Flight Attendant Radiation Dose from Solar Particle Events

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Introduction: Research has suggested that work as a flight attendant may be related to increased risk for reproductive health effects. Air cabin exposures that may influence reproductive health include radiation dose from galactic cosmic radiation and solar particle events. This paper describes the assessment of radiation dose accrued during solar particle events as part of a reproductive health study of flight attendants. ***Methods:*** Solar storm data were obtained from the National Oceanic and Atmospheric Administration Space Weather Prediction Center list of solar proton events affecting the Earth environment to ascertain storms relevant to the two study periods (1992–1996 and 1999–2001). Radiation dose from exposure to solar energetic particles was estimated using the NAIRAS model in conjunction with galactic cosmic radiation dose calculated using the CARI-6P computer program. ***Results:*** Seven solar particle events were determined to have potential for significant radiation exposure, two in the first study period and five in the second study period, and over-lapped with 24,807 flight segments. Absorbed (and effective) flight segment doses averaged 6.5 μGy (18 μSv) and 3.1 μGy (8.3 μSv) for the first and second study periods, respectively. Maximum doses were as high as 440 μGy (1.2 mSv) and 20 flight segments had doses greater than 190 μGy (0.5 mSv). ***Discussion:*** During solar particle events, a pregnant flight attendant could potentially exceed the equivalent dose limit to the conceptus of 0.5 mSv in a month recommended by the National Council on Radiation Protection and Measurements.

Keywords: absorbed dose, effective dose, conceptus, reproductive health.

FLIGHT ATTENDANTS are occupationally exposed to galactic cosmic radiation as well as radiation from solar energetic particles produced during coronal mass ejections and solar flares. Galactic cosmic radiation (GCR) is the result of supernova explosions and is composed primarily of protons (85%), helium nuclei (12%), heavier nuclei (1%), and electrons and positrons (2%). The primary particles that make up GCR, having energies up to 10^{20} eV, impinge isotropically upon the Earth's atmosphere (8). The composition of radiation from solar particle events (SPEs) is similar to that generated by GCR, but the particles are accelerated at lower energies (between 10^6 and 10^{10} eV) (1), thus significant dose from these events is generally only a concern at higher altitudes and/or latitudes (11).

Previous studies evaluating the relationship between work as a flight attendant and adverse reproductive outcomes have indicated increased risks, although results are inconsistent (13). Air cabin exposures that may influence reproductive health include radiation dose from GCR and solar particle events, circadian rhythm disruption, environmental tobacco smoke, cabin pressurization, and pesticide exposure. The National Institute for Occupational Safety and Health (NIOSH) is currently studying the potential effects of work as a flight attendant on reproductive health. Outcomes of interest include spontaneous abortion, menstrual function (i.e., cycle length and variability), time-to-pregnancy, preterm birth, and birth weight.

This paper presents the assessment of radiation exposure at commercial aviation altitudes from SPEs. Although several studies have characterized dose rates from SPEs at commercial aviation altitudes (4,12,14), epidemiological studies of flight crew have not quantitatively evaluated dose from SPEs as part of overall occupational exposure, most likely because the data available have been insufficient to assess probable SPE exposure. Because NIOSH acquired detailed company records of actual flight segments flown, likelihood of SPE exposure could be ascertained, and SPE dose could be assessed and combined with GCR dose estimates.

METHODS

The cohort consists of 2174 women ages 18 to 45 who were employed as flight attendants at three major U.S. airlines with domiciles (or hubs) in Miami (Company X), Seattle (Company Y), and Detroit (Company Z). The study covers two time periods: 1 August 1992 through 31 July 1996 (Study Period A) and 1 November 1999 through 30 April 2001 (Study Period B). Employment records for each flight attendant study subject, including detailed individual flight history (i.e., actual flights worked), were obtained from each of the three airlines for both study periods. Flight history records for each flight worked during the two study periods contained information on origin and destination cities, date of

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flight, and local departure and arrival times. For each flight segment, local departure and arrival times were adjusted for daylight savings time and converted to Universal Time (UTC). Information on commuter and recreational travel were generally included in the company records; however, only flight date and origin and destination cities were available.

First, radiation dose from exposure to cosmic radiation was estimated using the CARI-6P computer program developed by the Federal Aviation Administration (FAA). CARI-6P estimates effective dose received by an individual on an aircraft flying between any two geographic locations assuming a Great Circle route (20). Total absorbed (μGy) and effective (μSv) dose (D_{CARI}) for each flight segment was estimated using the CARI-6P computer program. Regression equations based on 6784 flight plans from 1997 provided by the study companies and a previously developed algorithm were used to generate the required input data for radiation dose estimation using CARI-6P (i.e., taxi time, cruising altitudes, time at each cruising altitude) (7).

Radiation dose from exposure to solar energetic particles was estimated using the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model. The model was developed by scientists at the National Aeronautics and Space Administration (NASA) and is described in detail elsewhere (14,15). Briefly, the NAIRAS model is designed to provide real-time prediction of ionizing radiation exposure rates at commercial aviation altitudes. The NAIRAS code combines radiation transport calculations with real-time measurements of atmospheric density versus altitude and radiation incident on the Earth's atmosphere to provide predictions of both galactic cosmic and solar particle event radiation.

Solar storm data was obtained from the National Oceanic and Atmospheric Administraton (NOAA) Space Weather Prediction Center list of solar proton events affecting the Earth environment (http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt). NOAA defines a solar particle event as a flux of greater than 10 MeV protons at greater than 10 particle flux units (pfu). Solar storms of interest in terms of significant radiation exposure were assumed to be those storms with a solar proton flux greater than 900 pfu. Once relevant solar storms were selected, "date gates" were used to determine whether a flight segment occurred during the event and thus SPE dose should be calculated. The date gates were set at midnight (00:00 UTC) 1 d prior to the beginning of the SPE and at midnight (00:00 UTC) 1 d after the end of the SPE. A flight segment was considered to occur during the SPE if the flight segment start date/time or end date/time occurred between the date gates.

For each solar storm, NASA provided two data sets produced using NAIRAS: one data set containing dynamic (hour-by-hour) radiation absorbed and effective dose rate data covering each storm period and a second data set containing the average radiation dose rate for each entire storm period (event-averaged dose rate). Each data set provided by NASA contained both SPE dose rates and GCR dose rates as a function of time (hour-by-hour or dynamic data) or averaged over the storm period (event-averaged). The dynamic data are the dose rates on a 5-degree × 5-degree grid at altitudes from 0 to 90 km (roughly 230,000 data points per hour of the storm for the dynamic data set).

Although cruising altitude is variable for each flight segment, it was necessary to estimate a single most representative altitude for each flight segment for SPE dose estimation. A representative altitude for each flight segment was chosen based on the distribution of weighted average altitudes obtained from a data set containing detailed flight plans for all flights over a 2-5 d period for the three study companies (7). Dynamic SPE dose rate data for the origin and destination city geomagnetic coordinates for each flight segment were used to estimate SPE doses for official or "segment" travel (i.e., flights flown as part of the regular work schedule) because detailed information on flight segments flown (i.e., origin/destination and arrival/departure times/dates) were available:

$$D_{SPE} = D_{CARI} \times \frac{1}{2}\left[\frac{1}{t}\sum_{i=1}^{t}\left(\frac{\dot{D}_{i,SPE}}{\dot{D}_{i,GCR}}\right)_{ori} + \frac{1}{t}\sum_{i=1}^{t}\left(\frac{\dot{D}_{i,SPE}}{\dot{D}_{i,GCR}}\right)_{dest}\right]$$

where $\dot{D}_{GCR}$ = NAIRAS-calculated GCR dose rate at the flight segment origin or destination city; $\dot{D}_{SPE}$ = NAIRAS-calculated SPE dose rate at the flight segment origin or destination city; D_{CARI} = CARI-6P-calculated GCR dose for flight segment; and t = time period of the flight segment.

Event-averaged SPE dose rate data were used to estimate SPE doses for commuter and recreational flights because only flight date, (i.e., no departure and arrival times) and origin/destination city were available:

$$D_{SPE} = D_{CARI} \times \frac{1}{2}\left[\left(\frac{\dot{D}_{SPE}}{\dot{D}_{GCR}}\right)_{ori} + \left(\frac{\dot{D}_{SPE}}{\dot{D}_{GCR}}\right)_{dest}\right]$$

Absorbed doses from solar particle events for flight segments that were below 10% of the minimum CARI-6P-calculated absorbed dose from GCR for all flight segments were assumed to be within the estimated uncertainty of dose from GCR and were set to zero. Flight segment doses and cumulative doses estimates for individual flight attendants were summarized using descriptive statistics.

RESULTS

Fig. 1 shows the study periods A and B in relation to Solar Cycles 22 and 23, respectively. Study period A occurs near the minimum at the end of Solar Cycle 22, whereas study period B occurs near the maximum of Solar Cycle 23. Start and end dates and times, duration, and proton flux for each solar particle event are shown in **Table I**. Solar storm proton flux (integral 5-min averages for proton energies > 10 MeV) varied between

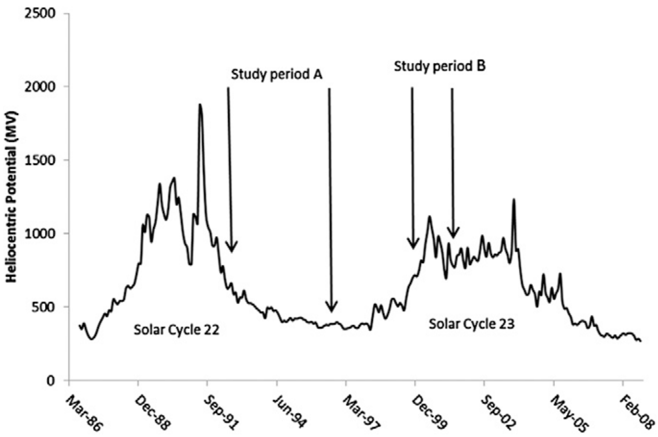

Fig. 1. Average monthly heliocentric potentials versus month/year for the two solar cycles corresponding to the study periods of interest (21).

940 pfu for Event 5 (study period B) to 24,000 pfu for Event 3 (study period B). Only two solar storms of any potential dose significance (out of seven) occurred during study period A, which encompassed 4 yr, while five solar storms with potential dose significance (out of 20) occurred during study period B, which encompassed only 1.5 yr.

From a total of 1,692,691 flight segments coinciding with study period A and 461,536 flight segments coinciding with study period B, 9890 (0.6%) and 14,917 (3%) flight segments, respectively, were determined to have occurred within the date gates established for SPE. Only 1411 (0.08% of total) flight segments in study period A (2 events) had significant (nonzero) SPE dose, while 6593 (1.4% of total) of flight segments in study period B (5 events) had significant SPE dose. There were significant doses in 752 flight segments designated as commuter or recreational travel occurring during both study periods combined.

Descriptive statistics for absorbed and effective doses per flight segment resulting from exposure to SPE radiation during each of the seven events are shown in **Table II** and show the distributions to be highly skewed. For calculation of SPE dose rates, the representive cruising altitude was determined to be the median time-weighted average altitude for each flight segment (10 km; mean = 9.7 km; SD = 1.5 km). **Fig. 2** shows the calculated absorbed and effective doses per flight segment from SPE radiation for each study period in comparison to GCR doses calculated using CARI-6P during the same time period. Median and 75th percentile absorbed dose per flight segment from SPE radiation for each of the seven SPEs by study company (**Fig. 3**) also reflect route differences between airlines which impact SPE exposure. Mean doses for commuter/recreational travel varied from 0.0040 μGy (0.016 μSv) for Event 2 ($N = 1$ flight segment) to 1.4 μGy (4.4 μSv) for Event 3 ($N = 96$ flight segments).

DISCUSSION

This is the first comprehensive assessment of SPE for over 2 million flights as part of an epidemiological study. Because these routes were flown by U.S. flight crews and were primarily domestic flights, there are few data in the literature with which to compare these results. Clucas et al. (3) used the Atmospheric Radiation Model to calculate ambient-equivalent dose rates for a London-New York flight at conventional aviation altitudes during the 14 July 2000 solar storm (Event 3). Total ambient-equivalent flight dose calculated for the London-New York flight was 10 μSv compared to an effective dose of 633 μSv calculated for the same route during the same event in this study. Lantos and Fuller estimated ~70 and 50 μSv dose equivalent for Event 3 and Event 7 (15 April 2001), respectively, for a Paris-San Francisco Airbus A340 flight using the SiGLE model (10). These exact flight routes were not part of the airline flight schedules during the study periods; however, comparable routes assessed in this study included London-Los Angeles (90 μSv) and Paris-San Jose, CA (202 μSv).

Cumulative doses from occupational exposure to SPE radiation vary with the number and size of the SPEs that occur during a flight attendant's work. Flights occurring during periods of maximum solar activity are more likely to coincide with SPE; however, dose received from an SPE occurring during a flight depends on the magnitude of the event. Comparison of doses from GCR and SPE in Fig. 2 demonstrates the relatively constant and isotropic nature of GCR compared to the varying intensity and anisotropy of SPE radiation (2,10). Also, dose received during a SPE is strongly dependent on altitude as well as geomagnetic latitude. For example, nonflying pregnant women in the three airline hubs of Miami,

TABLE I. STUDY-ASSOCIATED SOLAR PARTICLE EVENTS.

Event	Event Start[a]	Event End[a]	Duration (h)	Proton Flux (pfu)
Study period A				
1	20:00 30 Oct 1992	16:00 04 Nov 1992	116	2700
2	03:00 20 Feb 1994	01:00 22 Feb 1994	46	10,000
Study period B				
3	11:00 14 Jul 2000	15:00 17 Jul 2000	76	24,000
4	00:00 09 Nov 2000	10:00 11 Nov 2000	58	14,800
5	17:00 24 Nov 2000	05:00 25 Nov 2000	12	940
6	00:00 05 Apr 2001	13:00 08 Apr 2001	85	1110
7	14:00 15 Apr 2001	16:00 17 Apr 2001	50	951

[a] Universal Time (UTC)

TABLE II. ABSORBED AND EFFECTIVE DOSE PER FLIGHT SEGMENT FOR EACH STUDY-ASSOCIATED SOLAR PARTICLE EVENT.

		Absorbed Dose (μGy)			Effective Dose (μSv)		
Event	***N***	**Mean ± SD**	**Median**	**Maximum**	**Mean ± SD**	**Median**	**Maximum**
1	1238	7.4 ± 34	0.58	445	20 ± 92	1.5	1243
2	173	0.31 ± 0.56	0.024	2.2	0.85 ± 1.6	0.067	6.3
3	1585	8.2 ± 28	0.15	271	22 ± 73	0.41	710
4	1350	1.3 ± 3.4	0.098	39	3.6 ± 9.6	0.28	115
5	440	0.21 ± 0.19	0.15	1.2	0.53 ± 0.49	0.38	3.2
6	1869	0.072 ± 0.11	0.034	1.2	0.20 ± 0.34	0.097	4.0
7	1349	3.9 ± 14	0.18	123	10 ± 37	0.47	330

Only significant (nonzero) doses are included.

Seattle, and Detroit (essentially at sea level) during Event 3 were potentially exposed to peak dose rates of 0.085, 0.15, and 0.12 μSv · h^{-1}, respectively, and 5.4 and 4.2 μSv · h^{-1} in London and New York, respectively.

Because of the anisotropy of the SPE radiation during a solar storm, using the Great Circle Route estimation rather than the actual flight plan for a given flight to calculate SPE dose can result in significant under- or overestimation (6,10). Additionally, SPE dose rates vary by several orders of magnitude with time during the event (14). For example, effective dose rates at London Heathrow (at 6.2 mi/10 km altitude) varied from 0.00000018 μSv · h^{-1} to 480 μSv · h^{-1} during the course of Event 3, with the largest dose rates occurring during the first 3 h of the storm (240-480 μSv · h^{-1}) and smaller dose rates occurring for the remainder (maximum of 11 μSv · h^{-1}). Thus, the hours during which flights between a given origin and destination occur during a SPE have a significant effect on the magnitude of the SPE dose as seen in the large difference between the ambient-equivalent dose estimated by Clucas et al. (3) for the London-New York flight and the effective dose calculated in this study. Variation in SPE dose rates with time is also evident in the difference between SPE doses estimated for actual known flight segments using dynamic data versus SPE doses estimated for commuter/recreational travel flight segments using event-averaged data, likely resulting in underestimation of SPE dose.

The FAA supports dose limits recommended by the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) (19). The ICRP recommends an equivalent dose limit of 1 mSv to the embryo/fetus for the remainder of the pregnancy and the NCRP recommends an equivalent dose limit of 0.5 mSv per month to the embryo/fetus (9,16). Newly published protective guidance from the NCRP still recommends a 0.5 mSv per month equivalent (18). During air travel, the body is exposed uniformly (i.e., near-isotropic geometry) to galactic and/or solar radiation, thus the effective dose calculated by CARI-6P is a reasonable and conservative estimate of the equivalent dose to the conceptus (20).

Research has suggested that no damage to the conceptus is observed at absorbed doses less than 50 mGy

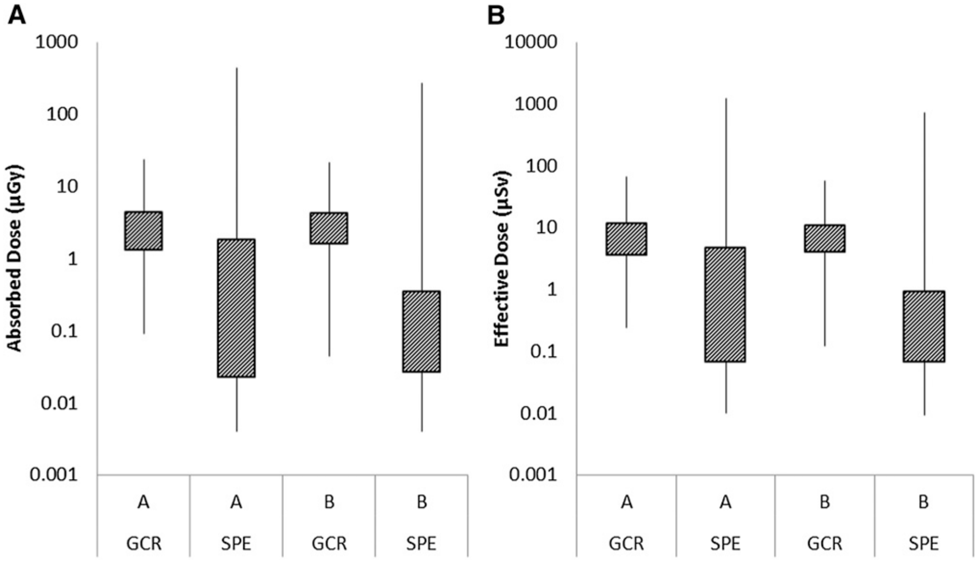

Fig. 2. A) Absorbed and B) effective doses per flight segment from GCR and SPE radiation for study period A (1411 flight segments) and study period B (6593 flight segments). Lines indicate data ranges (min, max) and boxes indicate the interquartile ranges. Only segments with significant (nonzero) estimated SPE dose are represented.

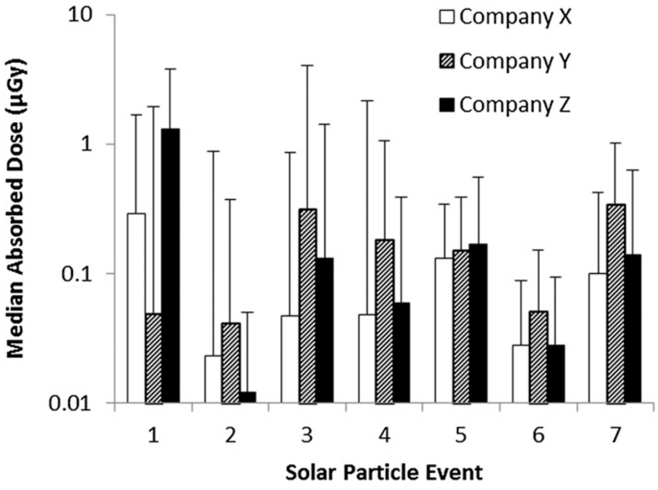

Fig. 3. Median and 75th percentile absorbed dose per flight segment from SPE radiation for each event for study company X (Miami domicile), Y (Seattle domicile), and Z (Detroit domicile). Only segments with significant (nonzero) estimated SPE dose are represented.

(50 mSv equivalent dose) (5). However, a study of female veterinarians performing more than five radiographic examinations per week indicated a statistically significant excess risk of spontaneous abortion (22). According to the NCRP, average annual effective dose for monitored veterinary workers varied between 0.28 and 0.51 mSv for 2003–2006 (17).

This study shows that although flight through a significant SPE is a relatively infrequent occurrence on the commercial routes in our sample, there is a potential for a pregnant flight attendant working on a single flight traveling through an SPE to receive an effective dose in excess of the NCRP-recommended equivalent dose limit to the conceptus of 0.5 mSv per month and/or the ICRP recommended equivalent dose limit of 1 mSv for the pregnancy. Future enhancements of the NAIRAS system include a proposed 2-h warning system for SPE exposure, which would allow for rerouting of flights more effectively than the few minutes of warning currently available to commercial airlines. Mitigation of exposure to GCR and SPE radiation while pregnant could be achieved by flying routes at lower altitudes/latitudes and/or reducing the amount of time spent flying.

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