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Comparing different methods of estimating cosmic radiation exposure of airline personnel

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Abstract In Europe, several studies are currently underway to investigate the cancer risk of pilots and cabin crew exposed to low-level ionizing radiation of cosmic origin. Although no individualized exposure measurements of airline personnel are available, exposure assessment based on job history data is feasible. However, there is a marked variability in the level of detail of these data between studies in different countries and between subcohorts in national studies raising the issue of comparability of exposure estimation. In this paper we investigate the comparability of several methods of exposure assessment in a large German cohort of pilots and cabin crew. We found that the correlation between the estimates obtained by the four approaches analysed, is relatively high, ranging from 0.85 to 0.97. The precision attainable in the exposure assessment is higher than in many other epidemiological studies but can be refined further with simulation studies and comparison with ongoing and future on-board measurement programmes.

Introduction

Possible health effects of cosmic radiation have been causing concern among aircraft personnel (and frequent flyers) for some time, with radiation-induced cancer and risks to fetal development being the major issues.

Attention and awareness of cosmic radiation became focused in 1991 when the International Commission on Radiation Protection (ICRP) published the recommendation that natural sources of radiation should be classified as occupational exposures for aircrew [1]. In Europe, the Council Directive 96/29 EURATOM [2] lays down basic standards of radiation protection that now have to be implemented by the airlines. Therefore, exposure estimates are needed.

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Although data of cancer risk after exposure to low-dose radiation from radiobiological models and other epidemiological studies are available, little is known about the specific risk after exposure to cosmic radiation, mainly in the particular circumstances that are experienced by aircrew.

In contrast to other groups of occupationally exposed persons, such as nuclear power workers, individual radiation measurements for aircrew cannot easily be obtained due to practical obstacles in dosimetry. Cosmic radiation consists of a large neutron component (about 50% at usual flight altitudes) that requires special dosimetric approaches. These have currently only been implemented in research programmes involving the selection and calibration of adequate measurement apparatus, numerous measurement flights on typical routes and additional computations to adjust for unmeasured quantities [3, 4, 5]. Some reports from national boards give estimates of the possible exposures [6, 7].

Little is known about the health effects as such and in particular about their relationship to levels of radiation received. Epidemiological studies among pilots and cabin crew published up to 1998 have recently been reviewed in this journal [8]. So far, no consistent picture has emerged on site-specific cancer mortality or incidence among these occupational groups, except for melanoma incidence and female breast cancer incidence [9, 10]. Recently, four European cohort studies have confirmed the increases in melanoma incidence [11, 12, 13] and mortality [14]; the study among Danish pilots also revealed increased rates of acute myeloid leukaemia which was not observed in a recent North American PMR (proportional mortality rate) study [15].

In terms of exposure assessment, only two studies among civil aircrew have attempted to obtain individual radiation dose estimates [13] based on the method described in [16]. In two studies, surrogates are used, such as haul type (long or short haul aircraft) [14] or flight hours [11].

In a number of ongoing European epidemiological studies [17], including one performed by the German authors, more detailed data will be collected. However, not all of the studies which are supposed to be analysed jointly can provide the same data. Therefore, in this study we have investigated how different approaches of estimating individual exposure can be compared, using data from our large cohort mortality study among German flight personnel.

Materials and methods

We have investigated different methods of exposure assessment in the framework of an epidemiological study, motivated by the fact that very basic data are available for the whole cohort, while more detailed information are obtainable only for subsets of pilots and/or cabin crew.

Cohort data

The cohort consists of 5195 pilots and 19,794 cabin crew employed by 1 of 2 German airlines [Lufthansa German Airlines and Lufttransportunion (LTU)] for a minimum of 6 months in the period 1960–1997. For all cohort members, the duration of employment is documented (n=24,989).

For a large number of pilots (n~4500), job history data (annual flight hours per aircraft type) are known since beginning of employment (these data are not available for cabin crew and are lacking for ~700 retired pilots). For this analysis, we restricted the analysis to the job history data of 509 retired pilots, because these are the first complete, checked and validated data available at the current state of the study.

In addition, electronic records of flight data are available for 3983 (non-retired) pilots, containing the most detailed information on performed flights between, and including, July 1997 – June 1998. Airlines record these data and often base part of the pilots' salaries on flight hours. In the German study computerized records are only available since 1992. This database records the essential parameters of each single flight performed by each pilot, including origin, destination, total duration and taxi times on ground. We have chosen to refer to this data set as "logbook", and to the analyses using this data set as using the "logbook method", because of the close analogy to the logbooks which pilots used to write on a personal basis in earlier times in aviation history. This is considered to be the best basis for individual radiation exposure estimation. Since the MD11 aircraft was taken into service during our observation period, MD11 pilots did not accumulate many flight hours and were excluded from analysis to prevent bias, thus reducing the number of pilots by 11 to 3972.

Finally, company flight schedules dating back to 1960 have been used.

Dose estimation methods

We used four approaches to obtain individual dose estimates, two of which require the use of special computer software (CARI-5E, described below):

1. The "logbook method" evaluating logbook data with CARI (considered to be our "gold standard")
2. The "JEM approach" combining job history data with a job-exposure matrix (JEM) computed from flight schedules with CARI
3. "Flight hours surrogate" using individual cumulative flight hours, as a surrogate for the radiation dose
4. Using total duration of employment as a surrogate.

Table 1 Exposure quantities that can be computed based on the two sources of exposure information

Method	Job histories of 509 retired pilots	Logbooks of 3972 active pilots for 1 year
Duration of employment	Yes	No
Flight hours surrogate	Yes	Yes
JEM dose estimate	Yes	Yes
Logbook based dose estimate	No	Yes

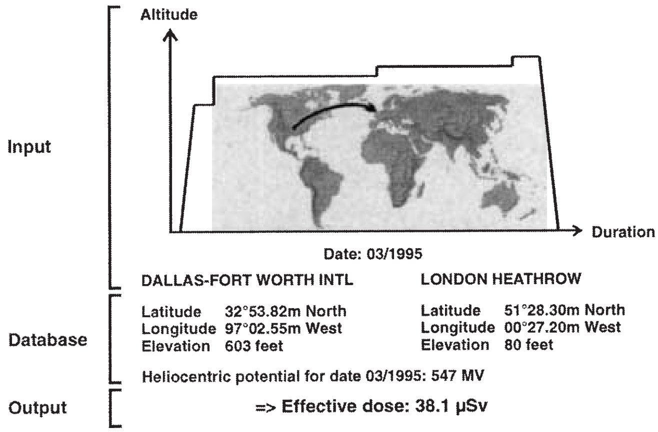

Fig. 1 Input and output of CARI-5E software

Table 1 summarizes which exposure quantities can by computed based on the two sources of exposure information.

Software

In order to estimate the radiation dose received by a person aboard a single flight, we used a computer software developed by physicists. This software is based on theoretical models of particle flux and interactions in the atmosphere, on the results of measurement flights and on biological knowledge about radiation effects in body tissue [18]. The CARI-5E software computes an "effective dose equivalent" for the human body (in μSv). Figure 1 illustrates the data CARI requires as input (airport of departure and arrival, calendar date, duration and altitude profile of individual flights) and what additional data CARI stores in an internal database to compute the output. In contrast to other computer codes, CARI is intended for non-expert users and sacrifices some computational precision (claimed to be about 4%) for ease of use. The simplifications include the assumption that the flight route follows a great circle on the Earth's surface and the interpolation of radiation dose rates from values pre-calculated for a set of regularly spaced geographical coordinates. On the other hand, the program menu allows the user to enter airports by standard "baggage tag" IATA or ICAO codes instead of geographical coordinates, to enter flight data easily and to manage files with sets of flights. The latest version of CARI is available at http://www.cami.jccbi.gov/AAM-600/610/600Radio.html.

Logbook method

CARI can be directly applied to personal logbook data, since these contain most of the information required. The flight altitude profile is the only information that has to be supplied from other sources. We consulted an expert panel (a group of experienced pilots) to determine average flight altitude profiles for all relevant aircraft types and different flight duration categories. This allowed individual annual radiation doses and flight hours to be computed from logbooks for 3972 pilots for the period of 1 year. As such data are only available in our cohort since 1992, retrospective calculations covering the whole cohort period cannot be performed.

Job-exposure matrix (JEM) approach

This approach, based on estimating average radiation dose rates per aircraft type and year, was first applied in the Norwegian study [19]. Airline flight schedules (from 1960 up to now) list all destinations serviced by the airline in a given time period. This allows doses for each flight of a flight schedule to be computed in a similar fashion as above, resulting in mean dose rates per aircraft type and time period (for one individual), expressed in μSv/h. Thus, dose rates reflect both the in-flight performance characteristics of each aircraft type (e.g. altitude etc.) and the set of destinations flown to. This information is summarized as a job-exposure matrix (JEM), a table of dose rates by aircraft type and year. Combining these data with individual job histories in terms of annual flight hours and aircraft type information, individual doses can be calculated on an annual or cumulative basis, prospectively as well as retrospectively.

Note that this approach assumes an approximately homogeneous distribution of flights for every pilot on a given aircraft type (now referred to as "route homogeneity assumption"), i.e. every pilot has flown a similar number of times to a similar set of destinations. According to the airline companies, this assumption is true throughout the study period.

Flight hours surrogate

A straightforward method for dose estimation is to use only individual flight hours from the job histories without the JEM information. Although considered less exact than the former approach, since differences between aircraft types are not taken into account, this is considered to be a better surrogate for radiation dose than total duration of employment. This approach is chiefly motivated by the possible unavailability of cohort-specific JEM data for other European studies that are to be combined in a pooled analysis.

Duration of employment

It is reasonable to assume that information on duration of employment will be available for all cohort members of every cohort in the pooled analysis. Duration of employment is, however, the crudest surrogate measure for radiation exposure.

Statistical analysis

The statistical analysis was performed using the software SPSS 8.0 (SPSS, Chicago, Ill.). Spearman correlation coefficients were computed to investigate the association of the different dose estimation methods.

Results

The available data allows two types of comparisons to be made. The first addresses the correlation between dose estimates based on logbook data and dose estimates based on the JEM approach. The second comparison addresses the correlation between dose estimates based on data from actual job histories with dose estimates based on the JEM approach.

Tables 2, 3 and 4 show the distribution of the analysed variables (JEM dose estimates, flight hours, duration of employment). Variation of flight hours (Table 2) is to a large degree independent of the aircraft type flown. The estimated radiation dose rates aboard long haul aircraft types, i.e. aircraft types with an average flight duration of over 4 h, are clearly elevated in comparison to other aircraft types (Table 3). The estimated annual radiation dose of long haul aircraft pilots is elevated as well, even though these pilots also spend some time aboard short haul aircraft. Annual flight hours in the job history data (Table 4) are slightly lower (481 h/year) than those from logbook data (Table 2), reflecting the increase of annual flight hours after 1960.

In a first type of comparison, we investigated the correlation between:

1. individual doses estimated by the logbook method
2. those estimated by the JEM approach
3. the flight hours surrogate.

Table 2 Distribution of yearly flight hours from logbook data of 3972 pilots in the period July 1997–June 1998 (*SD* standard deviation)

Aircraft license	Number of pilots	Median	Mean	SD
A300	276	507	471	117
A310	38	474	439	131
A320	894	576	517	172
A340	326	651	605	148
B737	957	558	525	120
B747	1043	603	546	183
B757/B767	345	770	726	165
DC10	93	505	458	157

Table 3 Distribution of yearly dose estimate (mSv) and dose rate (μSv/h) from logbook data of 3972 pilots in the period July 1997–June 1998 (*SD* standard deviation)

Aircraft license or aircraft type	Number of pilots	Mean flight duration (h)	Dose			Dose rate Mean
			Median	Mean	SD	
A300	276	2:16	1.07	1.03	0.31	1.52
A310	38	1:46	1.00	0.94	0.38	1.21
A320	894	1:28	1.03	0.97	0.36	1.39
A340	326	8:56	2.36	2.23	0.57	3.70
B737	957	1:26	1.03	1.00	0.28	1.58
B747	1043	7:41	2.12	1.92	0.68	3.21
B757/B767	345	3:12/5:41	2.03	1.92	0.45	2.37
DC10	93	2:53	1.17	1.08	0.42	2.21

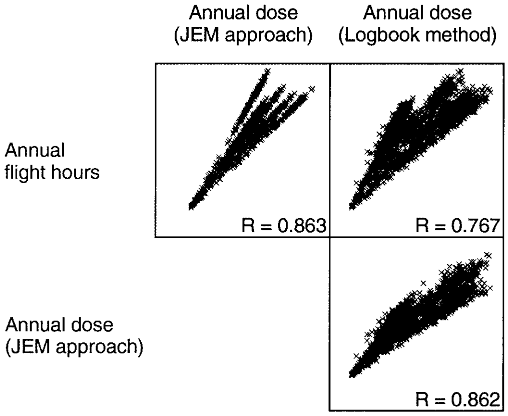

Fig. 2 Correlation of annual flight hours and radiation dose estimates by the JEM approach with radiation dose estimates based on logbook data of 3297 pilots in the period July 1997–Juni 1998

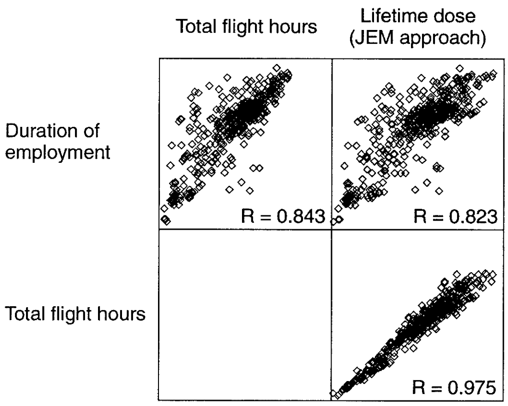

Fig. 3 Correlation of lifetime radiation dose estimates based on job history data of 509 retired pilots (for all aircraft types combined)

This was done using the data of the 3972 pilots included in the logbook data base. This comparison, however, covers only the period of 1 year, the year which is contained in this data base.

The results in Table 5 show that the dose estimates obtained by the JEM approach compare well with the ones obtained by the logbook method (*R*=0.849 to *R*=0.943), all of the regression coefficients being significant to the 1% level. As illustrated in Fig. 2, the estimation error by the JEM approach is proportional to the true dose, an expected phenomenon in this setting.

In the second type of comparison, we used the first 509 available job histories that were complete and valid to compare the correlation of the JEM approach with the flight hours surrogate and the total duration of employment. This second comparison lacks the gold standard logbook data but on the other hand covers the whole career of these individuals, not only 1 year.

A pilot's career typically involves several changes of licensed aircraft type (each of which differs in terms of dose rate), so that a lower correlation is to be expected between lifetime flight hours and lifetime dose computed by the JEM approach. We were surprised to find that it is still excellent (*R*=0.975, see Fig. 3 and Table 6). Even the correlation between duration of employment and lifetime JEM dose estimates is rather high (*R*=0.823).

Table 4 Variable distribution from 509 complete job histories of retired pilots, encompassing the whole career, (SD standard deviation

Method	Median	Mean	SD
Duration of employment (years)	29.1	26.6	8.6
Flight hours	14229	12999	5207
Flight hours per year	495.4	480.6	131.0
JEM dose estimate (mSv)	37.9	35.4	14.2

Table 5 Correlation between JEM and logbook dose estimated by aircraft license

Aircraft license	Number of pilots	Spearman correlation coefficient
A300	276	0.849
A310	38	0.873
A320	894	0.895
A340	326	0.916
B737	957	0.869
B747	1043	0.921
B757/B767	345	0.894
DC10	93	0.943
Overall	3972	0.859

Discussion

For exposure assessment of airline personnel exposed to ionizing cosmic radiation, a variety of methods exist, ranging from flight specific measurements to computations based on logbook data, or computations based on the JEM approach, or computations based solely on employment period.

Historical epidemiological studies so far have not been able to incorporate such detailed information and have usually relied on rather crude measurements. Using a data set that allows a comparison of several methods, we could show that there is good correlation between these different approaches. The main factor for variability in the dose accumulated by different individuals is individual variations in annual flight hours. The influence of aircraft type on the dose accumulated during a whole career is much less, since a pilot flies several different aircraft types during the career. Nevertheless, one should expect to observe lower lifetime doses for pilots having most of their career in the earlier part of the time period considered in this project, since there was more extensive use of propeller aircraft (yielding much lower dose rates).

Other unmeasured influential factors to the radiation dose received, such as departure from the route homogeneity assumption, or differences between the true flight altitude profile and the one specified by the expert panel, do not play as important a role as flight hours according to our investigation. Furthermore, very little is known about variations of the individual exposure to ionizing

Table 6 Correlation (Pearson) of dose estimates from job history data

Method	Flight hours (total career)	JEM dose (mSv)
Duration of employment (years)	0.843	0.823
Flight hours (total career)	–	0.975

radiation from occasional solar flares. However, these factors will be investigated further in a sensitivity analysis, refining previous results [20].

In spite of these uncertainties, we can now estimate doses for cabin crew fairly well by using the only accessible information in our study, duration of employment. The overall correlation of a pilot's duration of employment with the dose estimate computed from logbooks covering the whole career (if such information was available), is probably better than the product of R=0.823 from Table 6 and R=0.849 from Table 5 (i.e. 0.699).

Simulation studies on the effect of these errors in estimation of risk estimates, using an adequate error model, are currently underway and will provide a means of correcting both point estimates (if necessary) and confidence interval limits.

Although similar data as those described above are available for most of the major European airlines, not every European study group has assembled a JEM. A first comparison of the Norwegian [19], Finnish and German JEMs showed that differences do exist and are not always negligible, so the German JEM may not be adequate for other airlines. This is mainly due to differences between airline flight schedules and flight corridors used by the aircraft in Europe.

In summary, our analysis shows that various degrees of refinement of exposure estimation lead to comparable results. For epidemiological purposes, such as the ongoing cohort study, the estimation errors inherent to the different approaches could be quantified and were furthermore found to be of comparatively small magnitude. This is a clear advantage when it is desired to compare different epidemiological studies.

Onboard measurement programmes for further validation and comparisons with computational results, in continuation of recent measurement programmes [21], could be helpful in further refining the current knowledge about the radiation exposure of flight personnel.

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