THE NIOSH/FAA WORKING WOMEN'S HEALTH STUDY: EVALUATION OF THE COSMIC-RADIATION EXPOSURES OF FLIGHT ATTENDANTS

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***Abstract*—Air crew are exposed to elevated levels of cosmic ionizing radiation of galactic and solar origin and are among the more highly exposed occupational groups to ionizing radiation in the United States. Depending on flight route patterns, the annual dose may range from 0.2 to 5 mSv. By comparison, the average annual radiation dose equivalent of occupationally exposed adults in the United States is estimated to be 1.1 mSv. Cosmic-radiation dose depends primarily on altitude and geomagnetic latitude and to a lesser degree on solar activity. Although the International Commission on Radiological Protection has recommended that air crew exposures to natural radiation in-flight be treated as occupational exposures, United States flight crew exposures to natural cosmic radiation are not regulated or typically monitored. There are approximately 148,000 air crew (flight deck crew and flight attendants) in the United States.**
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INTRODUCTION

AIR CREW are exposed to elevated levels of cosmic ionizing radiation of galactic and solar origin and are among the more highly exposed occupational groups to ionizing radiation in the United States. Depending on flight route patterns, the annual dose may range from 0.2 to 5 mSv (O'Brien and Friedberg 1994). By comparison, the average annual radiation dose equivalent of occupationally exposed adults in the United States is estimated to be 1.1 mSv (EPA 1984). Cosmic-radiation dose depends primarily on altitude and geomagnetic latitude and to a lesser degree on solar activity. Although the International Commission on Radiological Protection (ICRP) has recommended that air crew exposures to natural radiation in-flight be treated as occupational exposures (ICRP 1991), United States flight crew exposures to natural cosmic radiation are not regulated or typically monitored. There are approximately 148,000 air crew (flight deck crew and flight attendants) in the United States (ATA 1995).

The scientific literature suggests that female flight attendants may experience an increased risk of miscarriage, menstrual disorders, and other adverse reproductive outcomes (Cameron 1969; Farrell and Allen 1973; Preston et al. 1973; Iglesias et al. 1980; Vaughan et al. 1984). Estimates of cosmic-radiation exposure indicate that frequent air travel may expose pregnant flight attendants to ionizing radiation levels that exceed recommended limits (ICRP 1991; Friedberg et al. 1992; NCRP 1993, 1995). The National Institute for Occupational Safety and Health (NIOSH), in collaboration with the Federal Aviation Administration (FAA) and the Department of Defense Women's Health Research Program, is currently conducting studies of the reproductive health of female flight attendants. The primary concerns are cosmic-radiation exposures and circadian rhythm disruption, although other factors and exposures such as physical activity and cabin air contaminants are also being considered.

The first study will examine past reproductive outcomes using questionnaire data to be collected from approximately 3,500 United States flight attendants. Outcomes to be examined include miscarriage, menstrual function, and fertility. A second study is evaluating the feasibility of biomonitoring for ovulatory function by measuring hormone levels in urine and saliva. As part of this study, 46 flight attendants from two major United States airlines and 25 teachers from the same domiciles collected daily urine and saliva samples for one menstrual cycle, kept a daily diary for three months, and wore an activity monitor to measure sleep disruption. Teachers serve as a comparison population for both studies. Other current NIOSH/FAA studies include a cancer incidence and mortality study of former employees of an out-of-business United States airline company. For this study, personnel and work history records are available back to the 1940's, presenting an opportunity to evaluate breast and other cancers among flight attendants. Incident cancer cases among approximately 12,000 women employed as flight attendants will be identified from records

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and questionnaires. All of these studies require estimation of cosmic-radiation dose, based on individual flight histories, questionnaire data, or domiciles worked. This estimation will be made using a computer program.

As part of the epidemiologic studies of health in female flight attendants, NIOSH is conducting a study to measure cosmic-radiation and cabin environmental exposures aboard commercial aircraft. Cosmic-radiation absorbed dose and dose equivalent are being measured using tissue equivalent proportional counters (TEPC). Cabin environmental parameters being monitored include ozone, carbon dioxide, carbon monoxide, nitrogen oxides, volatile organic hydrocarbons, temperature, relative humidity, pressure, noise, environmental tobacco smoke (on smoking flights), and extremely low-frequency electromagnetic fields. Measured cosmic-radiation doses will be compared to calculated dose estimates made with the CARI computer program developed by the FAA (Friedberg et al. 1992, 1993, 1997). The CARI estimates will be used for dose reconstruction for the epidemiologic studies. This research is currently being conducted; described here are the study design, field survey methods, cosmic-radiation detection instrumentation and some of the cosmic-radiation measurement results. The cabin environmental quality methods are described elsewhere (Waters et al. 1996).

OBJECTIVES

The study objectives are: (1) to measure cosmic-radiation levels as a function of altitude, distance/duration, and changes in flight latitude and longitude, (2) to compare the cosmic-radiation dose equivalent data measured with the TEPCs for specific flight segments with cosmic-radiation equivalent doses calculated by CARI, (3) to characterize current exposure levels and variability of cabin environmental parameters on aircraft types flown by flight attendants in the NIOSH epidemiologic studies, and (4) to evaluate the relationship between aircraft type and environmental parameters.

STUDY DESIGN

The study design reflects a balance between the optimal designs for cosmic-radiation characterization and for cabin air quality and environmental characterization. For cosmic-radiation characterization, the determinants of dose are proximity to Earth's geomagnetic poles (longitude and latitude), altitude, duration of flight, and presence of radioactive materials aboard the aircraft. Thus the primary design objective was to include flights that traverse a diversity of global paths, including trans-arctic circle or over-the-pole flights, trans-equatorial flights, long-haul north-south and long-haul east-west flights. Information regarding transport of radioactive materials is being collected.

The primary determinants for air quality and cabin environmental parameters are aircraft type (make, model, ventilation system), flight duration, passenger loading percentage, whether smoking is permitted, and to a certain extent, altitude and longitude and latitude (e.g., for ozone). "Aircraft type" is a surrogate for factors such as ventilation rate, air filtration efficiency, ratio of recirculated to fresh exchange air, cabin volume, and ventilation patterns, which are difficult to measure directly on passenger flights. Flight altitude is highly correlated with flight duration and is not considered as a separate study design variable. Flight duration is stratified into three categories: short (<2 h), medium (2 to 8 h), and long (>8 h). Therefore, the study design objectives for assessment of cabin environmental quality are to include different aircraft types, short, medium and long duration flights, and polar and non-polar flights. Stratification by either passenger loading percentage and smoking status of flights is not a design objective but these factors are recorded. All the planned flights have >50% passenger loading in coach. Table 1 summarizes the 33 flights stratified by length, primary direction, and aircraft type for this study.

Table 1. Study design matrix for the NIOSH/FAA Working Women's Health Study measurement flights.

Primary flight direction	Duration: Short (<2 h)	Duration: Medium (2–8 h)	Duration: Long (>8 h)
North-South	MD80 B737 (2)[a] above 50 N	A300 (2) MD80 (1) B747-100 (2)	MD11 (2) trans-equat
East-West	B737 (2)	B757 (3) B747-100 (2) A320 (2)	B747-200 (2) trans-Pacific
Both North-South and East-West		B767-300 MD80 (2) B737-400 (2) B727 D10 (2)	B777 (2) above 50°N B747-100 (2) trans-equat

[a] Number in parentheses is number of flight segments.

METHODS

The TEPCs developed for the NIOSH study are patterned after those developed for the National Aeronautics and Space Administration to record radiation doses aboard the Space Shuttle. The TEPC design is similar to that described by Braby et al. (1995), including a 5-inch detector, with an A-150 tissue equivalent plastic wall filled with 7 Torr of tissue equivalent gas (propane) to simulate a cell size of 2 μm. The detector is connected to a 256 channel multichannel analyzer (MCA) with a lineal energy range from 0.2 keV μm^{-1} to 1,000 keV μm^{-1}. The energy resolution of the electronics is 0.1 keV μm^{-1} below 20 keV μm^{-1} and 5 keV μm^{-1} above 20 keV μm^{-1}. The full lineal energy spectrum is recorded every minute on one flash memory board with 4 megabytes storage capacity. Absorbed dose is calculated by summing the number of events per channel times the mean energy of each channel and multiplying by a factor, which includes the mass of the simulated site and the area of the site. Dose equivalent data are calculated based on quality factors (*Q*) in ICRP Publication 60, Table A-1 (ICRP 1991). Each TEPC is powered by a battery pack permitting 140 continuous hours of measurement and is housed in an aluminum rolling "carry-on" suitcase capable of being placed in the overhead compartment. Two TEPCs are used on each flight, identified as 1306 and 1307. Although on initial flights the two TEPCs were located separately (one towards the front of the aircraft and one towards the rear), they were placed within a few feet of each other on later flights. For the data presented here, the TEPCs were located separately.

Calibration of each TEPC is performed annually by the manufacturer using certified sources. A two level calibration is performed: the low-linear energy transfer (LET) region using a calibrated ^{137}Cs gamma-radiation source, and the high-LET region using an americium/beryllium neutron source. For the high-LET region, the TEPC is exposed to fission spectrum neutrons and the detector voltage is adjusted so as to place the proton edge at the proper channel of the MCA. This calibration yields a correction factor to be applied to the absorbed dose measurements. A check of the calibration in terms of absorbed dose is performed monthly and before and after each survey campaign by exposing the instrument to the calibrated ^{137}Cs check source. This check is primarily an indication of the necessity for refilling the detector with propane gas and recalibration.

The TEPCs were readied for minute-by-minute data collection prior to entering the plane and placed in the overhead bin for data collection during the flight. Gate departure, take-off, touchdown and gate arrival times were recorded. The TEPC measurements presented here reflect the period from take-off to touchdown, or actual flight time. Each TEPC was operated from "gate-to-gate," including during those periods associated with take-off and landing. This necessitated obtaining permission to operate the equipment from the avionics engineering staff of each of the participating airlines as well as the captain of each flight.

Pilots were asked to record flight altitude from the altimeter and geographical position (longitude and latitude) from the flight management system every 30 min on each flight survey and for every change in altitude, and compliance was generally good. Pilots were also queried about radioactive material shipments on each flight; none were transported on the flights described here.

CARI-4Q estimates were computed for the same origin-destination city pairs as the survey flights using the same flight times and altitudes as recorded by the pilots of the survey flights. Times of altitude changes recorded by the pilots were verified by the plot of the TEPC measurements of absorbed dose over time, since the altitude changes induce an immediate and discernable shift in the absorbed dose level.

MEASUREMENTS OF COSMIC-RADIATION DOSE

Graphs of four flight segments are presented in Fig. 1 through Fig. 4. Fig. 1 is a graph of the absorbed dose and cumulative dose equivalent as a function of time for Seattle (48 °N latitude) to Miami (26 °N). The two uppermost lines plot the absorbed dose in Grays for the two TEPCs. Over the first cruise altitude of 37,000 ft, a slight decline in the absorbed dose is noticeable as the latitude declines. At the second cruise altitude of 41,000 ft the decline in dose as latitude decreases is more

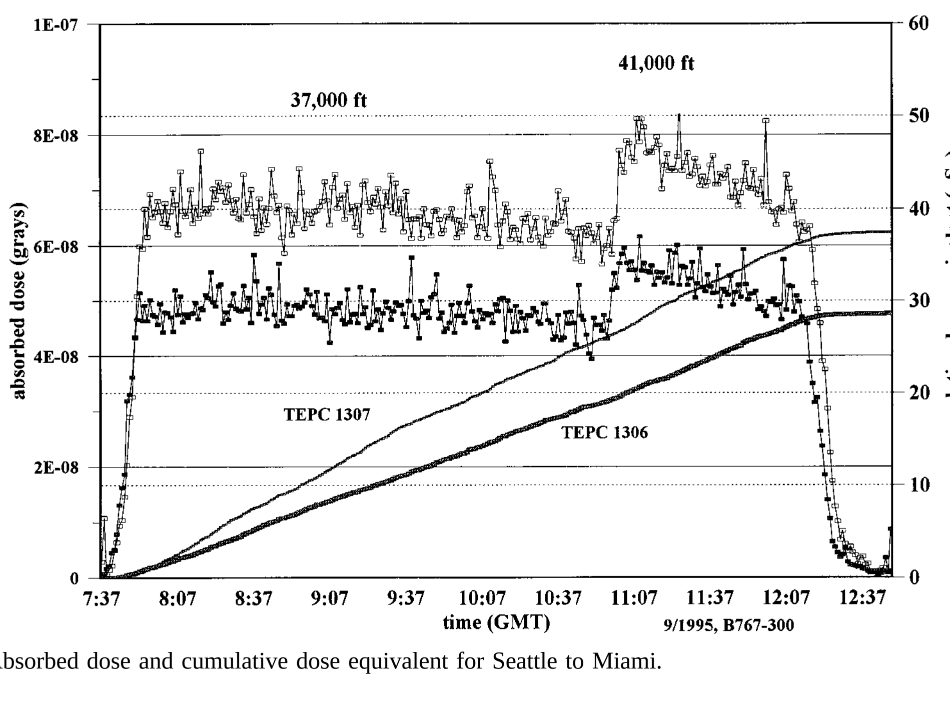

Fig. 1. Absorbed dose and cumulative dose equivalent for Seattle to Miami.

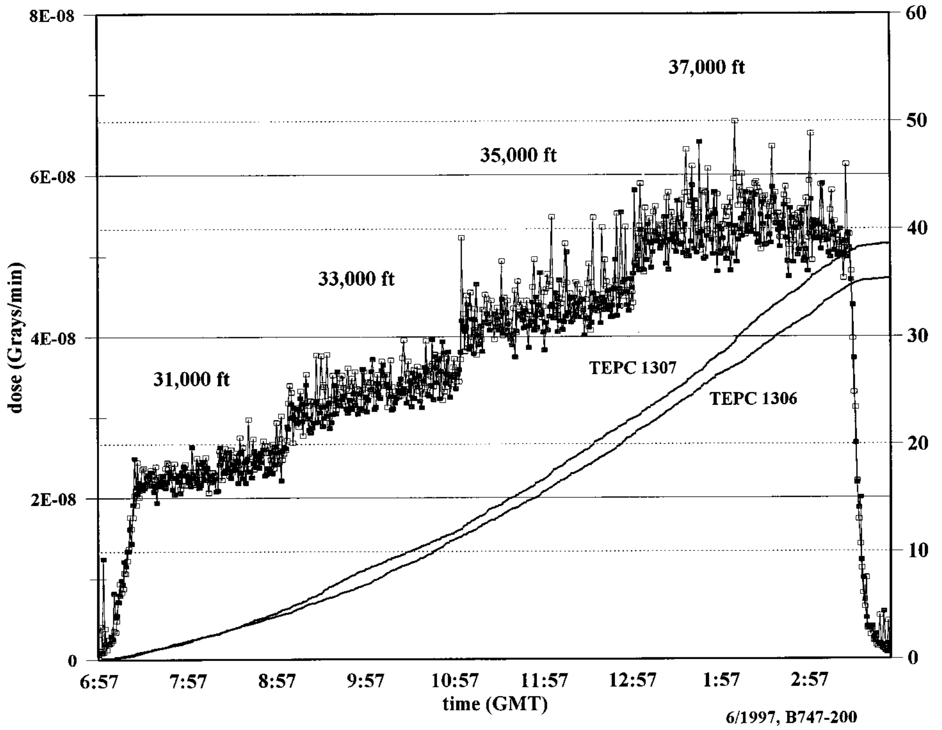

Fig. 2. Absorbed dose and cumulative dose equivalent for Tokyo to Los Angeles.

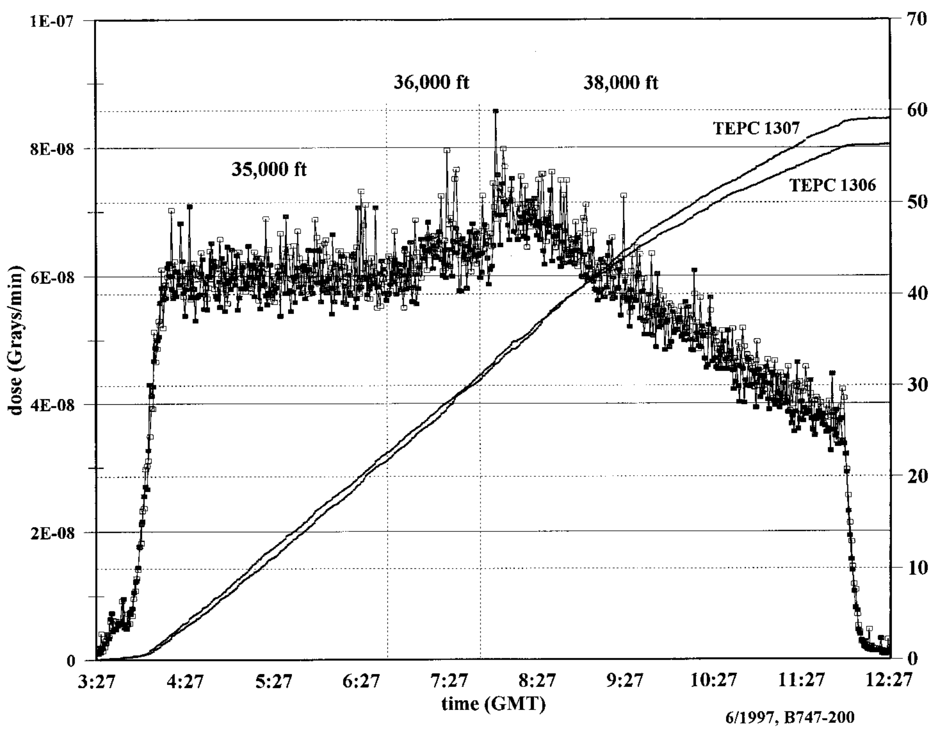

Fig. 3. Absorbed dose and cumulative dose equivalent for Seattle to Tokyo.

marked. The lower lines are cumulative dose equivalent over the flight for the two TEPCs. The cumulative dose equivalent for TEPC 1306 is 28.6 and 37.4 μSv for TEPC 1307. Another feature of this data is the discrepancy in measurements between the two TEPCs, about a 28% difference. Following this flight the TEPCs were

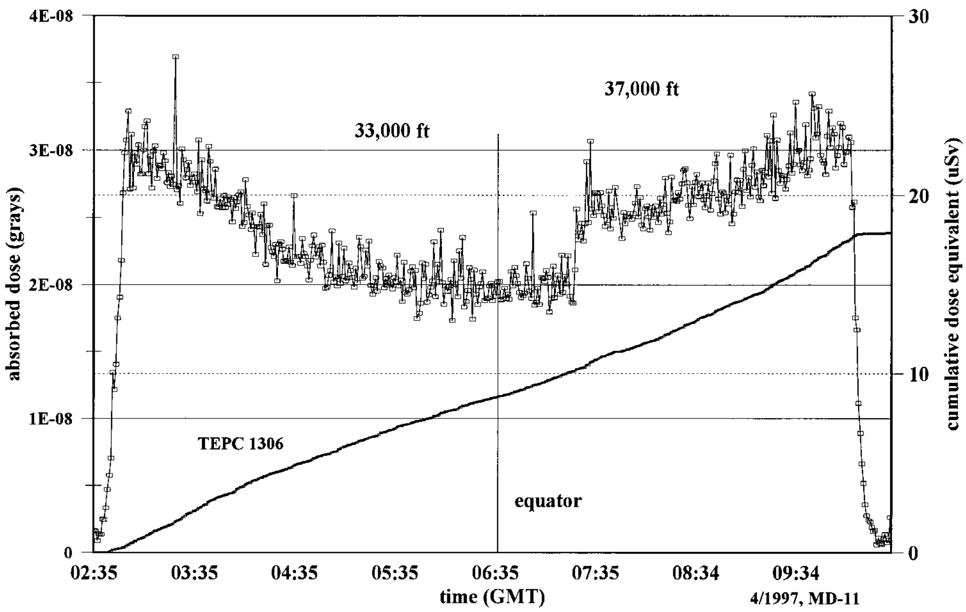

Fig. 4. Absorbed dose and cumulative dose equivalent for Miami to Buenos Aires.

recalibrated and subsequent differences between the instruments were reduced as evidenced in Fig. 2 and Fig. 3.

Fig. 2 shows the absorbed dose and cumulative dose equivalent as a function of time for a flight from Tokyo (36 °N) to Los Angeles (34 °N). Four cruise altitudes were flown. The flight was flown at 41 °N for the 6.5 h between 8:00 and 14:30 GMT. Despite this fact, within each of the cruise altitudes of 33,000, 35,000, and 37,000 ft a slight increase in the absorbed dose is evident within each flight level. This is probably due to the change in geomagnetic field between Tokyo (140 °E) and Seattle (122 °W). The cumulative dose equivalents for the two TEPCs were 35.4 and 38.6 μSv, an 8% difference. Another feature of this plot is the increase in variability of the minute-to-minute absorbed dose as altitude is increased. At higher altitudes the probability of higher energy particles being detected is greater.

Fig. 3 shows the radiation dose for a flight between Seattle (47 °N) and Tokyo (36 °N). The latitudes covered during the time spent at 35,000 ft ranged from 50 to 57 °N. The reason absorbed dose changes very little at 35,000 ft while the latitude increases is that primary particle flux increases very little above 50 °N at solar minimum (McAulay et al. 1996). The plot shows that the average absorbed dose during this period did not change. While cruising at 38,000 ft, the latitude declined from 58 to 36 °N, with a marked decline in absorbed dose over this period. The measured cumulative dose equivalents for the two TEPCs were 56.3 and 59.1 μSv, a 4.7% difference.

The radiation dose for a flight from Miami (26 °N) to Buenos Aires (35 °S) is shown in Fig. 4. Only one TEPC was functional for this flight. While moving towards the equator at 33,000 ft the absorbed dose declines slightly, then increases slightly upon crossing the equator. The geomagnetic field between 10 °N and 20 °S in this region (60 to 70 °W) is relatively unchanging. The measured cumulative dose equivalent for TEPC 1306 is 17.9 μSv.

Measurements of cosmic-radiation absorbed dose and dose equivalent are summarized in Table 2 for 17 commercial flights. Flights are ordered by flight times, which range from 36 to 540 min. Aircraft altitudes ranged from 22,000 to 41,000 ft. In some cases, both TEPCs were not available for measurements and the single TEPC measurements are presented. Absorbed doses ranged from 0.23 μGy (Kotzebue-Nome) to 27.6 μGy (average for Seattle-Tokyo). The average Q for the flights (not shown in Table 2) ranged from 1.55 (Miami-Buenos Aires) to 2.08 (Seattle-Tokyo). Minute-by-minute Q were highly variable and their range was much greater, including values $>$10. Average cosmic-radiation dose equivalent levels reported for the 17 flight segments in Table 2 ranged from 0.64 to 57.7 μSv.

Dose equivalent rates based on block hours ranged from 0.91 μSv h^{-1} (Kotzebue, Alaska to Nome, Alaska) to 6 μSv h^{-1} (Seattle to Miami). Based on these data, annual radiation dose equivalents for a flight attendant flying 900 block hours per year would range from 0.819 to 5.4 mSv.

Table 2 also presents the CARI-4Q estimates of the flight equivalent dose, computed using the flight times and altitudes of the measurement flights. In general the CARI-4Q estimates of equivalent dose are lower than the measurements for the same flight segments, although for one very short high-latitude flight [Nome (65 °N) to Anchorage (61 °N)] the CARI-4Q estimate was higher than the measured dose equivalent. The percent difference ranges from +11 to −46% for flights less than 2 h

Table 2. Measurements of cosmic-radiation absorbed dose and dose equivalent and CARI-4Q estimates of equivalent dose for 17 commercial flights.

Origin–destination city pairs	Cruise altitudes (1,000 ft)	Flight time (min)	Block time (h)	TEPC 1306 absorbed dose (Gy)	TEPC 1307 absorbed dose (Gy)	TEPC 1306 dose equivalent (Sv)	TEPC 1306 dose equivalent (Sv)	TEPC average DE (Sv)	Dose equivalent rate (Sv h^{-1} block time)	CARI-4Q equivalent dose (Sv)	Percent difference between TEPC, CARI-4Q
Kotzebue–Nome	25	36	0.7	0.23	ND[a]	0.64	ND	0.64	0.91	0.34	−46
Anchorage–Nome	33	74	1.5	1.31	1.99	2.89	3.71	3.3	2.2	2.8	−15
Nome–Anchorage	33	83	1.5	1.35	ND	2.78	ND	2.78	1.85	3.1	+11
San Francisco–Seattle	35	96	2.0	2.62	3.46	5.81	6.23	6.02	3.01	3.8	−37
Miami–Dallas	22, 31	143	2.7	3.22	4.47	6.26	8.79	7.52	2.79	2.9	−61
Miami–Boston	29, 27	160	3.0	3.03	ND	5.81	ND	5.81	1.94	4.1	−29
Boston–Miami	35	175	2.9	6.49	ND	12.1	ND	12.1	4.17	8.6	−29
Seattle–Anchorage	35	181	3.4	4.71	6.93	10.2	14.9	12.5	3.68	11.3	−9.6
Anchorage–Seattle	33	198	3.6	6.01	8.25	12.5	18.7	15.6	4.33	10.9	−32
Tokyo–Saipan	37	210	3.7	4.51	4.66	7.8	7.3	7.55	2.04	5.4	−28
Dallas–San Francisco	35, 23	208	3.8	6.05	8.2	12.2	15.3	13.7	3.61	8.0	−41
Saipan–Tokyo	29	225	4.1	3.13	3.28	5.4	5.5	5.45	1.33	3.4	−38
Seattle–Miami	37, 41	311	5.5	13.6	18.6	28.6	37.4	33.0	6.0	22.3	−32
Miami–Buenos Aires	33, 37	475	7.9	10.9	ND	17.9	ND	17.9	2.27	14.8	−17
Buenos Aires–Miami	28, 29, 35, 37	521	8.7	12.0	ND	19.3	ND	19.3	2.22	16.5	−14
Tokyo–Los Angeles	31, 33, 35, 37	534	9.3	19.3	20.1	35.4	38.6	37.0	3.98	24.5	−34
Seattle–Tokyo	31, 35, 36, 38	540	9.7	27.1	28.1	56.3	59.1	57.7	5.95	32.2	−44

[a] ND = not determined due to instrument unavailability or failure.

long, from −9.6 to −61% for flights between 2 and 8 h in length, and from −14 to −44% for flights longer than 8 h.

DISCUSSION

Radiation dose equivalent levels measured represented a complex function of duration of flight, latitude, and altitude. Based on data that have been collected thus far during the NIOSH/FAA study, radiation dose equivalent levels that would be experienced by a flight attendant are well below current occupational limits recommended by the ICRP and the FAA of 20 mSv y^{-1} (5 y average) (ICRP 1991; Friedberg et al. 1992). When compared to the average annual radiation dose equivalent of occupationally exposed adults in the United States of 1.1 mSv (EPA 1984), flight attendants flying 900 or more block hours per year on high-dose rate routes can be exposed to doses that exceed the average occupational exposure. The NCRP recommends a monthly equivalent dose limit of 0.5 mSv to the embryo/fetus (excluding natural background and medical radiation) once the pregnancy is known (NCRP 1993). The ICRP recommends the radiation limit during pregnancy be 2 mSv (ICRP 1991). Only flight attendants flying both a large number of hours during pregnancy, e.g., 100 h per month, and strictly the highest dose rate routes, e.g., 0.006 mSv per block hour, would exceed the NCRP monthly guideline.

One of the objectives of this measurement campaign was to compare CARI-4Q dose estimates with measured doses on a limited number of flights. This was done to assess the uncertainties in estimating flight segment doses using CARI-4Q from flight attendant work histories. CARI-4Q estimates of equivalent dose range from 11% higher than TEPC measurements of dose equivalent to 61% lower (median 32% lower), with no trends identifiable with respect to flight length or route. Some possible explanations for the differences are (1) the dimensions of the TEPC detector are such that the measurements are comparable to a dose equivalent at the surface of the body, whereas CARI-4Q estimates the equivalent dose to the bone marrow and skeletal tissue; and (2) the TEPC measurements are made in the aircraft whereas the CARI-4Q calculations do not take into account any effect of the aircraft. With regard to the latter, Foelsche et al. (1974) compared neutron spectra and tissue doses from neutrons measured in high-altitude aircraft (B-57F) and under balloons, and reported that the aircraft masses did not increase the neutron spectra and tissue doses by more than 5 to 10%.

A recent version of CARI (CARI-LF) calculates an improved estimate of the contribution of neutrons to the dose, and preliminary results indicate that the equivalent dose estimates are higher than calculated by CARI-4Q. Also, CARI-LF expresses dose as effective dose (using tissue weighting factors given in ICRP 1991), which generally results in higher dose estimates than dose to the bone marrow and skeletal tissue.

Another possible source of variation between the TEPC measured dose equivalent and the equivalent dose estimated by CARI-4Q is that different dose modifying factors are used to generate dose equivalent and equivalent dose. The TEPC LET spectrum is modified by the quality factors (Q_L) in Table A-1 of ICRP Publication 60. Q_L is a function of the unrestricted LET. CARI-4Q particle flux spectra are modified by the radiation weighting factors in Table A-2 of ICRP Publication 60. A further complication is that the quantity measured by the TEPC is LET (y), which is related to LET in a complex way (ICRU 1986). International Commission on Radiation Units and Measurements' Report 40 (ICRU 1986) defines quality factors Q_y for use with y. In using Q_L instead of Q_y to evaluate the TEPC y spectrum without first converting the y spectrum to a LET spectrum, one assumes the y and LET spectra are the same. Differences in dose equivalent evaluated using Q_y and Q_L have not been calculated for the flights in this report.

The approximation of the LET computed from the TEPC is based on energy transferred within a defined spherical volume. This restricted LET is referred to as Q_y. The relationship between Q_L and Q_y compare quite closely for particles that have an unrestricted LET of 1,000 keV μm^{-1} or less. However, significant departure from this close relationship may be introduced if the flux field contains particles having an unrestricted LET of greater than 1,000 keV μm^{-1}. The portion of particles having this characteristic is assumed to be small at aircraft cruise altitudes, however. Accordingly, the contribution to measurement variation is considered to be minimal and the lineal energy transfer Q_y, computed from the TEPC is considered to be equivalent if not a close approximation to the unrestricted LET Q_L.

Radiation dose limits recommended by NCRP, ICRP, and FAA are aimed at avoiding deterministic effects and minimizing the risk of stochastic effects, including carcinogenesis. The NIOSH/FAA epidemiologic studies currently underway may shed light on the effects of cosmic-radiation doses received at aircraft altitudes on the reproductive health of female flight attendants.

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