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ENVIRONMENTAL CARCINOGENESIS

# Cosmic Radiation Exposure and Cancer Risk Among Flight Crew

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## ABSTRACT

Nearly 20 epidemiologic or related studies of cancer incidence and mortality have been published during or since 2000, with several reporting increased risks of female breast cancer among flight attendants and melanoma among both pilots and cabin crew. Occasionally, excesses of other cancers have been observed, but not consistently. Although the real causes of these excess cancer risks are not known, there is concern that they may be related to occupational exposures to ionizing radiation of cosmic origin. It is possible that confounding risk factors may partially or totally explain the observed relationships, but several investigations are beginning to address lack of past adjustment for reproductive factors and sun exposure with improved study designs. With progress in aviation technology, planes will fly longer and at higher altitudes, and presumably the number of flights and passengers will increase. To respond responsibly to the real and perceived risks associated with flying, more extensive data are needed, but special efforts should be considered to ensure new projects can genuinely add to our current knowledge.

*Key Words:* Cancer; Cosmic radiation; Epidemiology; Review; Occupation; Air crew; Pilots; Flight attendants; Chromosomal aberrations.

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## INTRODUCTION

In the United States, it is estimated that close to 175,000 workers are employed as flight personnel in commercial airlines.[1] Over half of these workers are flight attendants, most of whom are women. Aircrews are exposed to elevated levels of ionizing radiation, primarily from cosmic radiation, and may be exposed to electromagnetic fields from cockpit instruments. Flight personnel are often also exposed to jet fuel, engine exhaust fumes, onboard pesticides, and, in the past, to second-hand cigarette smoke. In addition, aircrews suffer from circadian rhythm disruption due to erratic hours and long-haul flights that traverse multiple time zones.

Since the 1990s, several epidemiologic studies of cancer incidence and mortality have reported increased risks of female breast cancer among flight attendants[2–7] and melanoma among both pilots and cabin crew.[7–17] Excesses of other cancers have been observed, but usually in single studies.[14,15,18–20] Although the causes of these excess cancer risks are not known, there is concern that they may be related to occupational exposures to ionizing radiation of cosmic origin. Annual radiation dose estimates vary, depending largely on a worker's job (cockpit or cabin crew), type of flights (long or short haul), and number of hours flown, but it is estimated that flight personnel receive an annual dose ranging between 0.2 and 9.1 mSievert (Sv)[a] per year.[21] Aircraft personnel working predominantly on long-haul high-latitude flights would receive an annual radiation dose of about 5 to 9 mSv.[22] This dose is substantially larger than the most recent annual limit of 1 mSv recommended by the International Commission for Radiological Protection (ICRP) for the general public.[23] It also is higher than the annual average dose of most nuclear workers, radiologic technologists, and industrial radiographers,[24] but is less than one-half of the 20 mSv annual dose limit recommended for occupational exposure.[23] However, in contrast to other occupational radiation exposures that have decreased over time, exposure to flight crew is expected to increase because commercial flights will likely be longer and at higher altitudes as aircraft technology improves. The most recent United Nations Scientific Committee on the Effects of Atomic Radiation report[24] estimates that the lifetime risk of dying from radiation-associated cancer is about 1% following an exposure of 100 mSv. The lifetime risk of cancer death without radiation exposure is 15% to 25%. The lifetime risk of developing cancer is about 2% following an exposure of 100 mSv, or double the mortality risk.

[a]A sievert is the international unit of dose equivalent to the amount of absorbed dose multiplied by a quality factor of the type of radiation exposure.

## COSMIC RADIATION

### Types of Radiation

In high-altitude commercial aircraft the major form of radiation exposure is from cosmic rays. The term "cosmic radiation" was first used in 1926 to distinguish it from radiation at ground level.[22] The primary natural background portion of cosmic radiation is largely composed of high-energy particles, predominately protons, with a relatively small component of alpha particles and heavier ions. Secondary radiation is generated by energetic particles as they collide and interact with air nuclei and other intervening matter. These reactions mostly produce protons, neutrons, electrons, and gamma and X-rays. For aircrew, the secondary charged particles and neutrons are responsible for most of the radiation dose. Additional radiation exposure comes from highly variable solar cosmic radiation. The exposure level depends on the solar cycle and solar activity. Solar cosmic radiation also consists of charged particles, largely protons, but the energy of these particles is usually lower than those of cosmic radiation.[25–27] Cosmic rays easily penetrate the body and, therefore, are a concern in relation to the health of those exposed. It is estimated that more than 50% of the radiation exposure at altitudes relevant for commercial jet aircraft is from high-linear energy transfer (LET) radiation, particularly neutrons.[27] This is considerably more than the minimal high-LET exposure received by nuclear, industrial, and medical workers.

### Biological Effects of Low- and High-LET Radiation

The biological effects of low- and high-LET radiation vary. To quantify differences in radiation quality, the relative biological effectiveness (RBE) is calculated as the ratio of the dose of low-LET $\gamma$ radiation and the dose of the high-LET radiation of interest that results in the same biological effects. High-LET exposure confers more biological damage than low-LET, mainly because of the higher amount of ionizations occurring in tissue, but the RBE also depends on dose and the amount and timing of fractionation.[28] Much less is known about the biological effects of low-dose exposure to high-LET than to low-LET. Largely based on animal experiments, the RBE of neutrons (an important

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exposure for aircrews) seems to range from 5 to 20, depending on the dose and the energy of the neutron exposure. For neutrons, the RBE increases with decreasing dose so the RBE would be expected to be close to 20 for the low-dose exposure of aircrew.

## Factors Influencing the Amount of Radiation on a Flight

Several factors determine the extent and type of cosmic radiation exposure incurred by flight crew or frequent fliers. One factor, altitude, predominates, but latitude also contributes significantly to variation in cosmic radiation. Rare solar events can eclipse annual recommended exposure limits within a few hours.

### Altitude

As mentioned previously, high-energy particles bombard the earth's atmosphere and generate secondary particles. As these particles descend toward earth, they lose energy, thereby reducing radiation levels as the altitude decreases. This is not entirely true near the equator and above 60,000 feet, but is accurate at 20,000 to 40,000 feet, the altitude range most often flown by subsonic commercial jets.[29]

### Latitude and Geomagnetic Shielding

The earth's magnetic fields are greatest at the equator and decrease from there to the poles. Because magnetic fields shield radiation particles, cosmic radiation exposure is higher in the polar regions. As with altitude, latitude also creates variation in cosmic radiation components, with electrons and photons combined equivalent to neutrons in the contribution to dose (about 40%) at 40,000 feet near the equator, but at high latitudes neutrons are the single largest radiation component (50%).[29] However, estimating the proportion of the dose attributable to neutrons increases in uncertainty as the neutron component becomes larger, primarily due to variation in the measurements of neutrons and the conversion factors dependent on neutron energy levels.[22,27] By far, the most efficient shielding is from the earth's atmosphere and magnetosphere, without which the annual radiation dose at the earth's surface would be above 1 Sv.[25]

### Solar Activity

Solar activity follows an 11-year cycle in which low-energy subatomic particles from the sun increase and decrease, inversely affecting the amount of cosmic radiation. Solar activity or solar winds carry irregularities in magnetic fields, dispersing the cosmic particles.[29] Thus, at the times of greatest activity when the magnetic field irregularities are strongest, radiation levels are the lowest. The fluctuation is most pronounced at high altitudes and latitudes.[24] Solar events are rare, but can contribute significant doses if crew members or passengers are flying at high altitudes. The most recent significant event occurred in 1956, with an estimated radiation dose of 1 mSv per hour at 20 km.[24]

### Flight Duration, Rate of Ascent or Descent

The cumulative amount of cosmic radiation exposure per flight also depends on the distance flown and the amount of time to reach or descend from cruising altitude. Obviously long-haul flights involve higher per-flight exposures than flights of short duration.

## Estimating Radiation Exposure and Dose

Unlike nuclear and medical workers, who wear radiation badges to measure their occupational exposure, aircrew are not routinely monitored. Measuring dose to aircrew is challenging because simple dosimeters, such as those worn by other occupational groups, do not measure the full spectrum of radiation exposures during flight. Thus, epidemiologic studies usually need to estimate exposure retrospectively using whatever information can be obtained. There are three main methods for measuring exposure in flight crew: analytic dose reconstruction, onboard physical measurements, and biomarkers of exposure (biodosimeters). Combinations of these can be used to improve accuracy. The most commonly used method in epidemiologic studies has been analytic dose reconstruction based on job history information obtained from crew members enrolled in the study, the employing airline, aviation authorities, and/or employee unions. These data can be very detailed for each flight or rather sparse. Ideally, one would want to know the aircraft type, flight dates, altitude, latitude, solar activity, flight duration, and rate of ascent and descent for each flight segment. The collected data are then entered into a computer software program that can calculate an individual crew member's estimated dose. Various versions of the CARI computer software program, developed by the U.S. Federal Aviation Administration, have been used in epidemiologic studies because the CARI program can estimate the radiation dose received during any given flight.[29,30]

In reality, all these data are rarely available, and exposure assessment often depends on substantially more limited information. When detailed information

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*Table 1.* Published studies of chromosomal aberrations by publication year in flight crew.

| Author, year | Description of study subjects,* dose estimation method | Aberration type | Mean frequency: Exposed | Mean frequency: Comparison group | Comments |
|---|---|---|---|---|---|
| Scheid et al., 1993[35] | 11 male pilots (P)<br>5 female flight attendants (F)<br>Historical control group (H)<br>No doses calculated | Dicentrics and rings/cell | Individual results:<br>0.0041 (P)<br>0.0051 (F)<br>0.0108 (F)<br>0.0032 (F) | 0.0005 (H) | Selected subjects characterized by significantly higher dicentrics and rings, as compared with a historical group. |
| Heimers et al., 1995[36] | 9 aircrew members<br>3 ground personnel (G)<br>15 laboratory personnel (L)<br>No doses calculated | Dicentrics/1000 metaphases | 2.19±0.77 | 0.7±0.49 (G)<br>0.3±0.17 (L) | Dicentrics were significantly higher in aircrew members as compared with (L) or (L) and (G), but not with (G) only. |
| Romano et al., 1997[39] | 192 pilots, technicians, and flight attendants<br>55 nonflight personnel<br>No doses calculated | Total cells % frequency:<br>Dicentrics and rings<br>Dicentrics<br>Rings | <br>0.148<br>0.116<br>0.032 | <br>0.064<br>0.055<br>0.009 | Aircrew members had significantly higher dicentrics plus rings, but not dicentrics or rings separately as compared with the non-flight personnel. |
| Zwingmann et al., 1998[53] | 23 flight engineers<br>23 ground personnel<br>Dose calculated from flight records: ~6 μSv/hr of flight | Chromosomal aberrations (type unspecified)/100 metaphases | 2.1±0.3 | 1.5±0.3 | Chromosomal aberrations elevated in flight engineers as compared with ground personnel, but was not significant. |

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|---|---|---|---|---|---|
| Wolf et al., 1999[40] | 58 female flight attendants<br>56 female Berlin subjects (B)<br>29 female ground personnel (G)<br>No doses calculated | Dicentrics and rings/1000 cells | 1.3±0.2 | 1.3±0.2 (B)<br>1.4±0.2 (G) | No significant difference in dicentrics and rings between flight attendants and both comparison groups. |
| Heimers, 2000[37] | 18 Concorde pilots<br>10 male laboratory personnel<br>Dose estimated by inflight radiation monitoring of 11 to 37 mSv/yr, but not used in analyses | Cells with dicentrics/1000 cells | 2.4±0.4 | 0.3±0.2 | Dicentrics were significantly higher in pilots as compared with the laboratory personnel. Decreased dicentrics for pilots with the most years flying. |
| Cavallo et al., 2002[38] | 48 male long-haul aircrew<br>48 male ground crew<br>No doses calculated<br>Dose–response calculated over quartiles of flight hours | Dicentrics, rings, gaps, breaks per 200 metaphases; micronuclei; translocations per 300 metaphases | | Number of aberrations not stated; but were higher in long-haul aircrew vs. ground crew.<br>Dicentrics: $p=.16$<br>Gaps and breaks: $p=.003$<br>Micronuclei: $p=.11$<br>Translocations: $p=.008$ ($p$-values based on group differences) | Pilots chosen for $\geq 18$ years flight experience (5 years international flying), or at least 7000 flight hours.<br>Linear increase (in translocations) over first three quartiles of flight hours, then decreased nearly to control level. |

*Descriptions of specific exposed and unexposed individuals are indicated for ease of chromosomal aberration comparison by group.

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on past flights is not available, surrogate measures of exposure are used (e.g., cumulative block hours, that is, the amount of time from taxiing out of one airport to taxiing into the next), duration of employment, home domicile of crew member, or aircraft-type license. In two studies comparing different analytic dose reconstruction approaches for estimating dose, a high correlation was found, even though the level of information used ranged from detailed pilot logbook data for each flight to the very crude surrogate measure of total years of employment.[1,31] Grajewski et al.[1] did, however, find that using block time as a surrogate for exposure underestimated dose by about 4%.

Onboard physical radiation measurements have been made, and they show fairly good agreement with the dose estimates obtained using the CARI computer program. Measurements using physical dosimeters on 44 Belgian long-haul flights indicated that the CARI computer program dose estimates and the dosimeter measurements were similar for low LET, but that the CARI program estimated higher neutron doses than the dosimeter measurements.[32] Other comparisons between flight dose measurements and analytic dose reconstruction methods have found them to be relatively consistent.[22]

As an alternative method for measuring radiation exposure, various biomarkers have been proposed. The most successful has been quantifying the number and type of chromosomal aberrations in lymphocytes using a technique called fluorescence in situ hybridization (FISH).[33] For evaluating past radiation exposure, stable chromosome aberrations such as translocations are best because they can persist for many years,[34] although there is some debate about whether even stable aberrations may diminish with time since exposure. Unstable chromosome aberrations, such as dicentrics (chromosome with two centromeres) and ring chromosomes or acentric fragments, are also induced in the cell by radiation; however, these types of aberrations are lethal to cells and usually do not persist past a few cell divisions.

Both stable and unstable chromosomal aberrations have been assessed in pilots and flight attendants (Table 1). Nearly all studies of cockpit crew reported elevated levels of dicentric and ring chromosomes compared with a control group (ground airline personnel or laboratory personnel).[35–39] In contrast, in the only study performed among female cabin attendants, the numbers of dicentrics and rings did not differ from those found among female ground personnel or women from Berlin.[40] Interpreting the findings from cytogenetic studies of unstable aberrations is problematic because the results indicate more recent exposures and are not really a cumulative biodosimeter. However, because stable and unstable translocations are believed to be produced in roughly equal numbers,[41] they appear to indicate that pilots have increased cytogenetic damage that could be related to their occupation. Cavallo et al.[38] evaluated stable translocations among ground crew and long-haul pilots who had 18 or more years of flying, 5 years on international routes, and at least 7000 flight hours. The authors found significantly elevated levels of stable translocations ($p$=.008). The number of aberrations showed a linear increase over the first three quartiles of flight hours and then a curious decline in the fourth quartile to nearly the aberration levels in the controls.

Although none of the biomarker studies used their results to quantify dose, the results suggest that aircrew are exposed to appreciable cumulative radiation doses, or possibly chemical carcinogens, because the lower level of stable chromosome aberration detection for FISH is believed to be about 300 mSv among persons younger than 60 years of age.[42] For unstable chromosome aberrations as evaluated in most of these studies, the detection level would be expected to be higher. Thus, FISH could be reflecting the grouped nature of the analyses, the additional exposure received during flights outside the regular work schedule (e.g., recreational air travel or commercial flights for work commuting), or the greater damage caused by high-LET radiation exposure.

## OTHER EXPOSURES PERTINENT TO AIRLINE FLIGHT CREW

Other exposures incurred by flight crew include electric and magnetic fields (EMF) generated by cockpit instrumentation, resulting in highest exposure in the cockpit and forward-serving section of the aircraft.[43] More recent summaries of the literature suggest that human health effects from EMF exposures are likely minimal,[44,45] so EMF probably need not be a main concern for flight crew. Circadian rhythm disruption from crossing multiple time zones has been proposed as a factor that may increase the risk of hormone-related cancers.[10,20,46,47] Disentangling the effects of circadian rhythm from exposure to cosmic radiation is extremely difficult without fairly accurate radiation dose estimates and detailed flight information.[1] Diesel fuel and exhaust fumes,[48] environmental tobacco smoke,[49,50] pesticide spraying of aircraft,[4] and not shutting down the weather radar after the plane has landed[30] are additional, potentially nontrivial, exposures that might modify cancer risk alone or in combination. Unfortunately, the health risks

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associated with most of these environmental hazards are largely unknown.

The extent to which any of these exposures could be a confounder (a factor that is correlated with both the disease and exposure under study) in the evaluation of the relation between cosmic radiation and cancer site warrants some discussion. In studies of aircrew, a confounder would have to be correlated with the specific cancer being studied and radiation dose. For example, because radiation dose is highly correlated with duration of employment, reproductive factors such as age at first childbirth might be confounders for breast cancer. Potential confounding is a primary concern when the magnitude of an association is small, particularly when the risk is less than about twofold because uncontrolled confounding could be the true cause for an observed association. As is described later, most cancer risks observed in studies of aircrew are well below twofold and, therefore, potential confounding from exposure to other risk factors is an important limitation in most epidemiologic studies conducted so far.

## HUMAN HEALTH EFFECTS

### Biological Measures

A long history of in vivo and in vitro laboratory experiments has established that radiation is an efficient inducer of chromosomal aberrations. As described previously, the frequency of chromosome aberrations in examined aircrew was higher than in comparison groups in most published studies. The meaning of increased chromosomal aberration levels (as related to elevated cancer risk) is not known with certainty, but the best data are from a European cohort study of 3541 Nordic and Italian individuals who had their stable translocation levels determined by FISH and were followed for cancer occurrence.[51] For those characterized with a high chromosomal aberration frequency (top tertile), cancer risk was significantly increased 1.5- and twofold in the Nordic and Italian cohorts, respectively.

Other indices evaluating potential adverse biological events include DNA damage (single- or double-strand DNA breaks), unscheduled DNA synthesis, and micronuclei formation. One study of 36 aircrew and 36 ground staff found no differences in DNA damage as measured by the Comet assay.[52] Another study measured numerous indicators of oxidative DNA damage and cytogenetic effects among 23 flight engineers and 23 ground personnel, finding no significant differences in *hprt* mutation frequency, micronuclei, or chromosomal aberrations.[53] However, the authors found significantly higher levels of 8-oxodG/dG and unscheduled DNA synthesis among the flight engineers than ground personnel, suggesting DNA adduct formation and DNA repair activities were elevated as a possible consequence of radiation exposure.

### Cancer Risks

After a comprehensive epidemiologic review of aircrew was published in 2000,[54] there have been at least 18 additional reports, including 1 meta-analysis[55] and 2 pooled studies of pilots from Nordic[16] and European[18] countries, and a pooled study of European flight attendants.[56] The sophistication of the studies has increased over the last two decades from proportional mortality studies (generally considered hypothesis generating) to analytic cohort and case-control studies for hypothesis testing. Summaries of studies conducted among pilots and other crew, such as navigators and flight attendants, that were published in 1990 or later are presented in Tables 2 and 3. It can be seen that malignant melanoma, other skin cancers, and female breast cancers are frequently elevated. A radiation-related increased risk may be plausible for female breast cancer based on the large elevated radiation-associated risks observed at low doses in other radiation-exposed populations.[57–60] The relationship between malignant melanoma and radiation exposure is less well defined, partly because melanomas are rare among the Japanese, about whom the most is known regarding radiation-related cancer risks.[58,61] A strong dose-related association between X-ray and gamma radiation and basal cell skin carcinoma has been reported in several irradiated cohorts, but these risks were seen at relatively high doses, generally above 1 Sv.[61–63] Nevertheless, elevated melanoma and other skin cancer risks have been remarkably consistently reported among flight crew.[7–17,56] More recently, Blettner et al.[17] reported an elevated melanoma mortality risk [standardized mortality ratio (SMR) = 1.8; 95% confidence interval (CI): 1.2–2.7] in a large pooled study of 27,797 male airline cockpit crew and Zeeb et al.[56] found a suggestive increase in melanoma mortality among 11,079 male flight attendants (SMR = 1.9, 95% CI: 0.7–4.4), however risk was not related to employment duration in either study. Although no studies have been able to include sun exposure habits in analyses of melanoma and non-melanoma skin cancer, one key study compared several host skin characteristics and sun exposure factors among Icelandic pilots and flight attendants to those in an age- and gender-matched random subset of the Icelandic

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*Table 2.* Summary of pilot studies reporting cancer outcomes published between 1990 and 2003.

| Author, year | Study design, study outcome measure,* description of study subjects, time period | Cancer sites | Findings: Risk estimate | Findings: 95% Confidence interval | Number of cancer cases | Comments |
|---|---|---|---|---|---|---|
| Blettner et al., 2003[17] (9 European countries combined) | Cohort, cancer mortality (SMR) Male Danish, Finnish, German, Greek, Icelandic, Italian, Norwegian, Swedish, and British airline pilots (n = 27,797), 1961–1997. | All cancers | 0.7 | 0.6–0.7 | 677 | Study used the cause-specific population mortality rates for each country from the World Health Organization or national statistics offices. Employment duration analyzed by Poisson regression with few relationships seen except increased colon cancer risk with increasing years of flying. |
| | | Melanoma | 1.8 | 1.2–2.7 | 25 | |
| | | Lung | 0.5 | 0.4–0.6 | 153 | |
| | | CNS | 1.2 | 0.9–1.7 | 41 | |
| | | Non-CLL Leukemia | 1.1 | 0.7–1.7 | 21 | |
| Paridou et al., 2003[80] | Cohort, cancer mortality (SMR) Male greek airline pilots (n = 843), 1960–1997 | All cancers | 0.6 | 0.3–0.9 | 17 | Study used the cause-specific mortality rates for the Greek population from the World Health Organization and the National Statistics Service. Small sample size precludes stable risk estimates for specific cancer sites. *Data included in Blettner et al., 2003.* |
| | | CNS | 1.8 | 0.4–0.5 | 3 | |
| Zeeb et al., 2002[81] | Cohort, cancer mortality (SMR) Male German airline pilots ($n$ = 6061), 1960–1997 Dose–response analyzed by Poisson regression. | All cancers | 0.6 | 0.4–0.7 | 76 | Average estimated radiation dose was 80.5 mSv. German population rates provided expected numbers. In internal analyses, longer employment duration (but not estimated dose) showed increased risk for all cancer mortality ($p$ trend = .025). |
| | | Brain | 1.7 | 0.7–3.6 | 7 | |
| | | Lung | 0.3 | 0.1–0.6 | 10 | |
| Ballard et al., 2002[66] | Cohort, cancer mortality (SMR) Male Italian airline pilots ($n$=3022), 1965–1996 | All cancers | 0.6 | 0.5–0.8 | 62 | Longer employment durations showed increasing SMRs for non-CLL (chronic lymphocytic) leukemia in male cohort members (includes male flight attendants). |
| | | Lung | 0.4 | 0.2–0.7 | 15 | |
| | | Non-CLL leukemia | 1.7 | 0.6–3.9 | 5 | |
| Pukkala et al., 2002[16] (5 studies combined) | Cohort, cancer incidence (SIR) Male Danish, Finnish, Icelandic, Norwegian, and Swedish airline pilots ($n$=10,032) followed for 17 years through 1996–1997 | Melanoma | 2.3 | 1.7–3.0 | 56 | Country-specific cancer registries used. Dose–response observed for melanoma skin cancer and cumulative μv. Prostate cancer risk increased for pilots with >10,000 block hours vs. <5000 block hours (RR=3.9). |
| | | Other skin | 2.1 | 1.7–2.8 | 27 | |
| | | Basal cell carcinoma | 2.5 | 1.9–3.2 | 61 | |
| Hammar et al., 2002[8] | Cohort, cancer incidence (SIR) Male Swedish airline (n=1490) and military pilots (n=2808), 1951–1996 | Airline: Melanoma | 2.5 | 1.3–4.5 | 11 | Study used the Swedish National Cancer Registry to link incident cancers. Significant deficits found for stomach, colon, and rectal cancers. *Data included in Pukkala et al. (2002).* |
| | | Military: Other skin | 2.1 | 1.2–3.4 | 17 | |

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|---|---|---|---|---|---|---|
| Rafnsson et al., 2000[10] | Cohort, cancer incidence (SIR) Male Icelandic commercial pilots ($n$=458), 1955–1997 | Melanoma | 10.2 | 3.3–23.8 | 5 | Melanoma risk higher for increased mSv of cosmic radiation exposure and for crossing multiple time zones. *Data included in Pukkala et al, (2002).* |
| Haldorsen et al., 2000[11] | Cohort, cancer incidence (SIR) Male Norwegian commercial pilots ($n$=3701), 1946–1994 | Melanoma<br>NMSC† | 1.8<br>2.4 | 1.1–2.7<br>1.3–4.0 | 22<br>14 | Study used the Cancer Register of Norway to link incident cancers. Significant trend for melanoma by dose. No significant cancer deficits found. *Data included in Pukkala et al. (2002).* |
| Ballard et al., 2000[55] (six studies included in analysis) | Meta-analysis. Combined six studies of cancer incidence and mortality (RRs) among male pilots ($n$=4) and female flight attendants ($n$=2). Studies published between 1986 and 1998. | Mortality:<br>Melanoma<br>Incidence:<br>Prostate | <br>2.0<br><br>1.7 | <br>1.0–3.8<br><br>1.2–2.3 | <br>11<br><br>40 | Used fixed effects model and SES correction factor for summary RR. Brain tumor risk nonsignificantly elevated. Significant deficits found for cancer mortality at all sites and lung cancer mortality in fixed-effects model. |
| Gundestrup & Storm, 1999[12] | Cohort, cancer incidence (SIR) Male ($n$=3390) and female ($n$=87) Danish cockpit crew, 1943–1995. | Melanoma<br>Other skin | 2.4<br>2.3 | $p<0.05$<br>$p<0.05$ | 14<br>53 | Population-based study using the Danish cancer registry. Due to low number of females, results are given for males. Acute myeloid leukemia elevated (SIR = 2.9). *Data included in Pukkala et al. (2002).* |
| Irvine & Davies, 1999[13] | Cohort, cancer mortality (SMR) Male British Airways pilots ($n$=6209) and flight deck engineers ($n$=1153), 1950–1992. | Pilots:<br>Melanoma | <br>3.3 | <br>1.5–6.3 | <br>9 | Deficits for most cancer sites observed, except for nonsignificantly elevated SMRs of brain/CNS in pilots and flight deck engineers. *Data included in Ballard et al. (2000)* and *Blettner et al. (2003).* |
| Nicholas et al., 1998[20] | All cause and cancer deaths (PMR). Male and female U.S. commercial pilots and navigators ($n$=1538 deaths), 1984–1991. | Kidney and renal pelvis | 2.0 | 1.2–3.1 | 19 | PMRs adjusted for race, gender, age, and region of the United States. |
| Band et al., 1996[18] | Cohort, cancer incidence and mortality (SIR and SMR). Male Air Canada pilots ($n$=2740), 1950–1992. | Incidence:<br>Prostate<br>Acute myeloid leukemia | <br>1.9<br>4.7 | <br>1.4–2.5<br>2.1–9.3 | <br>34<br>6 | Referent was Canadian population. 90% confidence intervals are reported. Significant deficits for all cancers (mortality and incidence) and rectal, lung, and bladder cancer incidence. Brain tumors and melanoma somewhat elevated. *Data included in Ballard et al. (2000).* |
| Grayson & Lyons, 1996[14] | Cohort, cancer incidence (SIR and RR). Male U.S. Air Force aircrew ($n$=59,940), 1975–1989. | All sites<br>Melanoma<br>Bladder<br>All sites<br>Testis<br>Bladder | 1.2‡<br>1.5‡<br>2.1‡<br>1.3§<br>1.7§<br>3.3§ | 1.0–1.4<br>1.0–2.1<br>1.1–3.7<br>1.1–1.5<br>1.1–2.9<br>1.5–7.3 | 342<br>49<br>19<br>342<br>59<br>19 | Referent groups were SEER (SIR) and nonflying officers (RR, $n$=167,263). 99% confidence intervals are reported. Compared to SEER, significant deficit found for Hodgkin's disease. |

*(continued)*

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*Table 2.* Continued.

| Author, year | Study design, study outcome measure,* description of study subjects, time period | Cancer sites | Findings: Risk estimate | Findings: 95% Confidence interval | Number of cancer cases | Comments |
|---|---|---|---|---|---|---|
| Grayson, & Lyons, 1996[77] | Case-control, brain tumor incidence (OR). Male cases: aircrew ($n$=37), nonflying officers ($n$=193); male controls: aircrew ($n$=90), nonflying officers ($n$=830), 1970–1989. | Brain (unadjusted) (adjusted) | 1.8 1.2 | 1.2–2.7 0.8–2.0 | 230 230 | Adjustment factor was military rank, an indicator for socioeconomic status. |
| Kaji et al., 1993[82] | Cohort, mortality (SMR). Male ($n$=2327) cockpit crew of Japan Airlines, 1952–1988. | All cancer | 0.87 | 0.53–1.35 | 20 | Japanese males were the referent population. *Data included in Ballard et al. (2000).* |
| Irvine & Davies, 1992[15] | Cancer deaths (PMR) Male British Airways pilots ($n$=446 deaths), 1966–1989. | All cancers | 1.3 | 1.1–1.6 | 138 | PMR performed with pilot deaths using death proportions from the England and Wales population. Based on these results, a cohort study was initiated and the results reported in 1999 (Irvine & Davies, 1999). |
| | | Melanoma | 6.7 | 2.5–14.6 | 6 | |
| | | Brain/CNS | 2.7 | 1.2–5.1 | 9 | |
| | | Colon | 2.3 | 1.3–3.8 | 15 | |
| | | Prostate | 2.1 | 1.0–3.9 | 10 | |
| Salisbury et al., 1991[83] | Cancer deaths (PMR) Male pilots in British Columbia, Canada, ($n$=341 deaths), 1950–1984. | Colon | 1.5 | 0.6–3.3 | 6 | PMR performed with pilot deaths and using death proportions from the British Columbia population. |
| | | Brain/CNS | 1.8 | 0.5–4.5 | 4 | |
| | | Melanoma | 4.4 | 0.9–12.8 | 3 | |
| | | Hodgkin's disease | 2.4 | 0.3–8.8 | 2 | |
| Band et al., 1990[19] | Cohort, cancer mortality and incidence (SMR and SIR). Male Canadian Airlines International pilots ($n$=913), 1950–1988. | Mortality: brain | 4.2 | 1.4–9.5 | 4 | British Columbia (Canada) residents were the comparison population. 90% confidence intervals are reported. *Data included in Ballard et al. (2000).* |
| | | Rectum incidence: | 4.4 | 1.2–11.2 | 3 | |
| | | NMSC† | 1.6 | 1.1–2.2 | 26 | |
| | | Brain | 3.5 | 1.2–7.9 | 4 | |
| | | Hodgkin's disease | 4.5 | 1.2–11.7 | 3 | |

*Note 1*: The meta-analysis by Ballard et al.[55] included cancer site-specific data from Wartenberg and Stapleton, based on a personal communication that included the elevated breast cancer risk cited from Wartenberg and Stapleton.[4]
*Note 2*. The study by Lynge[68] included 620 male Danish pilots; however, no incident leukemias or cancers of the breast or bone were observed.
*Note 3*. The study by Irvine and Davies[15] did not explicitly state gender of the pilots, but was assumed to be of deaths among male pilots.
*SIR, standardized incidence ratio; RR, rate ratio; OR, odds ratio; SMR, standardized mortality ratio; PMR, proportional mortality ratio.
†NMSC is nonmelanoma skin cancer.
‡Point estimates are SIRs based on SEER cancer rates.
§Point estimates are RRs based on cancer rates in nonflying officers.

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population. Rafnsson et al.[64] found air crew were more likely to apply sunscreen and to vacation in sunny destinations than the general Icelandic population, however, these differences did not solely account for the increased melanoma risks observed in pilots and flight attendants.

Most cancer sites are considered to be radiogenic based on data from the atomic bomb survivors and studies of patients exposed to diagnostic or therapeutic radiation. The observed radiation associations are strongest for the leukemias [especially myeloid, but not chronic lymphocytic leukemia (CLL)], and cancers of the thyroid, female breast, lung, stomach, colon, bladder, and ovary (reviewed in Ref. [65]). However, gender, age at exposure, type of radiation, timing of exposure, concomitant exposures, and other factors are known to modify radiation effects. Increased risk of acute myeloid leukemia has been reported in two studies of flight crew, but these observations were based on only four and six cases.[12,18] Gundestrup and Storm[12] reported a significant fivefold increased myeloid leukemia risk associated with long-haul flying in excess of 5000 hours based on three of the four cases. Leukemia (excluding CLL) mortality was nonsignificantly increased 1.7-fold among male Italian flight personnel, with increasing standardized mortality ratios associated with longer employment duration.[66]

Female breast cancer risk is clearly elevated after radiation exposure, but exposures early in life are important and risk is low for radiation exposure after about age 40.[57] With the exception of four studies,[9,56,66,67] small to moderately elevated breast cancer risks have been observed in the flight crew studies that included women.[2–7,68] Only a few studies have reported breast cancer risk by number of years employed; thus, more confirmatory dose–response evaluations are needed. Dose–response analyses performed by Pukkala et al.[5] revealed no breast cancer cases up to 15 years after beginning employment. The standardized incidence ratio (SIR) was 3.4 (95% CI: 1.5–6.8) for 15 to 19 years of employment, and 2.1 (95% CI: 1.1–4.0) for 20 or more years, a pattern consistent with latency of solid tumors. Reynolds et al.[2] reported significantly elevated SIRs for breast cancer among flight attendants who had international flying assignments (SIR=1.8; 95% CI: 1.2–2.5), who had been employed for 15 years or more (SIR=1.6; 95% CI: 1.2–2.1), and who began their flight attendant careers younger than age 25 (SIR=1.7; 95% CI 1.2–2.3). Risks were not significantly elevated for flight attendants who had domestic assignments (SIR=1.2; 95% CI: 0.8–1.8), worked less than 15 years (SIR=1.0; 95% CI: 0.5–1.7), or began work as a flight attendant at 25 years or older (SIR=1.1; 95% CI: 0.7–1.7). More recently, Linnersjö et al.[7] evaluated breast cancer incidence among Swedish airline cabin crew and found a slight increase in risk (SIR = 1.3; 95% CI 0.9–1.7) that was only partly explained by reproductive factors, however, risk was unrelated to employment history. Rafnsson et al.[6] reported an odds ratio (OR) over 5-fold (OR=5.2; 95% CI: 1.6–17.4) for breast cancer among those who were employed 5 or more years before 1971 compared to those employed less than 5 years in 1971 or later. The finding is important because this is the first published study that accounted for reproductive factors in the analyses rather than linking to population-based family registries.

Based on six cases, one study has reported a nonsignificant excess of thyroid cancer incidence in female flight attendants (SIR=1.6; 95% CI: 0.6–3.4).[3] Because the thyroid gland is highly radiosensitive only in childhood,[69] a lack of a clear association with thyroid cancer is consistent with the literature.

Lung cancer, cancer of the esophagus, and cardiovascular disease occurrence among pilots and flight crew tend to be lower than expected, likely reflecting a lower prevalence of cigarette smoking. Cancers of the stomach are rare, and colon cancer risks have been inconsistent: infrequently elevated in flight crew[13,15] and significantly decreased in pilots.[8] Increased bladder cancer incidence has been reported among U.S. Air Force crew compared with nonflying officers.[14] Fairly consistent increased risks have been found for prostate cancer, particularly when studies were combined, resulting in increased statistical power.[15–17,55] This cancer, however, is not generally considered radiation sensitive (reviewed in Ref. [65]), implying that additional factors are probably involved. These other factors could be of a hormonal nature, from disruption of circadian rhythms, or could be due to heightened detection from annual prostate surveillance among actively flying commercial pilots.

## METHODOLOGIC ISSUES STUDYING AIRCREW

The strengths and limitations of epidemiologic studies of flight crews have been thoughtfully discussed in other reviews and commentaries.[54,70–73] The most salient concern is that enormous populations would be required to detect cancer risks at the low radiation levels experienced by flight crews.[74] Cosmic radiation dose reconstruction for a large number of pilots, although extremely tedious and costly, could be fairly straightforward using pilot and airline records and computer programs designed for estimating flight

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*Table 3.* Summary of flight attendant studies reporting cancer outcomes published between 1990 and 2003.

| Author, year | Study design, study outcome measure,* description of study subjects, time period | Cancer sites | Findings: Risk estimate | Findings: 95% Confidence interval | Number of cancer cases | Comments |
|---|---|---|---|---|---|---|
| Rafnsson et al., 2003[6] | Nested case-control (OR) Breast cancer cases (n=35) and age-matched controls (n=140), all female flight attendants, employed over 1947–1997. | Breast | 5.2 | 1.6–17.4 | 14 | Study was nested within a cohort of 1532 female Icelandic flight attendants. OR of 5.2 is for working ≥5 years (vs. <5 years) before 1971 and is adjusted for age at first live birth and employment after 1971. |
| Linnersjö et al., 2003[7] | Cohort, cancer incidence (SIR) Female (n=2324) and male (n=632) Swedish flight attendants, 1961–1996. | Female: | | | | Study used the Swedish National Cancer Register. Analyses of employment duration, flight hours, high altitude/long duration flights were conducted with no clear associations found for cancer overall, melanoma, or breast cancer. Reproductive factors explained some (10%), but not all, of the breast cancer risk. |
| | | All cancers | 1.0 | 0.8–1.2 | 76 | |
| | | Breast | 1.3 | 0.9–1.7 | 33 | |
| | | Melanoma | 2.2 | 1.1–3.9 | 11 | |
| | | Leukemia | 3.1 | 0.9–8.0 | 4 | |
| | | Male: | | | | |
| | | All cancers | 1.2 | 0.8–1.6 | 33 | |
| | | Melanoma | 3.7 | 1.3–8.0 | 6 | |
| | | NMSC† | 4.4 | 1.2–11.3 | 4 | |
| Zeeb et al., 2003[56] (8 European countries combined) | Cohort, cancer incidence (SMR) Female (n=33,063) and male (n=11,079) Danish, Finnish, German, Greek, Icelandic, Italian, Norwegian and Swedish airline flight attendants, 1961–1997 | Female: | | | | Study used the cause-specific population mortality rates for each country from the World Health Organization or national statistics offices. Complete flight records unavailable so employment duration was analyzed with no consistent relationships seen with cancer mortality. |
| | | All cancers | 0.8 | 0.7–1.0 | 171 | |
| | | Breast | 1.1 | 0.8–1.5 | 59 | |
| | | Melanoma | 0.4 | 0.0–1.4 | 2 | |
| | | Male: | | | | |
| | | All cancers | 0.9 | 0.7–1.1 | 119 | |
| | | Melanoma | 1.9 | 0.7–4.4 | 6 | |
| Paridou et al., 2003[80] | Cohort, cancer mortality (SMR) Female and male flight attendants (n=1835; gender-specific numbers not stated). 1960–1997 | Female: | | | | Study used cause-specific mortality rates for the Greek population from the World Health Organization and the National Statistics Service. No associations with employment duration and cancer risk were found. *Data included in Zeeb et al., (2003).* |
| | | All cancers | 0.8 | 0.3–1.7 | 6 | |
| | | Breast | 1.0 | 0.1–3.7 | 2 | |
| | | Male: | | | | |
| | | All cancers | 0.4 | 0.1–1.2 | 3 | |
| Blettner et al., 2002[67] | Cohort, cancer mortality (SMR) Female ($n$=16,014) and male ($n$=4537) German flight attendants, 1953–1997. | Female: | | | | The German population served as the comparison for the SMRs. Internal analyses of employment duration were also conducted. The breast cancer SMR did not increase with employment duration. *Data included in Zeeb et al. (2003).* |
| | | All cancers | 0.5 | 0.5–1.2 | 44 | |
| | | Breast | 1.3 | 0.7–2.2 | 14 | |
| | | Male: | | | | |
| | | All cancers | 0.7 | 0.4–1.2 | 21 | |

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| | | | | | | |
|---|---|---|---|---|---|---|
| Reynolds et al., 2002[2] | Cohort, cancer incidence (SIR) Female ($n$=6895) and male ($n$=1216) California (U.S.) flight attendants, 1988–1995. | Female: | | | | Study used the California State Cancer Registry. Breast cancer and melanoma elevated in females but significance based on ethnic comparison groupings. Breast cancer SIRs, but not melanoma, elevated for increased years of service, international routes, and younger age starting work. |
| | | Breast | 1.3 | 1.0–1.7 | 60 | |
| | | Melanoma | 1.8 | 0.9–3.2 | 12 | |
| | | Male: | | | | |
| | | All sites | 2.1 | 1.4–3.2 | 25 | |
| | | Kaposi's sarcoma | 7.8 | 4.3–12.8 | 15 | |
| Ballard et al., 2002[66] | Cohort, cancer mortality (SMR) Female ($n$=3428) and male ($n$=3418) Italian flight attendants, 1965–1996. | Female: | | | | Longer employment durations showed increasing SMRs for non-CLL (chronic lymphocytic) leukemia in male cohort members (includes male pilots). *Data included in Zeeb et al. (2003).* |
| | | All cancers | 0.9 | 0.5–1.4 | 18 | |
| | | Breast | 1.0 | 0.4–2.2 | 6 | |
| | | Male: | 0.7 | 0.5–1.0 | 28 | |
| | | All cancers | | | | |
| | | Non-CLL leukemia | 1.8 | 0.4–5.2 | 3 | |
| Haldorsen et al., 2001[9] | Cohort, cancer incidence (SIR) Female ($n$=3105) and male ($n$=588) Norwegian flight attendants, 1950–1994. | Female: | | | | Study used the Cancer Registry of Norway. Suggestive melanoma dose–response based on employment duration. Female breast cancer not increased (SIR=1.1). Little effect on breast cancer point estimates after adjustment for reproductive factors. |
| | | Melanoma | 1.7 | 1.0–2.7 | 19 | |
| | | Other skin | 2.9 | 1.0–6.9 | 5 | |
| | | Male: | | | | |
| | | Respiratory/ gastric | 6.0 | 2.7–11.4 | 9 | |
| | | Liver | 10.8 | 1.3–39.2 | 2 | |
| | | Melanoma | 2.9 | 1.1–6.4 | 6 | |
| | | Other skin | 9.9 | 4.5–18.8 | 9 | |
| Rafnsson et al., 2001[3] | Cohort, cancer incidence (SIR) Female ($n$=1532) and male ($n$=158) Icelandic flight attendants, 1955–1997. | Female: | | | | Cancers ascertained by population-based cancer registries. Nonsignificant increased cancer risks observed for brain, thyroid, bone, and Hodgkin's and non-Hodgkin's lymphoma. Confounding from selected reproductive factors did not explain elevated breast cancer risk. |
| | | All cancers | 1.2 | 1.0–1.6 | 64 | |
| | | Melanoma | 3.0 | 1.2–6.2 | 7 | |
| | | Breast | 1.5 | 1.0–2.1 | 26 | |
| Ballard et al., 2000[55] (six studies included in analysis) | Meta-analysis. Combined six studies of cancer incidence and mortality (RRs) among male pilots ($n$=4) and female flight attendants ($n$=2). Studies published between 1986 and 1998. | Incidence: | | | | Used fixed-effects model and SES correction factor for summary RR. Brain tumor risk nonsignificantly elevated. Significant deficits found for cancer mortality at all sites and lung cancer mortality in fixed-effects model. |
| | | Breast | 1.4 | 1.0–1.8 | 27 | |

*(continued)*



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*Table 3.* Continued.

| Author, year | Study design, study outcome measure,* description of study subjects, time period | Cancer sites | Findings: Risk estimate | Findings: 95% Confidence interval | Number of cancer cases | Comments |
|---|---|---|---|---|---|---|
| Wartenberg & Stapleton, 1998[4] | Cohort, breast cancer incidence (SIR) Retired flight attendants from a U.S. airline. Number studied not available. | Breast | 2.0 | 1.0–4.3 | 7 | Referent group not stated. Study report focused on DDT exposure from pesticide spraying on aircraft. *Data included in Ballard et al., (2000).* |
| Pukkala et al., 1995[5] | Cohort, cancer incidence (SIR) Female ($n$=1577) and male ($n$=187) Finnish flight attendants, 1967–1992. | Breast<br>Bone | 1.9<br>15.1 | 1.2–2.2<br>1.8–54.5 | 20<br>2 | Population-based study using Finnish Cancer Registry. Leukemia and melanoma also nonsignificantly increased. No real evidence for breast cancer dose–response. *Data included in Ballard et al. (2000).* |
| Lynge, 1996[68] | Cohort, cancer incidence (SIR) Female ($n$=915) and male ($n$=362) Danish flight attendants, 1970–1987. | Female: Breast | 1.6 | 0.9–2.7 | 14 | Given the small number of female flight attendants, although the point estimate for breast cancer is nonsignificant, the study supports an elevated breast cancer risk in cabin attendants. |

*OR, Odds Ratio, SIR, standardized incidence ratio; RR, rate ratio; SMR, standardized mortality ratio.
†NMSC is non-melanoma skin cancer.

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doses. For flight attendants, the dose reconstruction effort would be much more difficult because flight records often are not retained for long periods by the airlines and analytic studies would need to incorporate questionnaire data collected through personal or telephone interview or by mail, increasing costs and potential for recall bias. Another major concern is the difficulty of precise measurement of the neutron component of cosmic radiation and the insufficient understanding of the biologic effects of neutrons in human tissues. The very limited knowledge regarding neutron exposure and human health effects is well appreciated,[75] but there do not appear to be appropriate populations available for study.[76]

To date, cohort studies have compared cancer rates in aircrew to expected cancer rates in a general population with a similar age and gender distribution. Although this design can demonstrate increased or decreased cancer frequency in an exposed cohort, it precludes controlling for most other cancer risk factors, including socioeconomic status. To overcome this limitation, a few studies have been able to obtain cancer risk information from other sources, such as computer-linked birth registries[7,9] or population data.[3] Nested case-control studies of breast cancer and melanoma within existing pilot and flight attendant cohorts could prove fruitful in directly assessing the independent effect of cosmic radiation after controlling for reproductive factors in the evaluation of breast cancer and intermittent sun overexposure in the evaluation of melanoma risk.

As mentioned earlier, an enhanced risk of malignant melanoma has been found consistently in cohort studies of both pilots and flight attendants. Although some studies have reported that the melanoma risk increases with increased flight hours[12] or estimated radiation exposure (based on aircraft type and block hours),[11] most investigators have ascribed the association to recreational sun exposure of aircrews, but this may not entirely account for the relationship.[64] In addition, because nearly all the cohort studies that reported on melanoma risk used external referent populations, the higher socioeconomic status of pilots and flight attendants or underreporting of thin melanomas to registries could also reasonably account for the excesses observed. Until carefully designed studies, that collect detailed histories of intermittent sun and other exposures for individual flight crew workers and comparison subjects are conducted, the cause of the increased risk of melanoma cannot be discerned. As a case in point, by not accounting for the confounding influence of socioeconomic status, the observed SIR for melanoma was increased among U.S. Air Force aircrew. When analyses were adjusted for socioeconomic status by using an internal referent (other Air Force officers), the risk declined from 1.5 (99% CI: 1.0–2.1) to 1.2 (99% CI: 0.8–1.8).[14] Similarly, in a case-control study of brain tumors among U.S. Air Force aircrew, risk was reduced when analyses included military rank as a surrogate for socioeconomic status.[77]

## CONCLUSION

Although more than 30 studies of cockpit and cabin crew have been published since 1990, there still is not a clear cause-and-effect relationship between risk of any site-specific cancer and employment as a pilot or flight attendant. For the cancer associations that appear to be consistent with occupational exposure to cosmic radiation, such as breast cancer and malignant melanoma, it is still possible that confounding risk factors partially or totally explain the observed relationship. In addition, misclassification of radiation dose by use of surrogate exposure measures (years of working, block hours) may over- or underestimate doses that individual aircrew received, although such misclassification is more likely to bias estimates toward not finding an association. The statistical power (i.e., the probability that an elevated risk can be detected with a certain level of confidence) to detect slight or modest associations is often inadequate because the study size is too small. Thus, pooling the data from multiple studies of aircrew, such as was done by a group of European investigators, is a step in the right direction. To resolve the problem of potential confounding, future analytic studies must collect information on a variety of cancer risk factors. In addition, the quality of the dosimetry has to be improved substantially, especially for flight attendants, for any new study to add appreciably to current knowledge. If risk factor data, such as reproductive history and childhood and adult sun exposure can be collected, and adequate historical radiation dose reconstruction is feasible, investigators should consider designing new studies employing standardized collection instruments that would facilitate future data pooling to increase the likelihood of detecting modest associations. To date, studies of chromosomal aberrations, as a biomarker of exposure, have generally been small and have measured the frequency of unstable translocations. Large studies of aircrew have not been undertaken, partly due to the expense and time involved and partly because prevailing opinion suggests that radiation exposure in aircrew may be too low to observe a significantly increased aberration frequency. As new automated techniques become available, well-designed studies of stable chromosomal

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aberrations would be warranted to better quantify and characterize long-lasting aberrations. Analyzing the patterns of aberrations, including the ratios of inter- to intrachromosomal aberrations might provide a better understanding of the role of the high-and low-LET components of cosmic radiation exposure.[78]

The European Union has implemented radiation dose limits to aircrew based on the ICRP recommendations,[79] but the United States has not followed suit. However, the issue of cosmic radiation exposure and the potential for associated deleterious human health effects, ranging from cytogenetic damage to malignancies, is of importance to aircrew, other occupationally exposed workers such as couriers, and the flying public, particularly frequent fliers. With improvements in aviation technology, planes will fly longer and at higher altitudes, and presumably the number of flights and passengers will increase. If so, the cosmic radiation exposures incurred by aircrew and passengers will also increase resulting in heightened worldwide public concern. To respond fully to the real and perceived risks associated with flying, more extensive data are needed, but to prevent spending resources on unproductive research, special efforts should be considered to ensure new projects can genuinely add to our current knowledge.

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