Development of Historical Exposure Estimates of Cosmic Radiation and Circadian Rhythm Disruption for Cohort Studies of Pan Am Flight Attendants

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Background *The National Institute for Occupational Safety and Health is conducting cohort studies of flight crew employed by the former Pan American World Airways company (Pan Am) as part of an effort to examine flight crew workplace exposures and health effects. Flight crew are exposed to elevated levels of cosmic radiation and to disruption of circadian rhythm when flying across multiple time zones. Methods exist to calculate cosmic radiation effective doses on individual flights; however, only work histories which provided an employee's domicile (home base) history rather than a record of every flight flown were available.*
Methods/Results *We developed a method for estimating individual cumulative domicile-based cosmic radiation effective doses and two metrics for circadian rhythm disruption for each flight attendant: cumulative times zones crossed and cumulative travel time during the standard sleep interval.*
Conclusions *The domicile-exposure matrix developed was used to calculate exposure estimates for a cohort mortality study of former Pan Am flight attendants.* Am. J. Ind. Med. 52:751–761, 2009. *Published 2009 Wiley-Liss, Inc.*†

KEY WORDS: cosmic radiation; flight attendants; exposure assessment; aircraft; flight crew; retrospective

INTRODUCTION

Flight crew may be at increased risk of cancer due to workplace exposures [Whelan, 2003; Sigurdson and Ron, 2004; Buja et al., 2005, 2006]. The two primary exposures hypothesized as cancer risk factors are cosmic radiation exposure at aircraft altitudes and circadian rhythm disruption due to travel through multiple time zones. In addition to their biologic plausibility, these two exposures are judged to have sufficient variability in the air cabin environment to assess and analyze in regard to health outcomes. Other aircraft exposures have been described, but lack the variability necessary for health outcomes analyses.

Primary cosmic radiation interacts with molecules of the atmosphere and generates secondary and subsequent radiations at aircraft altitudes, including neutrons and charged particles with high relative biological effectiveness [Heinrich et al., 1999; Goldhagen, 2000]. The cosmic radiation effective dose received on an individual flight generally ranges from 5 to 100 μSv/flight although the effective dose received on polar routes can be significantly greater. Annual

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Accepted 6 July 2009
DOI 10.1002/ajim.20738. Published online in Wiley InterScience (www.interscience.wiley.com)

effective dose estimates range from 0.2- to over 7 mSv/year for air crew flying 600–1,000 hr/year [Friedberg et al., 1992; EURADOS, 2004]. The International Commission on Radiological Protection [ICRP, 1991] recommends an effective dose limit for radiation workers of 20 mSv/year averaged over 5 years, and for the public of 1 mSv/year. For pregnant radiation workers the recommended dose limit is 1 mSv (equivalent dose) upon declaration of pregnancy for the remaining gestation period [ICRP, 2007]. European Union member states implemented regulations for flight crew requiring assessment of exposure when exposure is likely to be more than 1 mSv/year (and adjustment of work schedules so that no individual exceeds 6 mSv/year [EURADOS, 1996]). Although the US Federal Aviation Administration (FAA) formally recognized that flight crew members are occupationally exposed to cosmic radiation in 1994 [FAA, 1994], there are no official dose limits for flight crew members in the United States.

Flight crew also experience circadian rhythm disruption when flying across multiple time zones. An International Agency for Research on Cancer working group recently concluded that shiftwork that involves circadian disruption is probably carcinogenic to humans based on sufficient evidence in experimental animals for the carcinogenicity of light during biological night and limited human evidence including data from studies of female flight attendants [Straif et al., 2007].

The National Institute for Occupational Safety and Health (NIOSH) is conducting cohort studies of flight crew employed by the former Pan American World Airways company (Pan Am) as part of an effort to examine flight crew workplace exposures and health effects. NIOSH obtained Pan Am employment records following the company's closing in 1991. Historical cumulative radiation dose and circadian disruption exposure metrics may be estimated directly from company records if individual flight histories are available. For the NIOSH studies of Pan Am flight attendants, only the domicile (home base) history was known, requiring new methods to assess historical flight attendant exposures.

We describe the methods we developed to estimate retrospective exposure to cosmic radiation and circadian disruption for individual flight attendants with known domicile histories but unknown individual flight histories. Our underlying assumptions were that (a) the relation between latitude and radiation effective dose combined with the varying latitudes of the domiciles would result in sufficient between-domicile dose variability to permit dose discrimination by domicile within era; (b) within era, the variability in the average exposures across domiciles could be exploited to estimate individual cumulative exposures providing more information than duration of employment; (c) the unique complex of flights flown into each domicile would lead to additional variability in the average exposure across domiciles and enhance the ability to discriminate between domiciles; and (d) the average number of time zones crossed per domicile-based flight attendant would vary by domicile.

METHODS

Study Cohort

The cohort was assembled from the personnel records of Pan Am, which are available for employees who stopped working for Pan Am in 1953 or later. Employees who were employed for at least 1 year as a flight attendant before Pan Am ceased operation in 1991, were U.S. citizens when they were hired, and who worked at least 1 day after January 1, 1953 were included in the cohort. In 1981, Pan Am bought National Airlines, another U.S.-based airline. For flight attendants who transferred to Pan Am from National when Pan Am bought National, the time employed as a flight attendant at National was counted towards the 1 year minimum. Flight attendants employed at National only were not included. The cohort included 11,324 workers, 1,393 (12.3%) of whom transferred to Pan Am from National. The cohort mortality study was approved by the NIOSH Human Subjects Review Board. As a records study, informed consent requirements were waived.

Additional Information Sources

Reference data collections consulted included the Air Transport Association Library (Washington, DC), the FAA Library (Oklahoma City, OK), and Pan Am archived records in the Special Collections Division, University of Miami Libraries (Coral Gables, FL). Aircraft model history references included Jane's All the World's Aircraft (periodical volumes 1930–1990), Davies' Airlines of the United States since 1914 (1983), and Davies' Pan Am: An Airline and its Aircraft (1987). The Airline Pilots Association provided pilot contacts who supplied technical information on Pan Am flight procedures and practices for both domestic and international flights from the 1930s to 1990s. Several Pan Am flight attendants were also consulted for information on procedures and practices during multiple employment eras.

Exposure Metrics: Selection of Domiciles/Eras

Duration of employment was computed as a surrogate of exposure for all cohort members. Three specific exposure metrics were estimated for a subset of the cohort: (a) cumulative cosmic ionizing radiation effective dose, (b) cumulative number of time zones crossed, and (c) cumulative time spent traveling in the standard sleep interval (SSI travel; i.e., travel between 10 PM and 8 AM at the flight attendant's home base domicile). It was not possible to develop these exposure metrics for all domiciles because of the large number of domiciles represented in the work histories and the correspondingly large number of flights arriving at and departing from those domiciles. Domicile era-specific exposure metrics for the time interval 1929–1991 were created for 10,164 flight attendants with 100% of their work history associated with one or more of these nine domiciles: Hong Kong, Honolulu, London, Los Angeles, Miami, New York, San Francisco, Seattle, and Washington DC. These domiciles were selected based on a preliminary analysis of domicile information in electronic company records before the cohort was constructed. Two matrices were developed for the Miami domicile to separately consider flight attendant work for National Airlines and work for Pan Am.

Flight schedule data were abstracted from the Official Airline Guide™ (OAG, periodical volumes 1930–1990) for the nine domiciles for the years 1930, 1935, 1940, 1945, 1950, 1955, 1961 (1960 data unavailable), 1965, and 1970. The OAG™ did not include flight schedules for all nine domiciles for all years, especially years prior to 1950 and during World War II. However, for each domicile, the years with flight schedule data generally agreed with the years the domicile appeared in the work history records. Data were abstracted for 1980 and 1990 for five of the nine domiciles, excluding Hong Kong, London, Seattle, and Washington DC. The use of a 10-year interval and a smaller number of domiciles for 1980 and 1990 was due to the large increase in flights/domicile in these years and limits on the amount of data that could be abstracted and coded. In addition to data for Pan Am, flight data for the Miami domicile of National were abstracted and coded separately. All data collected were for the month of April to minimize the effects of weather and daylight savings time. Era start and end dates were defined as the midpoints between consecutive years (e.g., for Pan Am—Miami, estimates based on flights in 1965 were applied to all time in the interval from 1 April, 1963 (the midpoint between 1961 and 1965) through 30 September, 1967 (the midpoint between 1965 and 1970)). Yearly estimates were assigned to their respective era. The first and last estimate for a given airline-domicile was applied to all time before and after the year, respectively.

Abstraction of Flight Segments

Only flights going into the domicile were abstracted because the numbers of flights between city pairs were approximately equal in both directions, and flight lengths in both directions were approximately equal. The data abstracted included flight date, origin and destination airports, local departure and arrival times, the number of connections within the flight (if any), each connection airport, flight number, aircraft model, and day(s) of week the flight operated. Flights with intermediate stops were coded as two or more separate flight segments in sequence. Multiple airport code conventions were converted to International Civil Aviation Organization (ICAO) airport codes. Extinct (non-functional) airports were coded as the nearest airport.

Rules for workday length and number of workday flight segments flown were based on information from Pan Am flight attendants. A flight attendant would usually work 5–12 hr per workday. If the block time (flight time plus taxi time) of the final flight into the domicile was shorter than 5 hr, then the previous flight with the same flight number and the connection time between the flights was grouped with the final flight to approximate a 5- to 12-hr workday.

Exposure Metric Estimation

Radiation effective dose, time zones crossed, and SSI travel time for each flight segment were estimated from the abstracted schedule data and other sources. Radiation effective dose was calculated using the FAA program CARI6P (Screen date 9/17/05). CARI6P is a version of CARI6 which estimates effective radiation dose for an individual flight segment [Friedberg and Copeland, 2003]. Assumptions were made to predict taxi time, ascent and descent times, and number and duration of cruise altitudes from block time for historical Pan Am routes by modifying a validated algorithm previously used to estimate flight doses from block time in epidemiologic studies [Grajewski et al., 2002] with information provided by former Pan Am pilots (Table I).

Aircraft designations changed over time and several designations existed for each model. Redundancies were eliminated to identify 39 unique aircraft models. Specification information for these models was collected, including certified ceiling altitude, cruising speed at altitude, typical cruise altitudes for flights of differing lengths, maximum and typical airspeeds at altitudes, and passenger capacity. The 39 aircraft models were further stratified by altitude to produce 13 altitude aircraft groups and 49 unique aircraft–era combinations. The number of flight attendants assigned to a given aircraft was estimated for each aircraft by era.

Block time was calculated as the difference between local departure and arrival times, adjusted for time zones. When flight departure and arrival times were unavailable, flight distance determined by great circle route formula (i.e., the shortest spherical distance between the two airports) and aircraft speed were used to estimate flight time. For great circle formula estimates, 45 min were added to flights of 500 min or less and 60 min were added to flights over 500 min to approximate block time including taxi, ascent, and descent times. Time zones crossed and SSI travel time were defined and calculated as described in Grajewski et al. [2003].

TABLE I. Assumptions Used to Estimate Radiation Dose From Block Time and Aircraft Group*

Flight segment block time (min)	Assumed one-way taxi time (in or out, min)	Assumed time to ascent to first altitude (min): Altitude <28 kft, 1960 and before	Altitude <28 kft, 1961 and after	Altitude ≥28 kft, all years	Assumed time to descent from first altitude (min)
<45	5	8	3	10	8
45–62	8	10	10	10	10
63–300	11	20	20	20	20
>300	11	25	20	25	25

Flight segment block time (min)	Assumed number of altitudes	Assumed duration of each in-flight altitude	Assumed ascent/descent time to/from second altitude (min)	Assumed ascent/descent time to/from third altitude (min)
≤300	1	All unaccounted time[a]	—	—
301–480	2	1/2 Unaccounted time	20	—
481+	3	1/3 Unaccounted time	20	20

Aircraft group typical model(s)	Years	Assumed cruise altitude (kft): 1st	2nd	3rd
Boeing747, 747SP	1970–1990	29	33	37
Boeing727	1965–1990	31	35	37
Boeing707	1961–1980	29	33	37
DouglasDC8, AirbusA300, A310	1965–1990	28	31	35
DouglasDC10	1980	29	33	37
Boeing377	1950–1955	23	27	31
Convair, Lodestar	1945–1961	21	28	—
DouglasDC6, DC7, LockheedL749	1950–1965	21	24	—
Curtiss46, Lockheed Super-H	1950–1961	18	22	—
DouglasDC3, DC4, Boeing307	1940–1955	20	—	—
Electra Prop, Dash7	1940–1990	17	—	—
Flying Boat	1930–1945	10	12	—
Landplane	1930	3	5	7

*Input to CARI dose estimation software is based on these assumptions; see text for details.
[a]Unaccounted time is block time not spent in taxi, ascent, or descent.

Calculation of Weighted Domicile-Specific Exposures

Briefly, domicile–era-specific estimates of radiation effective dose, time zones crossed, and SSI travel were frequency weighted for (1) the number of block hr/flight segment, (2) the number of times the flight segment occurred /week, and (3) the number of flight attendants that worked on the specific aircraft for that flight segment. Work history information was then merged with the weighted domicile–era-specific exposure rates to obtain an estimate of cumulative radiation effective dose, time zones crossed, and SSI travel for each flight attendant.

More specifically, the exposure rate for radiation effective dose, time zones crossed (TZ) and SSI travel for domicile i and era j was defined as a weighted average of the individual exposure rates (d_{ijk}; μSv/block hr for radiation; number of TZ/ block hr; or SSI travel min/block hr) for all flight segments k (as specified in the OAG™) going into domicile i during era j. The weights (w_{ijk}) were defined as the number of flight attendant block hr/segment/week which were given by

$$w_{ijk} = b_{ijk} \times s_{ijk} \times f_{ijk}$$

where b_{ijk}, s_{ijk}, and f_{ijk} are the number of block hr/flight segment, flight segments/week, and flight attendants/flight segment for domicile i, era j, and flight segment k. Finally, the exposure rate (d_{ij}; μSv/block hr for radiation; number of TZ/block hr; or SSI travel min/block hr) was given by

$$d_{ij} = \frac{\sum_k w_{ijk} d_{ijk}}{\sum_k w_{ijk}}$$

where k indexes the flight segments for all flights going into domicile i during era j.

Daily exposure estimates assumed an 80 block-hr month, a conservative estimate based on typical pilot union contracts. Cumulative exposure was computed for each of the three metrics by summing the product of the daily exposure estimates and the number of days associated with each time period over every time period in the individual flight attendant's work history. For 362 flight attendants for whom only the first and last date employed at National was available, exposure estimates while working at National were adjusted downwards 12%, the average percent of time that flight attendants at National with detailed work history information spent away from work while employed. Exposure estimates for time worked at Pan Am as a part-time flight attendant were discounted by 50%.

Statistical Methods

Mixed effects regression models were used to evaluate the domicile–era exposure estimates (MIXED procedure, SAS version 9.1.3, SAS Institute, Inc., Cary, NC). In these models, the estimated exposure rate was the dependent variable, year was treated as a fixed effect, and domicile was treated as a random effect. Both first- and second-order terms for year (i.e., year and year^2) were included to account for a nonlinear relation. We specified a compound symmetric covariance structure which provided between-domicile and within-domicile variance estimates. Separate models were fit for each of the exposure metrics (radiation, time zones, and SSI travel).

Cumulative exposure estimates for the individual flight attendants were summarized using simple descriptive statistics. Relations among duration of employment and the three cumulative exposure metrics were evaluated using Pearson and Spearman correlation coefficients.

RESULTS

A total of 6,224 flight segments were analyzed. Table II shows the weighted average exposure rates by domicile and year. The exposure rate for radiation effective dose was highly correlated with the exposure rate for time zones crossed ($r_{Pearson} = 0.88$); however, the exposure rate for SSI travel was less correlated with the rates for radiation effective dose ($r_{Pearson} = 0.18$) or time zones crossed ($r_{Pearson} = 0.11$). Results of the mixed effects regression modeling of the domicile–era-specific exposure rates are provided in Table III. After adjusting for calendar year effects, the estimated between-domicile variability was similar to estimated within-domicile variability for both radiation effective dose rate and time zones crossed rate; however, for SSI travel, the estimated within-domicile variability was more than four times higher than the estimated between-domicile variability. This suggests that a domicile-based matrix for assessing radiation and time zones crossed may be more appropriate than a domicile-based matrix for SSI travel. Figure 1 indicates the between-domicile variability of weighted average radiation effective dose rates for each era.

Summary statistics for duration of employment for 11,324 flight attendants and cumulative exposures to radiation, time zones crossed, and SSI travel for 10,164 flight attendants (who met the criterion of 100% of their work history associated with the nine selected domiciles) are provided in Table IV. The correlation coefficients in Table V indicate high correlation between duration of employment and the three cumulative exposure metrics.

The plots in Figure 2 indicate the relative collinearity of pairs of cumulative exposure metrics for individual flight attendants. The departures from collinearity seen in these plots are largely due to domicile differences. Among these pairs of metrics, relations between SSI travel and the other metrics are least correlated, while radiation versus TZ crossed is more highly correlated.

DISCUSSION

The exposure assessment method presented can be used when both flight timetables and domicile histories are available. The method provides circadian disruption exposure assessment not necessarily captured in duration of employment. It is most likely to be an improvement over using duration of employment as a surrogate of radiation exposure when the patterns of flights into and out of major domiciles vary by domicile and when the latitudes of major domiciles vary considerably. Although the method was developed for studies of flight attendants, it could be adapted for pilots. Three other methods [Tveten et al., 2000; Kojo et al., 2004, 2007] have been developed for estimating exposure to cosmic radiation for flight crew studies when individual flight histories are not available in company records. In contrast to the method based on aircraft type described by Tveten et al. (2000), our method can be used for studies of flight attendants who generally fly on a variety of

TABLE II. Weighted* Average Exposure Rates by Domicile and Year

Domicile	Year	Radiation effective dose rate (μSv/block hr)	Time zones crossed (#/block hr)	Travel in SSI[a] (SSI hr/block hr)
Hong Kong	1940	0.121	0.115	0.231
	1950	0.483	0.198	0.375
	1955	0.725	0.180	0.222
	1961	1.186	0.358	0.240
	1965	1.423	0.425	0.102
	1970	1.906	0.495	0.055
Honolulu	1940	0.166	0.105	0.105
	1950	1.209	0.209	0.227
	1955	1.222	0.268	0.152
	1961	1.683	0.437	0.348
	1965	1.626	0.504	0.377
	1970	1.805	0.517	0.474
	1980	1.715	0.500	0.637
	1990	1.841	0.396	0.000
London	1950	1.640	0.321	0.143
	1955	1.422	0.334	0.253
	1961	2.786	0.558	0.369
	1965	3.672	0.666	0.500
	1970	2.919	0.724	0.486
Los Angeles	1950	1.392	0.171	0.000
	1955	1.387	0.192	0.122
	1961	2.232	0.424	0.030
	1965	2.458	0.397	0.372
	1970	2.282	0.473	0.059
	1980	2.946	0.616	0.178
	1990	2.170	0.527	0.117
Miami	1930	0.108	0.022	0.052
	1935	0.121	0.030	0.000
	1940	0.280 (0.316)[b]	0.046 (0.000)	0.006 (0.284)
	1945	0.544 (0.733)	0.016 (0.000)	0.051 (0.331)
	1950	0.468 (0.727)	0.065 (0.007)	0.131 (0.231)
	1955	0.471 (0.676)	0.106 (0.025)	0.163 (0.173)
	1961	0.755 (0.850)	0.152 (0.118)	0.230 (0.154)
	1965	1.057 (1.596)	0.156 (0.232)	0.180 (0.177)
	1970	1.419 (2.035)	0.165 (0.340)	0.073 (0.121)
	1980	1.750 (2.458)	0.303 (0.367)	0.219 (0.159)
	1990	2.375	0.405	0.161
New York	1940	0.221	0.192	0.082
	1950	1.237	0.202	0.228
	1955	1.368	0.261	0.129
	1961	2.459	0.516	0.124
	1965	3.537	0.472	0.087
	1970	2.719	0.482	0.109
	1980	3.049	0.565	0.162
	1990	2.648	0.592	0.211
San Francisco	1940	0.182	0.111	0.111
	1950	1.425	0.186	0.780

(*Continued*)

TABLE II. (*Continued*)

Domicile	Year	Radiation effective dose rate (μSv/block hr)	Time zones crossed (#/block hr)	Travel in SSI[a] (SSI hr/block hr)
	1955	1.418	0.200	0.626
	1961	2.012	0.419	0.338
	1965	2.148	0.343	0.238
	1970	2.607	0.470	0.404
	1980	3.021	0.608	0.083
	1990	2.366	0.559	0.227
Seattle	1945	0.984	0.138	0.000
	1950	0.870	0.164	0.109
	1955	1.244	0.237	0.230
	1961	2.251	0.347	0.354
	1965	3.040	0.412	0.768
	1970	3.912	0.843	0.179
Washington DC	1965	4.394	0.511	0.072
	1970	2.632	0.527	0.056

*Domicile estimates were frequency weighted for number of block hours per flight segment, number of times the flight segment occurred per week, and number of flight attendants that worked on the specific aircraft for that flight segment. See text for details.
[a]Travel between 10 PM and 8 AM at the flight attendant's home base domicile.
[b]Value in parentheses represents National Airlines.

different aircraft types. Our method can also be used when information on the total number of flight attendants employed during different points in time is unavailable. This information is required by the record-based method described by Kojo et al. [2007]. They estimated average annual effective dose to a cabin crew member from flight timetables by calculating the total annual estimated effective dose for all cabin crew and then dividing by the total number of cabin crew during that year. Flight attendant numbers/year were not available in our study since we excluded a large number of flight attendants from the cohort (e.g., those employed less than 1 year and those who were not U.S. citizens when they were hired). Finally, our method avoids the problems inherent in collecting and using self-reported data on flights flown collected by questionnaire or interview as used in the method described by Kojo et al. [2004]. Their questionnaire-based estimate was approximately 80% higher than the effective dose estimated from flight schedules, which suggests that flight attendants may have over-reported their number of flights. We have also found [Grajewski et al., 2004] over-reporting of questionnaire self-reported block time and number of flight segments compared with company record-based estimates. Factors including domicile, block hr/year of work, and length of

TABLE III. Mixed Effects Modeling Results for the Estimated Exposure Rates

	Variance estimates[a]			
	Between domicile		Within domicile	
Metric	σ_b^2	Percent[b]	σ_w^2	Percent
Radiation (μSv/block hr)	0.302	54	0.253	46
Time zones crossed (#/block hr)	0.00788	48	0.00863	52
SSI travel[c] (SSI h/block hr)	0.00527	18	0.0238	82

[a]Adjusted for calendar year effects. See Statistical Methods Section for details.
[b]Percent of the total estimated variance.
[c]Travel between 10 PM and 8 AM at the flight attendant's home base domicile.

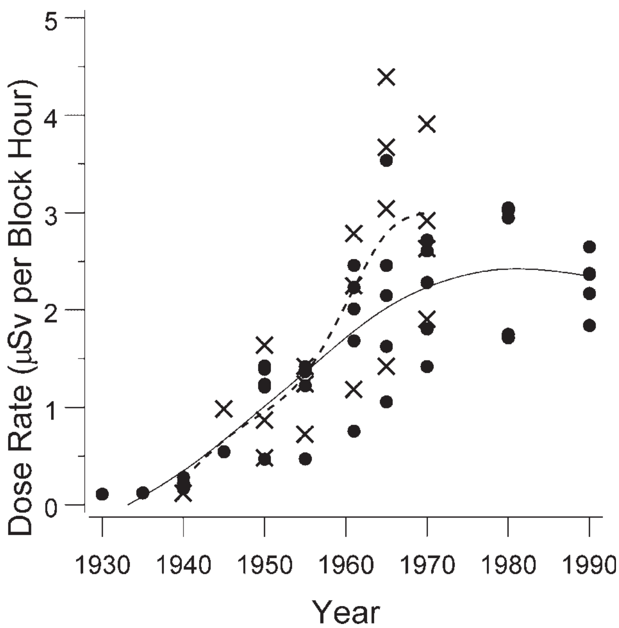

FIGURE 1. Relation between era and average radiation dose rates for each domicile–era combination. Trend lines were obtained using a LOESS smoothing function. Black dots and the solid trend line represent five domiciles with data through 1990 (Honolulu, Los Angeles, Miami, New York, San Francisco). Black Xs and dashed trend line represent four domiciles with data only through1970 (Hong Kong, London, Seattle, Washington DC).

employment affected the amount and direction of overreporting, but the reasons are not completely clear; consideration of compensable credit time did not fully account for overestimation of block time and flight segments. In turn, radiation effective dose estimates and time zones crossed were overestimated. For retrospective cohort mortality or cancer incidence studies, questionnaire-based exposure estimates also have other limitations compared to record-based estimates. Self-reported estimates may be subject to recall bias over long time periods, and decedent data are usually unavailable.

Few investigators have attempted to evaluate the role of circadian rhythm disruption in cancer risk among flight crew. Rafnsson et al. (2000) evaluated cancer risk among Icelandic pilots who ever flew over five time zones. In a nested case control study of Finnish flight attendants, Kojo et al. [2005] evaluated the risk of breast cancer associated with self-reported disturbances of sleep and menstrual cycle. In this study, we adapted validated methods for estimating circadian rhythm disruption in flight crew to a study for which individual flight histories are not available. The two metrics developed, time zones crossed and SSI travel, are related but not identical; SSI travel is more closely associated with sleep disturbance, while time zones crossed is closely related to desynchronization [Grajewski et al., 2003].

TABLE IV. Cumulative Exposure Estimates for Flight Attendants in the Pan Am Cohort Mortality Study

Cumulative exposure	No. flight attendants	Range	Arithmetic mean	Geometric mean[a]	Geometric standard deviation[a]
Duration of employment (year)	11,324	0.68–45	8.6	5.6	2.6
Radiation dose (mSv)	10,164	0.33–100	19.2	12.5	2.7
Time zones crossed	10,164	24–20,000	3,580	2,400	2.7
SSI travel (hr)[b]	10,164	7.4–15,000	1,570	920	3.0

[a]Cumulative exposure distributions were approximately lognormal.
[b]Travel between 10 PM AND 8 AM at the flight attendant's home base domicile.

TABLE V. Pearson (Above Diagonal) and Spearman (Below Diagonal) Correlation Coefficients for the Cumulative Exposure Metrics Among 10,164 Flight Attendants*

	Duration	Radiation	Time zones	SSI travel
Duration	1	0.95	0.92	0.83
Radiation	0.98	1	0.98	0.76
Time zones	0.96	0.99	1	0.78
SSI travel[a]	0.92	0.89	0.90	1

*$P < 0.0001$, all correlations.
[a]Travel between 10 PM and 8 AM at the flight attendant's home base domicile.

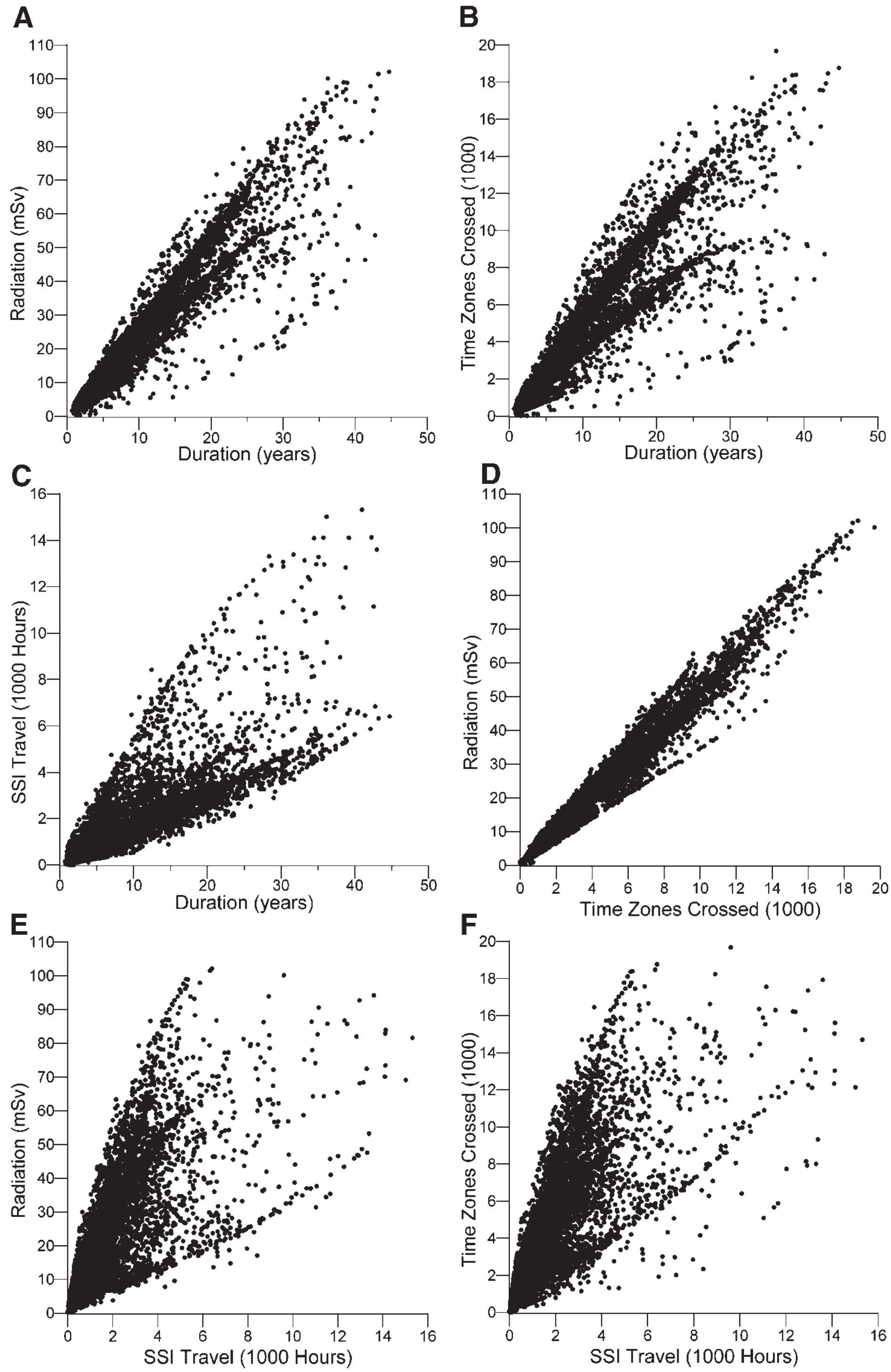

FIGURE 2. Relations between cumulative exposure metrics duration of employment, radiation, time zones crossed and SSI travel (travel between 10 PM and 8 AM at the flight attendant's home base domicile). Exposures are estimated for all flight attendants with 100% coverage in the domicile matrix.

Hammer et al. [2000] compared several record-based retrospective exposure assessment methods for studies of German pilots. They found a high correlation among the metrics evaluated, including duration of employment and cumulative radiation effective dose calculated from a job exposure matrix based on aircraft type. We also found a high correlation between duration of employment and estimated cumulative radiation. However, cumulative radiation effective dose and the other two exposure metrics show differences from duration alone (Fig. 2). The high collinearity between time zones and radiation effective dose reflects the largely East–West nature of the majority of Pan Am flights. However, in this study, the cumulative exposure metrics are naturally correlated because they are all derived from duration of employment. Thus, it may not be possible to separate these exposures in epidemiologic analyses of this cohort. Time zone—radiation collinearity can be reduced in studies by including flight attendants who work primarily North–South routes [Grajewski et al., 2002].

Retrospective exposure assessment for flight crew continues to challenge investigators. The benefits of this approach may be offset by the required records collection and processing. The primary limitation of the metrics we have presented is error introduced by the lack of actual flown flight segments. Specific data for individual flights, including differences in identical flight segments due to direction, might be able to reduce potential exposure collinearity and estimation error. Assumptions regarding number of block hours flight attendants worked per month as well as flight profile assumptions for input into the CARI program can add to overall misclassification. We did not include the assessment of exposures from deadhead (positioning) flights, recreational travel, or travel through solar particle events due to lack of data on specific flights, dates, and routes flown. The US airline seniority-based flight bidding system is also a potential source of uncertainty. However, our average annual flight attendant effective dose estimate (2.38 mSv/year, cumulative range 0.33–100 mSv) is consistent with estimates from other record-based studies [0.7–2.3 mSv/year, cumulative range 0.4–61.6 mSv, Kojo et al., 2007] and two studies of individual flight segments [2.3 mSv/year, Oksanen, 1998; 1.5–1.7 mSv/year, Grajewski et al., 2002].

Notwithstanding the consistency in average annual dose estimates across studies, there have been changes in air cabin exposures over time. In this study, relatively low radiation exposures in the 1930s increased over the study period (Fig. 1). The greatest variability appears to be during the years that a mixture of jet and non-jet aircraft was used. As jet aircraft became increasingly dominant, radiation exposure increased. SSI travel distributions seem less era- and domicile dependent, and the least correlated with the other metrics. Sleep disturbance, which is associated with SSI travel, is less associated with aircraft technology and has likely been a consistent occupational exposure for flight attendants over time.

A strength of this exposure assessment is the use of available company work history records of flight attendant domiciles rather than self-reported, recall-based estimates. Compared to duration of employment, the large number of individual flight segments and variability between domiciles in our combined database over an extended time period improve the assessment of circadian disruption career cumulative exposure, and may improve radiation exposure assessment, depending on typical routes flown. These methods were used for the NIOSH Pan Am flight attendant cohort mortality study, and will be adapted for a related breast cancer incidence study in former Pan Am flight attendants.

ACKNOWLEDGMENTS

We thank Gina Naco for her assistance with data analysis; Christine Gersic, Denise Giglio, Terri Hill, Kim Jenkins, Kathy Watkins, and Emily Wood for assistance with data collection and abstraction; and the Air Transport Association for access to OAG^{TM} schedules.

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