Radiation Dose Estimation for Epidemiologic Studies of Flight Attendants

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Background *NIOSH is conducting health studies of female flight attendants. Exposures of interest include cosmic radiation and circadian rhythm disruption, however, the data needed to estimate cumulative radiation dose are not found in work histories.*
Methods *We developed an algorithm to generate from work histories the required input data for Federal Aviation Administration radiation estimation software and evaluated whether effects of cumulative radiation dose could be distinguished analytically from effects of circadian rhythm disruption.*
Results *The algorithm has relatively low bias (< 6%) for longer flights, which contribute most to cumulative radiation dose. In one NIOSH study, 44 crew incurred an estimated average annual occupational dose of 1.5–1.7 mSv. Selection of a study population flying predominantly North–South flights can provide the necessary distinction between radiation and time zone crossing exposures.*
Conclusions *Methods developed will be useful for exposure assessment in cabin crew studies with relatively short study periods, (e.g., reproductive health studies) for which limited flight history details are generally available.* Am. J. Ind. Med. 41:27–37, 2002. *Published 2002 Wiley-Liss, Inc.*†

KEY WORDS: cosmic radiation; flight attendant; epidemiologic research design; occupational exposure

INTRODUCTION

Conventional aircraft cabins are the workplace of 172,000 United States air crew, including over 97,000 flight attendants [Air Transport Association, 1998]. Data suggest that air crew members in the US are exposed to ionizing radiation levels that are comparable to or higher than doses received by ground-based radiation workers [Wilson et al., 1995]. Using a Federal Aviation Administration (FAA) model for estimating radiation dose incurred by air crew during selected flights, a flight-year may result in radiation exposure levels ranging from 0.2 to 5 millisieverts (mSv) [O'Brien and Friedberg, 1994]. Recently, Bottollier-Depois et al. [2000] and Verhagen and Poffijn [2000] have measured cosmic radiation on small series of flights, and have estimated maximum annual doses of 4–5 mSv for air crew. Tveten et al. [2000] used annual block time and aircraft-specific dose rates in the absence of detailed work histories to estimate aircraft and year-specific exposure rate estimates for pilots which ranged from 0.07–4.3 μSv h^{-1}.

The National Institute for Occupational Safety and Health (NIOSH) is conducting two reproductive health studies of female flight attendants: (1) a prospective ovulatory function biomonitoring study of 44 flight attendants and (2) a retrospective reproductive health study of 2,000 flight attendants over the period 1992–1996. Teachers serve as an external comparison population for both studies. For both studies, NIOSH has obtained flight histories from the airline companies for eligible flight attendants during the relevant study periods. Workplace exposures that may contribute to adverse health effects for air crew include cosmic ionizing radiation and alterations of circadian

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rhythms from traveling across multiple time zones [International Commission on Radiological Protection, 1991; Harma et al., 1994]. Cumulative cosmic radiation dose will be individually estimated using flight histories and CARI, a computer model developed by the FAA [Friedberg et al., 2000] that estimates the effective dose of cosmic radiation received by an individual on aircraft flying between any two geographic locations. Circadian rhythm alterations will be estimated by flight history information such as the cumulative number of time zones crossed in flight.

Work history records containing flight histories suitable for detailed epidemiologic exposure assessment are generally maintained by US airlines for periods ranging from 1–5 years. Individual flight history records reflect the origin and destination cities flown and total airborne time, but do not include other factors which influence cosmic radiation dose, such as cruise altitudes and the amount of time spent in each phase of flight. Furthermore, the number of flights for which doses must be estimated in studies like these can be quite large (e.g., over two million flights for the retrospective study). Thus, an efficient and automated means to estimate dose from these work histories is necessary. We developed an algorithm for use with CARI to estimate cosmic radiation dose for epidemiologic studies of flight attendants. This algorithm describes a simplified simulated flight plan and provides estimates of duration of each phase of flight and cruise altitude which are needed as input to CARI. We report the results of testing the algorithm's sensitivity to changes in altitude and other flight parameters. We also describe an approach to create analytic separation between the effects of cosmic radiation dose and the effects of circadian rhythm disruption. Since many high altitude flights cross multiple time zones, the ability to distinguish these effects must be considered.

MATERIALS AND METHODS

Definitions

Figure 1 illustrates the terminology for a typical flight segment. A flight segment is a single flight between two cities without intermediate stops. Phases of flight are the time periods spent taxiing out from the gate, ascending to a single cruise altitude, cruising, descending, and taxiing into the gate. Although a single cruise altitude is illustrated, actual flights can have multiple cruise altitudes. "Block" time is the time from block removal from behind the aircraft wheels at the origin city gate to block placement behind the aircraft wheels at the destination city gate. Airborne time is the time from the moment the aircraft leaves the ground (takeoff) to the moment it touches down. Block time, by definition, is made up of airborne time plus taxi time. Individual flight histories contain block time only.

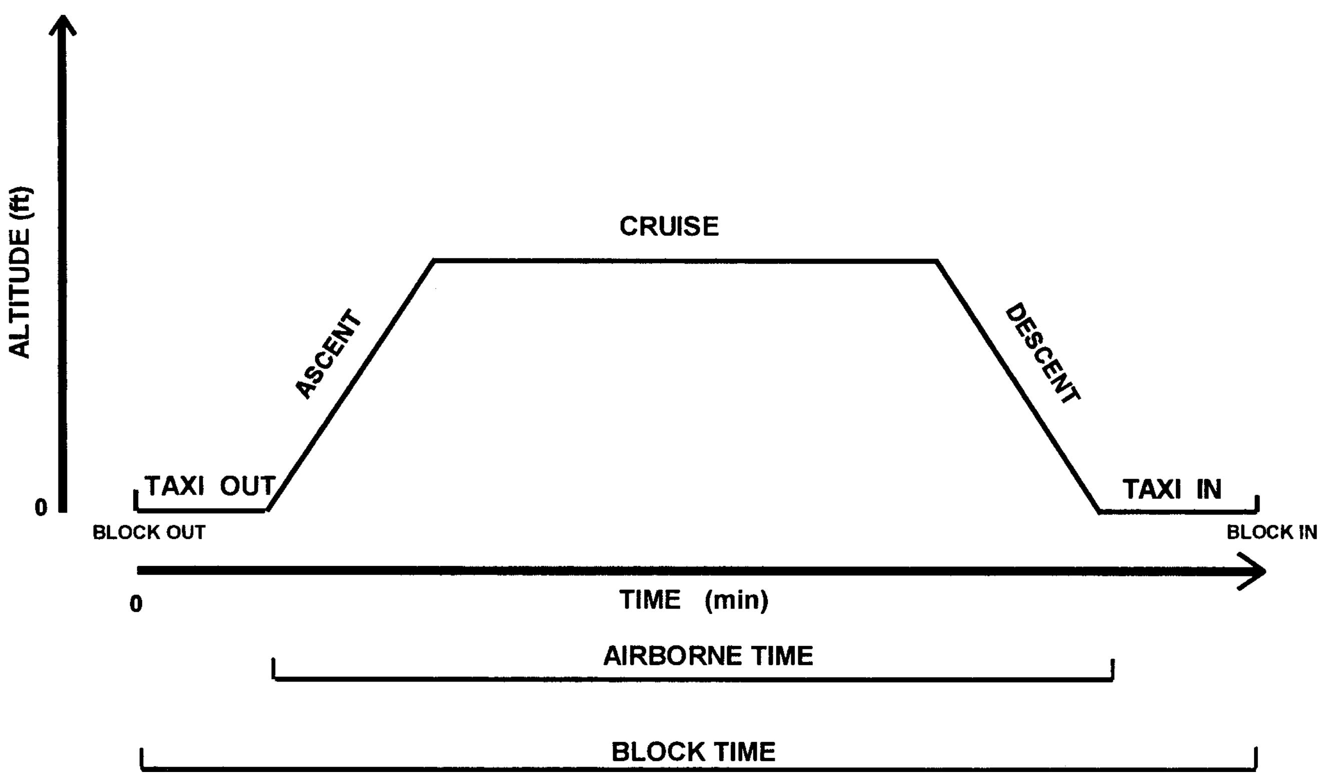

FIGURE 1. Phases of a flight segment.

Effective dose (ED, in this paper also called dose) is the sum of tissue equivalent doses weighted over all tissues using tissue weighting factors [International Commission on Radiological Protection, 1991]. Equivalent dose is the mean absorbed dose in a tissue or organ weighted by radiation weighting factors for each radiation type.

Data Sources

A variety of data sources were used to develop and improve the algorithm, and to examine separation of the effects of cosmic radiation and those of circadian rhythm disruption. The six datasets described in Table I were obtained from the airlines or were generated by NIOSH during study flights.

Calculation and Analysis of Dose Estimates

CARI version 6 was used to estimate the cosmic radiation ED for a given flight segment in microsieverts (μSv) [Friedberg et al., 1992, 1993, 2000]. Origin and destination city airport codes, flight date, and estimates of altitude, ascent time, cruise time at each altitude, and descent time are required as input to CARI. CARI incorporates radiation and tissue weighting factors recommended by International Commission on Radiological Protection [1991]. Solar activity cycle and geomagnetic field effects are accounted for by the program. PC-SAS software [SAS Institute, Inc, 1989] was used for all statistical procedures. With the exception of collinearity analysis, descriptive statistics were used in this work.

"Gold standard" refers to comparison data used to evaluate the algorithm's performance. Different datasets as described below and in Table I were used as gold standard data, depending on the analysis. "Bias" does not refer to epidemiologic bias, but rather the difference between algorithm and gold standard dose estimation results expressed as a percentage of the gold standard results.

Development and Testing of the Algorithm

Our aim was to produce an algorithm based on standard assumptions for flight altitude and time spent in each phase of flight and which, in conjunction with CARI, permits radiation dose estimation for study participants at several airline domiciles (cities). Data from the study companies and from flights flown for a concomitant exposure study provided initial estimates of the cruise altitudes and taxi, ascent and descent times for flights of different lengths of predominantly jet aircraft. The algorithm was then adjusted for better performance across all three study companies' data and all flight lengths by use of data sets #1–3 as described below.

Standardized flight length categories were necessary for the algorithm because flights of different lengths typically are flown at different altitudes, and have different times for each flight phase such as taxi-out, ascent, cruise, descent, and taxi-in. Flight length distributions from data set #1 were used to determine flight length strata (expressed as block time).

To select standard cruise altitudes, a database of flights flown for a concomitant cosmic radiation exposure assessment study provided the number and range of cruise altitudes for 37 flights (data set #2). Second, 14 pilots and flight operations managers provided information on typical cruise altitudes and the number of different altitudes by flight length based on their experience. Data sets #1 and 2 were also used to estimate standard times for each flight phase (see Fig. 1).

To test and improve the algorithm, we compared two dose estimates for each flight segment in data set #3, which contains detailed flight plans including cruise altitudes. One estimate was made using the algorithm and flight segment block times. A second estimate was made using the same flight segment's detailed flight plan data, without the algorithm. The median of the differences between these two estimates calculated for each individual flight was calculated as a percent of the flight plan dose estimate (gold standard) and expressed as bias, or

$$\frac{\begin{array}{c}\text{(Dose estimated from block time algorithm}\\ \text{– Dose estimated from flight plan)}\end{array}}{\text{Dose estimated from flight plan}} \times 100.$$

Effects of Changes in Cruise Altitude and Ascent/Descent Time on Dose Estimates

Unscheduled altitude changes of up to 4,000 ft from the original flight plan are not uncommon in flights greater than an hour in length, and are not recorded in flight histories. In order to explore the sensitivity of the dose estimates to deviations from the standard altitude assumptions and the ascent and descent time assumptions, these estimates were calculated for 10 specific flight segments, first for the standard set of conditions in the algorithm, and again to assess deviations from these standard conditions. For the evaluation of these deviations, bias is calculated as the difference between these two estimates expressed as a percent of the standard algorithm estimate. One flight length category (63–419 min) was chosen for this evaluation because it represents the majority of flight lengths studied. For altitude sensitivity, we compared effective dose estimates from a

TABLE I. Data Sources*

Dataset #	# segments[a]	Time frame	Description	Purpose	Variables available[b]			
					Block time[c]	Airborne time[d]	Altitudes	Time at altitudes
1	932	1995–97	All flights, 1 day/domicile/airline, Miami, Seattle, Detroit	1) Select flight, length strata 2) Evaluate taxi time assumptions 3) Evaluate altitude, ascent/descent time changes	x	x		
2	37	1996–98	NIOSH cosmic radiation measurement flights[e]	1) Select standard altitudes 2) Estimate times of flight components	x	x	x	x
3	6,785	1997	Detailed flight plans[f] for all flights; 2–5 days/domicile/airline, Miami, Seattle, Detroit	Test and improve algorithm	x	x	x	x
4	3,593	1995	3-month company flight histories of 44 flight attendants, Miami, Seattle	Estimate occupational radiation dose for NIOSH biomonitoring study flight attendants	x			
5	276	1995	3-month company recreational flight histories of 44 flight attendants, Miami, Seattle	Estimate recreational component of dose for NIOSH biomonitoring study flight attendants	x[g]			
6	1,180	1994	One-month company flight histories for 99 flight attendants, Miami, Seattle, Minneapolis–St. Paul	Evaluate cumulative radiation dose and time zones crossed	x			

*All datasets except for dataset #2 were obtained from the three airline companies participating in one or both of the NIOSH Flight Attendant reproductive studies ("study companies").
[a]A segment is a single flight between two cities without layovers or intermediate stops.
[b]All datasets contain origin city, destination city, and date of each flight segment.
[c]Block time is the time from when the blocks are removed from behind the aircraft wheels at the origin city gate until the blocks are placed behind the wheels at the destination city gate. Block time = airborne time plus taxi time.
[d]Airborne time is the time from when the aircraft leaves the ground at the origin city until it touches down at the destination city.
[e]Flights flown by the NIOSH exposure assessment team for a concomitant study [Waters et al., 2000].
[f]Flight plans are developed by the airline for each individual segment to provide the pilot with information about altitudes and time likely to be spent in each phase of flight.
[g]Estimated.

single cruise altitude to cruise altitudes 4,000 ft lower and higher. For sensitivity of ascent and descent times, we evaluated the effect of 5 min deviations from ascent and descent times on the effective dose for the same 10 flight segments.

Evaluation of Taxi Time Assumptions

Since the difference between airborne time and block time for a given segment equals taxi time, comparison of radiation doses for block and airborne times were used to assess whether the standard assumptions of taxi time were appropriate. Data set #1 was used with the algorithm to estimate dose from block and airborne times (gold standard) for 932 flight segments stratified by block time category. Bias between block and airborne times was calculated as above.

Dose Estimates for Biomonitoring Study Flight Attendants

The algorithm was used to calculate dose estimates for 44 flight attendants who participated in the NIOSH biomonitoring study (data set #4). Of the 3,593 recorded flight segments, 27 were not analyzed because the flight did not leave the origin city, and 45 were removed as outliers. We considered an outlier to be a flight segment whose block time was greater than the 95th percentile for study flights with the same origin and destination cities, and whose block time was longer by 30 min or more than the median block time for that flight segment. A flight was not considered to be an outlier, regardless of block time, if fewer than 10 study flights had the same origin and destination cities.

Radiation dose from unofficial (commuter and recreational) travel was estimated separately for each flight attendant from the estimated block times in data set #5. The records represent most but not all possible recreational air travel, since no record is kept of tickets purchased on other airlines. Only date, origin city, and destination city are available in company records. Block time for these segments was estimated using average segment times from data set #4 where available, or from information provided by the airlines.

Separation of Radiation and Circadian Rhythm Disruption Exposures

"Circadian rhythm disruption" refers to disruptions of biological rhythms in part caused by travel through multiple time zones. Many long East–West or West–East flights incur both an appreciable radiation dose and cross multiple time zones. To determine whether these two exposures were analytically separable for epidemiologic studies, we calculated variance inflation factors (VIFs) [Kleinbaum et al., 1998] for a regression model including cumulative time zones and cumulative estimated radiation dose as a measure of collinearity for each domicile separately and for the combined data. Data set #6 was used to calculate one month's cumulative time zones crossed and cumulative estimated radiation dose for 99 flight attendants at three domiciles. At the Seattle and Miami domiciles, North–South flights predominated. At the Minneapolis–St. Paul domicile, long haul East–West flights predominated.

RESULTS

Assumptions for a Typical Flight

Table II gives the standard assumptions used to estimate radiation dose for each flight segment from block time data. The algorithm and the variables available in work histories (flight date, origin and destination cities, and block time) are sufficient to estimate radiation dose with CARI.

For flight length categories, we evaluated airline-specific flight length distributions and found that each airline had a characteristic distribution of block times differing from the others. Based on these distributions, four flight length categories (<45, 45–62, 63–419, and ≥ 420 min block time) were established. The following cruise altitudes were selected as representative of flights in

TABLE II. Standard Assumptions Used in Algorithm to Estimate Radiation Dose From Block Time*

	Flight segment block time (min)			
	<45	45–62	63–419	≥ 420
One-way taxi time (min)	5	8	11	11
One-way ascent and descent time[a] (min)	3	10	20	20
Time at cruise altitude (min)[b]	Block time-16	Block time-36	Block time-62	Block time-62
Cruise altitude[a] (ft)	10,000	19,500	32,000	34,000

*Each flight segment assumes the following: one cruise altitude, equal ascent and descent times, and equal taxi-out and taxi-in times.
[a]Required as input variables to CARI in order to estimate radiation effective dose.
[b]Calculated as block time − ((2 × taxi time) + (2 × ascent/descent time)).

each flight length category: 10,000 ft for flights < 45 min long; 19,500 ft for flights 45–62 min long; 32,000 ft for flights 63–419 min long; and 34,000 ft for flights of 420 min or more. These altitudes were selected to represent the approximate midpoints of altitudes for flights in the category. Similarly, times for taxi-out, ascent, cruise, descent, and taxi-in were selected as representative of flights in each flight length category.

Figure 2 shows the relation between radiation estimates calculated from 6,785 detailed flight plans (Dataset 3) and those calculated for the same city pairs from the algorithm used with block times. The two estimates are generally close to each other and the plotted line of equivalence. Table III compares differences between these two methods of estimation. The three companies with domiciles at Miami, Seattle, and Detroit differed from each other in magnitude and direction of bias, and in development of the algorithm, minor adjustments of the assumptions were made to give the best overall approximation of dose calculated from the detailed flight plans. For the combined data, the radiation dose estimates using the algorithm underestimated the radiation dose using the actual flight plan (gold standard) by 3.6% or 0.13 μSv/flight segment. By company and block time category, median differences between flight plan and block time dose estimates per flight segment ranged from − 1.30 to + 0.25 μSv, with bias ranging from − 56.3 to + 27.6%.

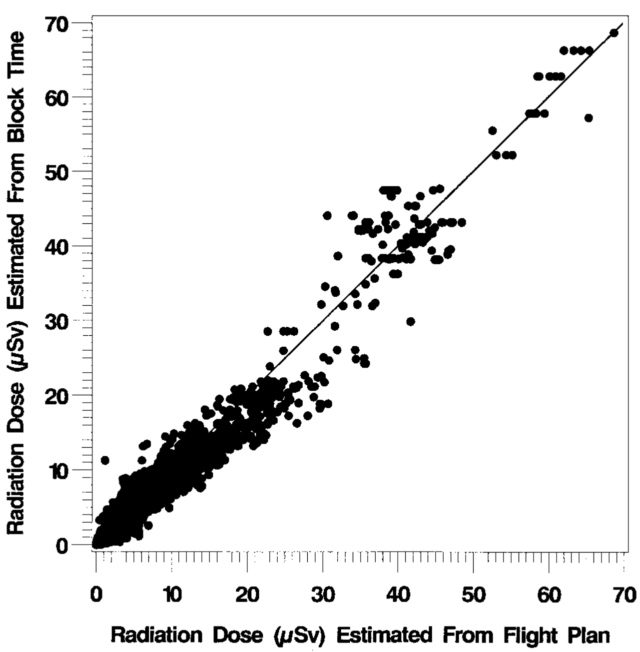

FIGURE 2. Estimated radiation dose from block times and planned airborne times for three airlines (N = 6,785).

TABLE III. Evaluation of Algorithm: Comparison of Estimated Median Radiation Dose (μSv) Per Flight Segment Calculated From Detailed Flight Plans and Algorithm Standard Assumptions Based Upon Actual Block Times for Flight Segments From Three Airline Companies (N = 6,785)

Block time	Company 1, Miami					Company 2, Seattle					Company 3, Detroit				
category (min)	N	Flight plan[a]	Block[a]	B−F[b]	% Bias[c]	N	Flight plan	Block	B-F	% Bias	N	Flight plan	Block	B−F	% Bias
< 45	—	—	—	—	—	93	0.13	0.08	−0.05	−42.5	48	0.11	0.09	−0.01	−9.1
45–62	21	0.29	0.39	0.08	27.6	296	0.98	0.43	−0.55	−56.3	242	0.54	0.40	−0.04	−8.3
63–419	1,627	6.57	6.36	−0.01	−0.2	1,852	5.56	5.17	−0.25	−4.7	2,366	4.07	4.45	0.06	1.4
≥ 420	113	23.00	20.20	−1.30	−5.8	—	—	—	—	—	126	39.40	42.30	0.25	0.5
Combined	1,762	6.75	6.49	−0.07	−1.1	2,241	4.88	4.51	−0.28	−9.0	2,782	3.85	4.18	0.02	0.7
Total, all companies	6,785	5.08	5.00	−0.13	−3.6										

[a]"Flight Plan" and "Block" are group median radiation dose (μSv) per flight segment calculated from detailed flight plans or block time using the algorithm, respectively.
[b]B−F = Median of (Dose estimated from block time using the algorithm − Dose estimated from flight plan), calculated for individual flight and block pairs.
[c]% Bias = Median of [((Dose estimated from block time using the algorithm − Dose estimated from flight plan) × 100)/Dose estimated from flight plan], calculated for individual flight and block pairs.

TABLE IV. Effect on Radiation Effective Dose Estimates (μSv) for 10 Flight Segments When Cruise Altitudes Vary From Algorithm Standard Assumptions

Block time (min)	Flight cities (origin–destination)	Altitude 32,000 ft (algorithm standard assumption)	Altitude 4,000 ft lower than standard		Altitude 4,000 ft higher than standard	
			Altitude 28,000 ft	% Bias[a]	Altitude 36,000 ft	% Bias
73	Los Angeles–San Francisco	1.2	0.85	− 30.9	1.7	+ 35.8
96	San Jose–Portland	2.9	2.0	− 31.7	4.0	+ 37.2
106	Sacramento–Seattle	3.8	2.6	− 32.1	5.2	+ 37.1
116	Seattle–Oakland	4.3	3.0	− 31.9	5.9	+ 37.0
126	Tegucigalpa–Miami	3.4	2.4	− 29.7	4.6	+ 33.8
155	Miami–New York	6.6	4.5	− 31.6	9.0	+ 36.7
166	Curacao–Miami	5.1	3.6	− 29.9	6.8	+ 33.7
208	San Juan, PR–New York	8.8	6.1	− 31.0	11.9	+ 35.5
369	Miami–La Paz	11.9	8.5	− 28.7	15.7	+ 31.9
394	Miami–Santa Cruz, Bolivia	12.7	9.0	− 28.8	16.8	+ 32.3

Numbers were rounded after calculations were performed.
[a]% Bias = [((Dose estimated from block time using specified altitude − Dose estimated from block time using algorithm standard assumptions) × 100)/Dose estimated from block time using algorithm standard assumptions].

Effects of Changes in Altitude and Ascent/Descent Time on Dose Estimates

Table IV shows radiation ED estimates for flights between ten cities using the assumptions given in Table II. Altitude deviations of 4,000 ft up or down will result in EDs which range from 32.1% lower to 37.2% higher than those derived from the standard flight altitude assumptions in Table II.

Table V displays the changes in ED estimates when ascent and descent times differ from the standard assumptions indicated in Table II for flights with cruise altitudes of 32,000 ft. The effect of underestimating or overestimating the ascent and descent times appears to be relatively small and becomes smaller as block time lengthens. For flights at 32,000 ft, 5 min deviations in assumed ascent and descent times contribute less than ± 10% change in the ED for flights longer than 2 hr and less than ± 2.5% for flights longer than 6 hr. Although these results will differ slightly depending on the latitudes of the flights examined, the overall contribution to error in the ED estimates by violations of the assumed ascent and descent times is very small. Cruise altitude deviations from standard assumptions appear to have a much greater effect on the ED than deviations in ascent and descent times.

Evaluation of Taxi Time Estimates

Because block time is made up of airborne time plus taxi time, the distribution of radiation doses estimated from block and airborne times by airline and block time category from 932 flights was used to evaluate taxi time estimates (Table VI). Taxi times were chosen to give the best approximation of dose calculated from airborne time alone over all three companies. The dose estimates from block time calculations differed from the airborne time estimates (gold standard) by − 0.33 to + 0.70 μSv. There was generally less than 10% difference in bias between estimates of dose from block vs. airborne time, with a range of − 6.1 to + 23.7%.

Dose Estimates for Biomonitoring Study of Flight Attendants

Table VII provides the ED estimates for 44 flight attendants using the block time algorithm. Miami and Seattle flight attendants received similar total yearly doses of 1.7 and 1.5 mSv, respectively, but the Miami flight attendants flew fewer flight segments of higher dose, and the Seattle flight attendants flew more lower-dose segments. Recreational travel accounted for 2–6% of the annual dose, and these flights were generally of lower dose than work-related flight segments.

Separation of Radiation and Circadian Rhythm Disruption Exposures

Figure 3 shows the joint distribution of monthly cumulative radiation dose and cumulative time zones crossed for 99 flight attendants from three domiciles. There are no formal criteria for the level of VIF which would indicate that these two exposures are too similar to separate

TABLE V. Effect on Radiation Effective Dose Estimates (μSv) for 10 Flight Segments When Ascent and Descent Times Vary From Algorithm Standard Assumptions

Block time (min)	Flight cities (origin–destination)	20 min ascent and descent times (algorithm standard assumption)	Ascent and descent times 5 min shorter than standard: 15 min ascent and descent times	Ascent and descent times 5 min shorter than standard: % Bias[a]	Ascent and descent times 5 min longer than standard: 25 min ascent and descent times	Ascent and descent times 5 min longer than standard: % Bias[a]
73	Los Angeles–San Francisco	1.2	1.6	+33.3	0.8	−33.3
96	San Jose–Portland	2.9	3.4	+16.4	2.5	−16.4
106	Sacramento–Seattle	3.8	4.3	+13.5	3.3	−13.5
116	Seattle–Oakland	4.3	4.8	+11.6	3.8	−11.3
126	Tegucigalpa–Miami	3.4	3.8	+9.3	3.1	−9.3
155	Miami–New York	6.6	7.0	+7.2	6.1	−7.0
166	Curacao–Miami	5.1	5.4	+6.3	4.8	−6.3
208	San Juan, PR–New York	8.8	9.2	+4.7	8.4	−4.6
369	Miami–La Paz	11.9	12.1	+1.7	11.7	−1.7
394	Miami–Santa Cruz, Bolivia	12.7	13.0	+2.4	12.5	−1.6

Numbers were rounded after calculations were performed.
[a]% Bias = [((Dose estimated from block time using specified ascent/descent times − Dose estimated from block time using algorithm standard assumptions) × 100)/Dose estimated from block time using algorithm standard assumptions].

analytically, but one rule of thumb is to consider a VIF of 10 or more as suggestive of collinearity [Kleinbaum et al., 1998]. Seattle- and Miami-based flight attendants incurred relatively more radiation dose and fewer time zone crossings than Minneapolis–St. Paul flight attendants. Minneapolis–St. Paul flight attendants' travel is more equally distributed between the two exposures, which were judged to be collinear (VIF = 34.4). By contrast, Miami and Seattle exposures were not collinear (VIF = 6.9 for Miami, 2.1 for Seattle). Thus, selection of a flight attendant study population whose flights are often North–South can provide the necessary analytic separation between these often colli near exposures, even if East–West flights are represented. The VIF for the combined dataset with all three domiciles was 3.7.

DISCUSSION

To facilitate exposure assessment for epidemiologic studies which use flight attendant work history data, and in the absence of data for altitudes and times of each flight phase, an algorithm with a standard set of assumptions is necessary to construct a flight attendant's cumulative cosmic radiation dose. The algorithm allows for conversion of block time data to radiation dose estimates using CARI. The radiation estimates from our block-time-only data using the algorithm were reasonably close to "gold standard" flight plan data with detailed flight information from three major airlines with very different routes.

Estimation of potential collinearity between radiation dose and time zones crossed, measures of two important aircrew exposures, suggests that for North American flight attendants, inclusion of a study population which flies predominantly North–South segments can provide the critical analytic separation necessary between these exposures, even if East–West flights are represented.

We applied the algorithm dose estimation methods to the work histories of 44 flight attendants in a biomonitoring study, and estimated average annual occupational doses of 1.5–1.7 mSv at the two study domiciles. Although flight attendants have reduced fare privileges for personal travel, recreational travel estimates generally contributed only 2–6% to flight attendant cumulative dose. These average annual occupational doses are well below current occupational limits recommended by the International Commission on Radiological Protection (ICRP) and the FAA of 20 mSv/year [ICRP, 1991; Friedberg et al., 1992] but slightly higher than the US average annual radiation dose of occupationally exposed adults of 1.1 mSv [U.S. Environmental Protection Agency, 1984]. However, there is great annual dose variability between workers and some flight attendants in our study incurred estimated annual doses as high as 3.5 mSv. Flight attendants who fly during pregnancy could exceed the ICRP recommended limit of 1 mSv to the conceptus during pregnancy [ICRP, 1997].

There are limitations to the use of the algorithm for estimation of radiation dose. First, the algorithm was developed and refined based on flight segment data from three companies. We are not certain that these data are representative of all North American flight patterns. The diversity in these data helped to create standard assumptions which work reasonably well for all three companies, but are not perfect for any one company. Second, the algorithm

TABLE VI. Evaluation of Taxi Time Estimates: Comparison of Estimated Median Radiation Dose (μSv) Per Flight Segment Calculated Using Algorithm Standard Assumptions From Actual Airborne and Block Times for One Day's Flights From Three Airlines (N = 932)

Block time category (min)	Company 1, Miami					Company 2, Seattle					Company 3, Detroit				
	N	Airborne[a]	Block[a]	B−A[b]	% Bias[c]	N	Airborne	Block	B−A	% Bias	N	Airborne	Block	B−A	% Bias
< 45	0	—	—	—	—	17	0.08	0.09	0.0	0.0	28	0.07	0.09	0.02	23.7
45–62	3	0.32	0.33	0.02	6.5	39	0.42	0.41	−0.03	−2.1	52	0.40	0.43	0.03	9.2
63–419	165	6.53	7.18	0.28	3.5	333	5.16	4.93	−0.33	−6.1	276	3.54	3.59	0.0	0.0
≥ 420	11	19.40	19.70	0.20	1.1	0	—	—	—	—	8	39.05	39.60	0.70	1.4

[a] "Airborne" and "Block" are group median radiation dose (μSv) per flight segment calculated using the algorithm from actual airborne and block times, respectively.

[b] B−A = Median of block time − airborne time radiation dose, calculated for individual airborne and block time pairs.

[c] % Bias = Median of [((Dose estimated from block time using the algorithm − Dose estimated from airborne time) × 100)/Dose estimated from airborne time], calculated for individual airborne and block time pairs.

is based on a typical flight pattern and standard time and altitude estimates for each component of the flight. Unscheduled changes in altitude sometimes occur due to unusual air traffic or meteorological conditions, aircraft type, and passenger load. These changes, which would result in different estimates of cosmic radiation dose, are not recorded in the work histories or flight plans. Third, the algorithm's assumed time variables are also subject to deviations. For example, taxi times may vary from the standard assumptions due to size of airport, size of aircraft, or unusual traffic patterns; ascent time may vary depending on aircraft and load; and cruise time may vary due to meteorological conditions or conflicting air traffic.

We anticipate that for most of these factors, effects on total dose estimates will be nondifferential for the time intervals assessed for crossectional or retrospective reproductive studies (e.g., 1 month–4 years). For longer term studies (e.g., cancer outcomes), these factors may differentially affect exposure estimates due to historical changes in flight patterns and aircraft. With this algorithm, unrecorded instances of prolonged taxi time or very low-altitude circling time prior to landing could result in an overestimation of radiation dose for these atypical flight segments. Exclusion of approximately 1.3% of our study flight segments as extreme block time outliers was a useful means to reduce dose overestimation from these atypical flights.

We also evaluated the effect of altitude and ascent/descent time deviations from the standard assumptions on the estimated radiation dose. Substantial differences in dose with small altitude changes indicate the importance of selecting the most representative value for the standard assumption for cruise altitude when estimating dose from work histories.

The algorithm has relatively low bias for flights greater than 62 min in length. Shorter flights incur greater bias because the algorithm could not be adjusted equally well for all flights. However, the shorter flights contribute far less to cumulative radiation dose than longer flights, which are generally at higher altitudes. The algorithm is an especially useful tool for epidemiologic studies where work histories are available, but where it is not feasible to access or utilize company or domicile-specific flight plans. Where it is feasible to collect and analyze flight plans, development of domicile and/or company-specific algorithms may diminish the bias observed in the study; however, it is not clear to what extent the bias will be reduced, and the data processing costs are considerable.

Finally, the dose estimation method depends upon the accuracy of CARI. NIOSH is evaluating this question in a series of 37 flights by comparing CARI estimates to direct readings from a tissue equivalent proportional counter.

Of the many exposures in the aircraft cabin environment with potential reproductive effects, we consider

TABLE VII. Radiation Effective Dose Estimates For 44 Flight Attendants

		Seattle (N = 24)		Miami (N = 20)	
		Mean ± SD	Range	Mean ± SD	Range
Estimated number of flight segments/year	Work-related[a]	316 ± 94	87–456	149 ± 100	9–375
	Recreational[b]	8 ± 19	0–93	32 ± 32	0–114
	Total	324 ± 95	87–459	180 ± 100	39–393
Estimated number of block hr/year	Work-related	632 ± 183	191–879	605 ± 304	78–1,070
	Recreational	14 ± 26	0–122	59 ± 53	0–203
	Total	646 ± 185	192–909	664 ± 311	181–1,272
Dose (μSv) /flight segment ± SD	Work-related	4.8 ± 0.6	3.9–5.8	12.5 ± 8.2	4.7–36.0
	Recreational	4.8 ± 3.8	0.3–11.9	4.6 ± 2.5	0.5–8.6
Estimated yearly dose (mSv) ± SD	Work-related	1.5 ± 0.4	0.5–2.3	1.5 ± 0.9	0.2–3.3
	Recreational	0.03 ± 0.05	0–0.2	0.1 ±0.1	0–0.4
	Total	1.5 ± 0.4	05–2.3	1.7 ± 1.0	0.4–3.5

[a]Data derived from detailed company work (flight) histories.
[b]Data derived from company records of employee recreational travel.

cosmic radiation and circadian rhythm disruption the two exposures of major importance. Regarding the use of cumulative time zones as a surrogate for circadian rhythm disruption, research currently underway at NIOSH suggests that this surrogate can be linked to biologically plausible biomarkers of circadian rhythm. Time zones can be calculated from flight attendant work histories and serve as a readily available single marker for this complex exposure.

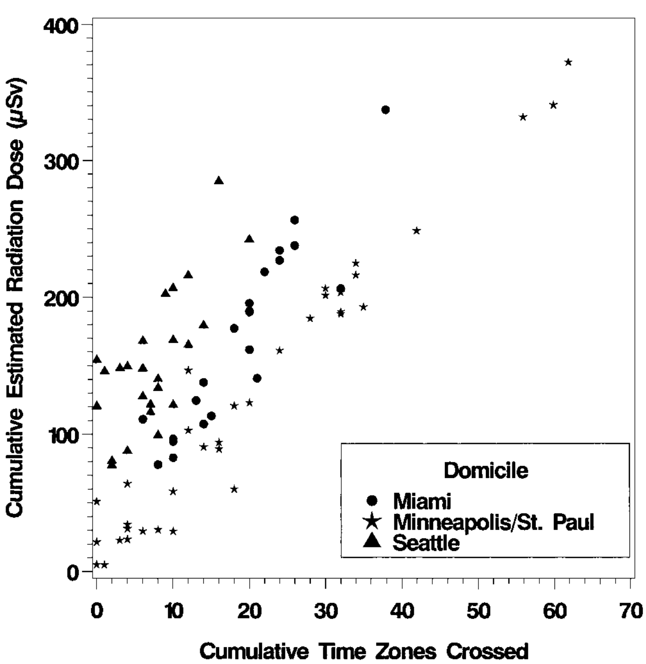

FIGURE 3. Cumulative radiation dose and time zone changes in 1 month for 99 flight attendants from Miami, Seattle, and Minneapolis–St. Paul.

The algorithm which we have developed will be of use in studies with relatively short study periods (5 years or less), for which flight histories are generally available. Despite the limitations of this simplified algorithm, these estimates are likely to provide high quality radiation exposure assessment for flight personnel in future epidemiologic studies.

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REFERENCES

Air Transport Association. 1998. Annual Report. Washington, DC: Air Transport Association.

Bottollier-Depois JF, Chau Q, Bouisset P, Kerlau G, Plawinski L, Lebaron-Jacobs L. 2000. Assessing exposure to cosmic radiation during long-haul flights. Radiat Res 153:526–532.

Friedberg W, Snyder L, Faulkner DN, Darden EB Jr, O'Brien K. 1992. Radiation exposure of air carrier crewmembers II, Department of Transportation Report No. DOT/FAA/AM-92/2. Oklahoma City, Oklahoma: U.S. Federal Aviation Administration, Office of Aviation Medicine.

Friedberg W, Duke FE, Snyder L, Faulkner DN, O'Brien K, Darden EB Jr., Parker DE. 1993. The cosmic radiation environment at air carrier flight altitudes and possible associated health risks. Radiat Prot Dosim 48:21–25.

Friedberg W, Duke FE, Snyder L, O'Brien K, Parker DE, Shea MA, Smart DF. 2000. Computer program CARI-6. Oklahoma City, Oklahoma: U.S. Federal Aviation Administration, Civil Aeromedical Institute.

Harma M, Laitinen J, Partinen M, Suvanto S. 1994. The effect of four-day round trip flights over 10 time zones on the circadian variation of salivary melatonin and cortisol in airline flight attendants. Ergonomics 37:1479–1489.

International Commission on Radiological Protection. 1991. 1990 Recommendations of the ICRP, ICRP Publication 60, Annals of the ICRP 21. Elmsford, New York: Pergamon Press.

International Commission on Radiological Protection. 1997. General Principles for the Radiation Protection of Workers, ICRP Publication 75. Elmsford, New York: Pergamon Press.

Kleinbaum DG, Kupper LL, Muller KE, Nizam A. 1998. Applied regression analysis and other multivariable methods. 3rd ed. Pacific Grove, CA: Duxbury Press. 798p.

O'Brien K, Friedberg W. 1994. Atmospheric cosmic rays at aircraft altitudes. Envir Intnl 20:645–663.

SAS Institute, Inc. 1989. SAS/STAT User's Guide 4th ed., Version 6, Volumes 1 and 2. Cary, NC: SAS Institute Inc. 1686p.

Tveten U, Haldorsen T, Rejtan J. 2000. Cosmic radiation and airline pilots: Exposure pattern as a function of aircraft type. Radiat Protect Dosim 87:157–165.

U.S. Environmental Protection Agency. 1984. Occupational exposure to ionizing radiation in the United States, U.S. EPA 520/1-84-005. Washington: U.S. Environmental Protection Agency.

Verhagen F, Poffijn A. 2000. Air crew exposure on long-haul flights of the Belgian airlines. Radiat Prot Dosim 88:143–148.

Waters MW, Bloom TF, Grajewski B. 2000. The NIOSH/FAA working women's health study: Evaluation of the cosmic-radiation exposures of flight attendants. Health Phys 79:553–559.

Wilson JW, Nealy JE, Cucinotta FA, Shinn JL, Hajnal F, Reginotto M, Goldhagen P. 1995. Radiation safety aspects of commercial high-speed flight transportation. NASA TP-3524. Hampton, Virginia: NASA Langley Research Center.