation incurred from 1 year of occupational flying from airline records of individual flight segments and equipment manuals to derive estimated doses for each flight. Tveten *et al.* (2000) estimated annual and career doses from pilot block hours on specific aircraft and estimated 5-year dose rates for those aircraft based on airline timetable domestic and selected international flights. Hammer *et al.* (2000) compared estimates based on 1 year of electronic records of individual flight segments with other estimation methods, including a job exposure matrix from flight schedules, cumulative flight hours, and duration of employment. They reported good correlation between these methods. However, our work suggests that assessment of individual flight segments over a pilot's career may provide a more specific estimation of radiation and circadian disruption than the previously published methods. This specificity does not guarantee analytic separability between metrics of radiation and circadian disruption. To reduce circadian disruption–radiation collinearity, flight crew who work primarily North–South routes can be included in study groups (Grajewski *et al.*, 2002).

We found that military flights were the second largest source of exposure for this group of pilots. Thus, military experience, often assessed from summary hours records, was a quantifiable component of occupational exposure rather than a nuisance covariate. We noted that the correlations between time zones, block times, and dose were not as strong for military flights as for those between these same metrics in data from all combined types of flight, which we have reported in other non-military flight crew exposure assessments (Grajewski *et al.*, 2002; Waters *et al.*, 2009). Because of the diversity of types of military flight, correlations between block time, time zones, and dose would likely be lower than those observed for commercial flights.

We were able to report cumulative particle-specific dose estimates for the study pilots. As expected, neutrons were a significant component of commercial aircraft effective or absorbed dose. Our cumulative ED (median 19.9 mSv; range 5.7–48.0) for this IARC Group I carcinogen is consistent with the IARC report of aircrew lifetime average and long haul pilot lifetime maximum neutron doses of 30 and 46 mSv, respectively (IARC, 2000). EMSs are also a significant component of absorbed dose. Although EMS relative biological effectiveness is low compared to neutrons, they may induce biological damage (NCRP, 2006).

Our characterization of circadian disruption is, to our knowledge, the first comprehensive long-term assessment of its kind in this occupational group. We used non-directional time zones crossed as an exposure metric because time zones are well correlated with a state of chronic disruption as biologically measured by an increase in the overnight variability of melatonin excretion in female flight attendants (Grajewski *et al.*, 2003). We also assessed SSI travel because it captures the separate but related exposure of sleep disturbance rather than the desynchronization reflected in cumulative time zones crossed (Grajewski *et al.*, 2003). Accordingly, SSI travel appeared to be weakly correlated to other metrics, as we have noted earlier (Grajewski *et al.*, 2003; Waters *et al.*, 2009). Flight crew who work primarily on short regional flights or North–South routes can incur significant SSI travel while crossing relatively few time zones.

We were able to provide a crude estimate of the frequency that a pilot might expect to travel through significant SPEs. Our SPE assessment was descriptive and conservative for several reasons. We did not have SPE assessment for flights before 1976. But because many of our pilots began their careers during this time, over half the flights during the missed time period were in lower altitude equipment clusters, and many of these would have been excluded. We also lacked sufficient data to determine whether a flight actually passed through a region affected at aircraft altitudes by the SPE. For example, removing the 45° geomagnetic latitude criterion for flight origin and destination increased our estimates slightly (estimated SPE exposures: a median of 7 times or once every 3.2 years of work). Finally, small or minor SPEs may add to total exposure. However, the combined satellite, time, altitude, and latitude criteria we chose increased the likelihood that an identified flight passed through an SPE, which enabled us to estimate the number of times a pilot could expect to be occupationally exposed to moderate or large SPEs.

The impact of SPE exposure on cumulative galactic cosmic radiation ED has been considered by a number of investigators. Applying estimates from previous work (Beck *et al.*, 2009; Matthiä *et al.*, 2009) to our data gives a very broad range of exposure estimates. A 20% ED increase (Matthiä *et al.*, 2009) from SPE possibly exposed flights in our data suggested an addition to the pilots' cumulative ED of a median 20.8 μSv or 0.06% increase (range 7–51 μSv or 0.02–0.21%). At the other extreme, adding 1 mSv to the ED (Beck *et al.*, 2009) for each possible SPE-exposed flight increased the pilots' cumulative ED by a median of 17 mSv or 43.7% (range 2–48 mSv or 7.7–220%). This wide variation in estimates affirms that SPE contribution to ED is time and location dependent. While our data estimates do not allow any additional time and location precision, they also do not rule out a significant contribution of SPEs to cumulative cosmic radiation exposure.

Generally, our median results were consistent with the literature. Annual ED estimates range from 0.2 to >7 mSv year^{-1} for aircrew flying 600–1000 h year^{-1} (Friedberg *et al.*, 1992; EURADOS, 2004). However, our study's hypothetical median US airline pilot would likely have triggered radiation monitoring (i.e. recording of estimated dose) according to the European Union criterion of >1 mSv year^{-1} (EURADOS, 1996), and it would seem possible for a female pilot (and perhaps other female flight crew) to exceed the ICRP guideline for pregnant radiation workers [recommended dose limit of 1 mSv (equivalent dose) upon declaration of pregnancy for the remaining gestation period; ICRP, 2008]. Furthermore, the ranges of these non-normally distributed metrics for radiation and circadian disruption suggest that there is a high-exposed group of airline pilots who may be at increased risk for the health effects of cosmic radiation and chronic circadian disruption compared to other pilots. Our data show that this may have been especially true in the most recent years of our study, from the 1990s to 2003. Changes in aircraft, increased polar routing, efforts to decrease fuel consumption and costs, and changes in crew contracts may each have played a role in the increases we have observed in pilots' flight exposures to radiation and circadian disruption.

Accurate assessment of radiation and circadian disruption exposures in flight crew appears to be of increasing public health importance. Identification of high-exposed pilots would be a valuable addition to an occupational health program if counseling or intervention were offered grounded in an understanding of this occupational group, including scheduling and seniority issues.

This assessment has several limitations. The extensive records collection and processing required for individual flight records, especially from handwritten pilot logbooks, may offset the benefits of this approach, or records of this nature may be unavailable. Like many non-regulated exposures with multiple record sources, multiple assumptions were made to allow inclusion of all exposure record sources in our metrics, which could have increased misclassification. The non-occupational exposures of the comparison group are far lower than the pilots' but may be reported with less accuracy; thus, comparisons within pilots stratified by exposure levels will be important in epidemiological analyses. When this work began, CARI was the only dose estimation software, which could process large numbers of flight segments for epidemiological studies. A Great Circle Route was assumed and SPE exposures were not estimated. We look forward to the adaptation of the real-time the National Aeronautics and Space Administration Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model (Mertens *et al.*, 2010). NAIRAS will provide global, data-driven real-time radiation exposure predictions of cosmic radiation and SPEs at commercial airline altitudes.

Despite these limitations, this assessment met our objectives of developing new methods to estimate pilot workplace exposures and describing those exposures in detail for a group of US commercial pilots. The methods described are a potential improvement over other exposure assessment methods for flight crew exposures. They offer the possibility of analyses of pilot and flight crew health outcomes, which will provide a clearer understanding of the separate contributions of components of cosmic radiation and circadian disruption exposures.

FUNDING

This work was part of the Intramural Research Program of the National Institute for Occupational Safety and Health (NIOSH). It was supported in part by an interagency agreement between NIOSH and the National Cancer Institute (contract Y1CP802904) and by the Intramural Research Program of the Division of Cancer Epidemiology and Genetics, National Cancer Institute.

SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

Acknowledgements—We thank the pilots and faculty whose participation, enthusiasm, and work history records made this research possible; Captains Joyce May and Michael Holland for invaluable consultant support; and the study airline, which provided records and expert consultation. We are indebted to David S. Evans, who made analysis of SPEs possible by processing and interpreting National Oceanic and Atmospheric Administration satellite data and to Christopher J. Mertens of the National Aeronautics and Space Administration, who provided geomagnetic latitudes. We acknowledge the assistance of Andrew Dent and Kevin Liske of the Public Health Geospatial Research, Analysis, and Services Program (GRASP) at Centers for Disease Control and Prevention, who provided geodetic latitudes, longitudes, and elevations. The Canadian Geodetic Survey Division of the Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, Ontario, provided elevations through the Canadian Spatial Reference System Online Database. Wallace Friedberg and Kyle Copeland of the FAA provided CARI6P software and consultation. The staff of Battelle Centers for Public Health Research and Evaluation (Louise Glezen, Katrina Spencer, and James Kerrigan) assisted with subject enrollment and data/flight record collection. We thank NIOSH contributors James Deddens for assistance with the current CARI input algorithm; Christina Lawson, Jeri Anderson, Lynne Pinkerton, and Elizabeth A. Whelan for review; and the intrepid statistical assistants who created our 523 387 record work history database from handwritten records and brought order to the thousands of location and aircraft equipment data: Kathy Watkins, Faith D. Armstrong, William Ehling, Kim Jenkins, Denise Giglio, Deanna S. Lengerich, and Christine M. Gersic.

REFERENCES

Beck P, Dyer C, Fuller N *et al*. (2009) Overview of on-board measurements during solar storm periods. Radiat Prot Dosimetry; 136: 297–303.

Buja A, Lange JH, Perissinotto E *et al.* (2005) Cancer incidence among male military and civil pilots and flight attendants: an analysis on published data. Toxicol Ind Health; 21: 273–82.

Buja A, Mastrangelo G, Perissinotto E *et al*. (2006) Cancer incidence among female flight attendants: a meta-analysis of the published data. J Womens Health; 15: 98–105.

El Ghissassi F, Baan R, Straif K *et al*. (2009) A review of human carcinogens—Part D: radiation. Lancet Oncol; 10: 751–2.

European Radiation Dosimetry Group (EURADOS). (1996) Exposure of air crew to cosmic radiation. A report of EURADOS Working Group 11, EURADOS Report 1996.01. In: McAulay IR, Bartlett DT, Dietze G *et al*. editors. European Commission Report Radiation Protection 85. Luxembourg: Office for Official Publications of the European Communities.

European Radiation Dosimetry Group (EURADOS). (2004) Radiation protection, cosmic radiation exposure of aircraft crew, compilation of measured and calculated data, issue No 140. In: Lindborg L, McAulay I, Bartlett T D *et al.* editors. Chapter VI, Summary, conclusions and recommendations. Luxembourg: Office for Official Publications of the European Communities. pp. 103–8.

Federal Aviation Administration. (1994) Advisory Circular No. 120–61, May 19, 1994. Crewmember training on inflight radiation exposure. Oklahoma City, OK: Federal Aviation Administration, Flight Standards Service.

Federal Aviation Administration. (2006) Advisory Circular No. 120–61A, July 6, 2006. In-flight radiation exposure. Oklahoma City, OK: Federal Aviation Administration, Flight Standards Service.

Federal Aviation Administration. (2009) FAA Aerospace Forecasts FY 2009-2025, Table 29, Active pilots by type of certificate. Available at http://www.faa.gov/data_research/aviation/aerospace_forecasts/2009-2025/. Accessed 22 April 2011.

Friedberg W, Copeland K. (2003) What aircrews should know about their occupational exposure to ionizing radiation. Oklahoma City, OK: Federal Aviation Administration, Civil Aerospace Medical Institute DOT Report No. DOT/FAA/AM-03/16.

Friedberg W, Snyder L, Faulkner DN. (1992) Radiation exposure of air carrier crew members II. Oklahoma City, OK: Federal Aviation Administration Office of Aviation Medicine DOT Report No. DOT/FAA/AM-92/2.

Goldhagen P. (2000) Overview of aircraft radiation exposure and recent ER-2 measurements. Health Phys; 79: 526–44.

Grajewski B, Atkins D, Whelan EA. (2004) Self-reported flight hours vs. company records for epidemiologic studies of flight attendants. Aviat Space Environ Med; 75: 806–10.

Grajewski B, Nguyen M, Whelan EA *et al*. (2003) Measuring and identifying large-study metrics for circadian rhythm disruption in female flight attendants. Scand J Work Environ Health; 29: 337–46.

Grajewski B, Waters MA, Whelan EA *et al*. (2002) Radiation dose estimation for epidemiologic studies of flight attendants. Am J Ind Med; 41: 27–37.

Hammer GP, Blettner M, Zeeb H. (2009) Epidemiological studies of cancer in aircrew. Radiat Prot Dosimetry; 136: 232–9.

Hammer GP, Zeeb H, Tveten U *et al*. (2000) Comparing different methods of estimating cosmic radiation exposure of airline personnel. Radiat Environ Biophys; 39: 227–31.

Heinrich W, Roesler S, Schraube H. (1999) Physics of cosmic radiation fields. Radiat Prot Dosimetry; 86: 253–8.

IARC. (2000) Ionizing radiation, Part 1, X- and γ-radiation and neutrons. In IARC monographs on the evaluation of carcinogenic risks to humans, Vol. 75. Lyon, France: IARC Press. ISBN 92 832 1275 4.

International Commission on Radiological Protection (ICRP). (1991) 1990 Recommendations of the International Commission on Radiological Protection. Oxford, NY: Published for the Commission by Pergamon, c1991. ISBN 0 08 041144 4.

International Commission on Radiological Protection (ICRP). (2008) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. New York, NY: Published for the Commission by Elsevier, c2008. ISBN 0-7020-3048-1.

Kojo K, Aspholm R, Auvinen A. (2004) Occupational radiation dose estimation for Finnish aircraft cabin attendants. Scand J Work Environ Health; 30: 157–63.

Matthiä D, Heber B, Reitz G *et al*. (2009) The ground level event 70 on December 13th, 2006 and related effective doses at aviation altitudes. Radiat Prot Dosimetry; 136: 304–10.

Mertens CJ, Kress BT, Wiltberger M *et al*. (2010) Geomagnetic influence on aircraft radiation exposure during a solar energetic particle event in October 2003. Space Weather; 8: S03006.

NCRP. (1993) Limitation of exposure to ionizing radiation. NCRP Report No. 116. Bethesda, MD: National Council on Radiation Protection and Measurements, cited in supplementary material.

NCRP. (2006) Information needed to make radiation protection recommendations for space missions beyond low-earth orbit. Bethesda, MD: National Council on Radiation Protection and Measurements NCRP Report No. 153.

Oksanen PJ. (1998) Estimated individual annual cosmic radiation doses for flight crews. Aviat Space Environ Med; 69: 621–5.

Sancar A, Lindsey-Boltz LA, Kang TH *et al*. (2010) Circadian clock control of the cellular response to DNA damage. FEBS Lett; 584: 2618–25.

Straif K, Baan R, Grosse Y *et al*. (2007) Carcinogenicity of shift-work, painting, and fire-fighting. Lancet Oncol; 8: 1065–6.

Tveten U, Haldorsen T, Reitan J. (2000) Cosmic radiation and airline pilots: exposure pattern as a function of aircraft type. Radiat Prot Dosimetry; 87: 157–65.

Waters MA, Bloom TF, Grajewski B *et al*. (2002) Measurements of indoor air quality on commercial transport aircraft. In: Levin H, editor. Indoor Air 2002: Proceedings of the 9th International Conference on IAQ and Climate, Vol. 4. Santa Cruz, CA: International Society of Indoor Air Quality and Climate. pp. 782–7.

Waters MA, Grajewski B, Pinkerton LE *et al*. (2009) Development of historical exposure estimates of cosmic radiation and circadian rhythm disruption for cohort studies of Pan-Am flight attendants. Am J Ind Med; 52: 751–61.

Whelan EA. (2003) Cancer incidence in airline cabin crew. Occup Environ Med; 60: 805–6.

Yong LC, Sigurdson AJ, Ward EM *et al*. (2009) Increased frequency of chromosome translocations in airline pilots with long-term flying experience. Occup Environ Med; 66: 56–62.