REVIEW

# Cosmic rays: are air crew at risk?

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This article reviews the current knowledge about cosmic rays and their possible effects on health of air crew, discusses research directions necessary for establishing and measuring the risks, and highlights the need for physicians and air crew to be informed, despite the inconclusiveness of the evidence. A literature review of computerised medical and scientific databases was carried out. Recent reports highlighting increased incidence of cancer among airline pilots and cabin crew have renewed concerns about possible exposure to harmful levels of cosmic radiation at altitude. Such low energy ionising radiation has been shown to cause double stranded DNA deletions and induce genomic instability in human chromosomes. In the field of microelectronics, cosmic rays have been shown to cause "hard" and "soft" errors in computer microchips, in a dose-response fashion with increasing altitude. Pregnant cabin crew members are of special concern. Although the epidemiological evidence is still inconclusive, we know enough to warrant a cautionary stance. The European Union (EU) leads the way in legislation.

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Since 13 May 2000, airlines in the EU are required to assess the in flight radiation exposure of air crew, to inform them of the health risks, and to control the dose to the foetus. Better designed epidemiological studies and more biologically founded laboratory models areneeded to establish and assess the risks. Meanwhile, physicians should be alerted and air crew informed, based on present, available knowledge.

The existence of invisible cosmic rays constantly bombarding the earth (discovered in 1912 by Victor Franz Hess in an experiment which won him the 1936 Nobel prize in physics) coupled with evidence of ionising radiation as a human carcinogen, has given rise to concerns that air crew may be occupationally exposed to an invisible health threat at altitude.

Reinforcing these concerns, of late, are several studies highlighting increased cancer incidence among air crew populations.[1–7]

In 1999, a United Kingdom National Radiological Protection Board survey showed that nuclear workers received a lower annual average dose of radiation (3.6 mSv a year) than air crew (4.6 mSv a year), raising questions as to whether regulatory and monitoring requirements should apply to air crew as well.[8]

Are air crew occupationally at risk? This article reviews what is known of cosmic rays and their possible effects on health of air crew; discusses research directions that are necessary for establishing and assessing the risks; and highlights the need for physicians to be alerted and air crew to be informed, based on information currently available.

## WHAT ARE COSMIC RAYS?

Cosmic rays are high energy, charged particles of extraterrestrial origin that constantly bombard the earth from all directions. Some come from our sun, but most are from deep space, having travelled thousands of light years to reach our planet.[9] Current theory suggests that they originate from supernovae—the death explosions of massive stars. The scientific evidence supporting this includes recent observations of the cloud dust of the supernova 1987A found in the large magellanic cloud, and direct measurements of cosmic rays by the advanced composition explorer satellite, launched in 1997 by National Aeronautics and Space Association.[10]

Upon striking the outer atmosphere of the earth, these high energy particles (mainly protons, $\alpha$ particles, electrons, positrons, and other heavy nuclei) produce secondary showers of lower energy, mostly unstable, charged particles. These in turn collide with yet other air molecules, creating still more showers that cascade to the ground. Only a small dose of low energy, ionising radiation (comprising a mixture of stable particles such as protons, neutrons and electrons, and transient ones such as muons and pions) eventually make it to sea level. Here (typically about the sixth cascade), the particle flux is approximately $1/cm^2.s$ compared with $100/cm^2.s$ at 15 km (or 60 000 feet) above sea level.[11]

The dose received by humans is determined by three main factors.

### Altitude

The Earth's atmospheric layer provides a shielding effect equivalent to 13 feet of concrete. Whereas at sea level the exposure is about 0.06 $\mu$Sv/h, at 35 000 feet above sea level (the cruising altitude of subsonic commercial aircraft such as Airbus or Boeing 747) the dose received is about 100 times more, at 6 $\mu$Sv/h.[12] And at 60 000 feet above sea level (the cruising altitude of the supersonic Concorde) the exposure is even much greater.

### Latitude

The geomagnetic field of the earth provides additional shielding. Charged particles striking the earth near the equator tend to be deflected along the magnetic field lines towards the poles. The

**Table 1** ICRP exposure limits: previous standards (1976) compared with current (1990) standards

| | Previous ICRP (1976) limits[21] (mSv/y) | Current ICRP (1990) limits[15] (mSv/y) |
|---|---|---|
| Occupational worker | 50 | 20 |
| Pregnant worker | 13 | 2 |
| Public | 5 | 1 |

result is that for any given altitude, the exposure increases as one moves away from the equator. The exposure at the same altitude over the poles is roughly twice that over the equator.

### Solar activity

The intensity of solar activity waxes and wanes according to an approximate 11 year cycle. During a solar flare event, the additional bursts of cosmic radiation unleashed towards earth and measured on board an aircraft, can reach as high as 10 mSv/h. For this reason, the Concorde is fitted with a special warning device that alerts the pilot to descend to a safer altitude whenever the safety limit of 0.5 mSv/h is reached. The International Civil Aviation Organization had in 1971 introduced a requirement for all passenger aircraft operating above 49 000 feet to be equipped with instruments to measure continuously, the total cosmic radiation being received.

## AIR CREW EXPOSURE AND HEALTH CONCERNS

The main concern with exposure of air crew to cosmic rays is the possible long term risk of radiation induced cancer and, in the case of pregnant air crew, possible harm to the foetus—mainly stochastic effects later in life and to a lesser extent, birth defects.

Friedberg *et al*[13] estimated the cumulative exposures of a group of United States air crew to be in the range 0.2–9.1 mSv a year, whereas Oksanen, with calculated individual doses reflecting actual flight profiles instead of simply assuming constant radiation exposure throughout the flight, obtained annual doses of 0.72–3.1 mSv for cabin crew and 1.08–2.83 mSv for pilots in Finland.[14] As a group, therefore, air crew tend to fall somewhere between the International Commission on Radiological Protection current recommended maximum permissible level for the public (1 mSv/y) and that for radiation workers (20 mSv/y, table 1).[15]

Based on these figures, and extrapolating from data for exposure to high dose radiation, Friedberg *et al* estimated that the increased risk of dying from cancer because of cosmic radiation received over 20 years of flying ranges from 0.1 to 5 in 1000.[13] Considering that the risk of dying from cancer in the adult United States population is about 220 in 1000 this increase in risk due to exposure to cosmic radiation is very small indeed. Nevertheless, it is still an added risk.

There is considerable concern for pregnant female crew members.[16–18] The International Commission on Radiological Protection, in setting the limit for pregnant workers at 2 mSv/y (table 1), apparently assumed that the dose to the foetus would be about half the dose at the surface of the mother's abdomen. But this assumption may not hold,[19] and the safe limit for foetuses of 1 mSv for the entire duration of pregnancy could easily be exceeded within 1 or 2 months of flying regular routes—for example, between New York and Athens. Following two extensive monitoring surveys which showed exposure on domestic routes to be on average, 1.1 mSv/y for technical crew, and 1.8 mSv/y for pilots (thus making it possible to exceed 1 mSv dose during a full 9 month pregnancy), Australia has unilaterally reduced the limit for its pregnant workers to 1 mSv/y.[20]

In assessing risks, it is important to remember that extrapolations are only as good as their underlying assumptions. Little is known of the radiobiological effects of low dose ionising radiation, much less that of low dose ionising radiation of the type and quantity which airline pilots and cabin crew are exposed to at altitude. A great deal of what we assume is therefore inferred by extrapolating from experience with high doses[21]—for example, from epidemiological studies of the victims of Hiroshima and Nagasaki, Chernobyl, as well as ground based laboratory studies involving acute exposures to a single type of radiation and at relatively high doses and dose rates.[22 23] But when it comes to cosmic radiation received during flight, not only are we dealing with much lower doses of mixed radiation fields, but also much lower dose rates. At these levels, we simply do not know if the harmful effects of ionising radiation behave in a dose-response or a threshold dependent fashion,[24] nor do we know what weighting factors to use when computing the probable exposures for the wide range of cosmogenic particles experienced at different altitudes.[25]

## ESTABLISHING RISK: EPIDEMIOLOGICAL APPROACHES

Several cohort studies have shown an increased incidence of cancer among pilots and cabin crew. For example, an excess incidence of breast cancer has been reported among Finnish[1] and Danish[26] airline cabin crew, with a standardised incidence ratio (SIR) of 1.9, 95% confidence interval (95% CI) 1.2 to 2.2 and SIR 1.6, 95% CI 0.9 to 2.7 respectively. A similar cohort study of Canadian pilots[2] has shown significantly increased incidences of prostate cancer (SIR 1.9, 90% CI 1.38 to 2.49) and acute leukaemia (SIR 4.72, 90% CI 2.05 to 9.31). Norwegian pilots[5] have also been found to have excess risks for malignant melanoma (SIR 1.8, 95% CI 1.1 to 2.7) and non-melanoma skin cancer (SIR 2.4, 95% CI 1.3 to 4.0). But on closer examination, these studies share the common problems of small cohorts and conspicuous confounders.[27] For example, increased rates of breast cancer could be attributed to reproductive factors such as nulliparity, and increased rates of melanoma to leisure time activities.[28] Moreover, various site specific cancers with increased incidence in some studies have not shown comparable increases (in some cases, they showed decreases) in other investigations.[29]

A meta-analysis of both published and unpublished cohort studies of air crew between 1986 and 1998 concluded that air crew seemed to be at risk of several types of cancer—melanoma, brain, prostate, and breast.[30] But it was not possible, based on these studies, to pinpoint cosmic radiation as the culprit. The authors recommended that future studies must also compare risks within cohorts by flight routes, work history, and exposure to cosmic and ultraviolet radiation, electromagnetic fields, and chemical substances.

These facts show the limitation of the epidemiological approach[31] to settle the issue. For, even if large enough cohorts (for instance, by pooling the results for several countries[32]) are found, the incriminating evidence will continue to elude us as long as no particular cancer or cancer death can be linked specifically to exposure to cosmic radiation (as distinct from other lifestyle, dietary, or environmental factors).[33 34] In the meantime, the worry over possible health risks will continue because the lack of epidemiological evidence for the existence of effects induced by cosmic rays at low doses, and low dose rates are no proof that such effects do not exist. What we need, ultimately, is a biologically founded, laboratory based model, to complement the epidemiological approach.

## LABORATORY BASED APPROACHES

Here, there are good grounds to think that the health risk of exposure to cosmic radiation is not zero. We know, for instance, that radiation mutagenesis principally proceeds through DNA deletions, and misrepair and misrecombination at DNA double stranded breaks.[35] We also know that a single track of low energy ionising radiation can produce a double stranded break in the DNA of a single cell nucleus.[36] A study of astronauts on a 4 month mission to the Mir space station (dosage received: 147.5 mSv) has shown significantly increased frequency of chromosomal aberrations after the flight, compared with samples obtained before the flight.[37] A significant increase in chromosomal aberrations has also been found in Concorde pilots compared with controls,[34] and indeed the same has been found in civilian pilots and cabin crew of subsonic aircraft.[38]

Even more worrying is the discovery in 1992 of a previously unknown pathway termed "radiation induced genomic instability",[39] by which radiation can subvert living cells. It was previously thought that when ionising radiation hits a living cell and damages its DNA, only when the damage is not satisfactorily repaired is it passed on to the daughter cells; now, repeated experiments in vitro and in vivo have shown that radiation can additionally inflict damage that shows up only after several generations of cell division.[40] This is particularly worrying as it raises the spectre of delayed genetic effects on the gene pool of future generations.[41]

## BEYOND THE MEDICAL LITERATURE

It is also instructive to look at the parallel world of microelectronics where it may come as a surprise to some biological scientists, there already exists a strong body of evidence on the deleterious effects of cosmic rays on microchips.[42]

For example, it has been known for some time now that the failure rate of electronics at aircraft altitudes is about 100 times greater than at sea level, and that cosmic rays are mainly responsible.[43] Although the higher energy particles can cause serious, permanent damage, called hard errors—for example, chip burnout—the lower energy particles are capable of causing soft errors—for example, flipping a logic bit from one to zero or vice versa—resulting in corrupted but reversible memories on computer chips.[44 45] Soft errors, or single event upsets in electronic parlance, can be corrected quite simply—for example, by rebooting a computer. The occurrences of soft errors have been shown in satellites, spacecraft, the Concorde, and commercial airliners.[46] Solar flare particle events pose the greatest problems, a not surprising fact as they are known to swamp satellite electronics and electrical power communications on earth.[47]

Adding credence to the theory that cosmic rays are responsible for these effects is a recently disclosed experiment conducted over a period of 16 years (1978–94) where a team at IBM tested about 800 dynamic random access memory devices in constant read mode at sea level, in mountainous regions (at 5000 feet and 10 000 feet) and in underground caves (shielding of 50 feet of concrete). They found that the higher the altitude, the more numerous the soft errors,[48] whereas initially, even after 3 months, the underground dynamic random access memory tested at zero soft errors. Since the release of the IBM report in 1996, there has been a considerable amount of research devoted to finding newer and better ways of protecting electronic devices intended for aircraft and space use from harmful radiation.[49–51]

This digression into the world of microelectronics is relevant to our discussion, in that it leads us to posit that as human chromosomes have no inbuilt protection against radiation induced double stranded DNA breaks and genomic instability—the rough biological equivalents, one might say, of electronic hard and soft errors respectively—it would be reasonable to infer that a similar vulnerability to cosmic rays might exist for human chromosomes as for microchips. Perhaps replicating the IBM study with biological tissue would be a logical next step in our search for a laboratory based model to establish causality.

### Main messages

- Air crew are occupationally exposed to potentially harmful levels of cosmic radiation at altitude.
- Several epidemiological studies point to increased incidence of certain cancers in air crew populations, but the link between cosmic radiation and cancer in air crew has not been established.
- Better designed epidemiological studies and more biologically founded laboratory models are needed, to establish and measure the risks.
- A precautionary stance in the meantime would be prudent.
- Legislation in the European Union since 13 May 2000, requires airlines to assess the in flight radiation exposure of air crew, inform them of the health risks, and control the dose to the foetus.

### Policy implications

- Aviation authorities around the world should adopt a precautionary stance, similar to that of the European Union (legislation) or the United States Federal Aviation Administration (education).
- Air crew should be informed of the risks so that they can make informed choices.

## SO, IS IT SAFE?

In the meantime, what should we tell aviators (and frequent flyers) who are anxious to know, "is it safe?". The findings of the epidemiological studies have been reported in the media under somewhat sensational headlines such as:

"Increased air travel responsible for jump in amount of natural radiation to which Britons are exposed",[52] and "frequent flyers on transatlantic flights are exposed to the equivalent of 170 chest *x* rays a year, putting them at increased risk of cancer".[53]

Should pregnant female cabin crew be grounded? Is a female cabin crew member with the BRCA1 gene, mutations of which carry a very high risk of developing female breast cancer,[54] at increased risk?[19] Unfortunately, the experts do not know, and are likely to remain divided in opinion[18 55] for some time.

Given the inconclusiveness of the evidence on the one hand, and the social, economic, and ethical implications of intervening on the other, our dilemma seems to be that we know enough to be concerned, yet not enough to act decisively. How this translates into practice in the real world is reflected by the unevenness of policy approaches across the globe.

### The European Union

The European Union (EU) is ahead of everyone else with occupational health legislation. In 1990, the International Commission on Radiological Protection recommended that exposures to natural sources of radiation during flight in jet aircraft should specifically be included as part of the occupational exposure of air crew.[56] This recommendation was adopted by the European Union in 1996 when it laid down its basic safety standards for radiation protection.[57] This has since been incorporated into the national laws,[58] so that since 13 May 2000, it has become mandatory for airlines in the European Union to take appropriate measures to assess the in flight exposure to cosmic radiation of air crew, to take into account the assessed exposure when organising work schedules, and to inform air crew of the health risks that their work involves. Additional provision is made for pregnant air crew so that the dose to the foetus will be "as low as reasonably achievable and unlikely to exceed 1 mSv during the remainder of the pregnancy". The European laws also require airlines to keep a record of the assessed exposure to cosmic radiation, to produce that record on request to the Civil Aviation Authority and to supply a copy on request to the air crew concerned.[59]

### The United States

The United States has also taken a precautionary, but more tentative, stance. The United States Federal Aviation Administration in 1992 acknowledged that pilots and flight attendants in conventional subsonic aircraft may receive more radiation annually than the average radiation worker—perhaps twice as much—and recommended that airlines educate their crew members about their risk of radiation.[60] However, this is only advisory, not mandatory. In 1999, the Federal Aviation Administration produced a computer programme (CARI-6, downloadable at http://www.cami.jccbi.gov/AAM-600/610/600Radio.html#CARI6EXE.), which enables airlines and aviators to estimate their own risks of exposure. CARI-6 calculates the amount of cosmic radiation received by a person on an aircraft flying between any two locations in the world, taking into account changes in altitude and geographic location from take off to touch down, and the particular stage of the 11 year solar cycle at the time of flight.[61]

### The rest of the world

In most of the rest of the world, (the few exceptions being Canada, Australia, and New Zealand) exposure to cosmic rays remains a little known, low priority, occupational health and safety issue.

## CONCLUSION

Current concerns over exposure of air crew to cosmic radiation are not without basis. However, the epidemiological evidence remains inconclusive, and will continue to be so for some time. In the meantime, questions by air crew, and increasingly by the frequent flying public,[62 63] about health risks of exposure cannot be ignored or sidestepped. Should they be told? What should they be told?

Recognising that knowledge and ignorance exist for both experts and lay people alike, Thomas Jefferson once said: "If we think the people not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them, but to inform their discretion".[64] Thus, while we await the results of better designed epidemiological studies and more biologically founded laboratory experiments, there is a need, in the meantime, to alert physicians and inform air crew (and frequent flyers) so that informed choices based on available information can at least be made. For those interested, educational materials issued by the Federal Aviation Administration[65] and the Association of European Airlines,[66] would be a good place to start.

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## COMMENTARY

Cosmic radiation is a complex and emotive subject. Professor Lim provides a significant contribution to the debate on cosmic radiation in aviation. His paper leaves many questions unanswered, but this is partly a reflection of the immaturity in knowledge of the epidemiology of chronic exposure to low dose, high energy ionising radiation.

The author correctly draws attention to the limitations of extrapolating from experience with high doses of ionising radiation, such as studies of the victims of Hiroshima, Nagasaki, and Chernobyl, to the radiobiological effects of the low doses of ionising radiation encountered in aviation.

There is no level of radiation exposure below which biological effects do not occur, but it is possible to estimate the probability of harm occurring, based on the exposures received.[1] Coupled with knowledge of the doses received by flight crew[2–4] and the available epidemiological studies,[5–8] evidence indicates a low probability of flight crew suffering health effects as a result of occupational exposure to cosmic radiation.

Lim suggests that there is an increased cancer incidence among aircrew populations, citing a number of authors. In fact, many of the references can equally be interpreted as showing a reduction in the expected incidence of cancers associated with ionising radiation, while showing consistent excess of melanoma and basal cell carcinoma. For example, Gundestrup and Storm,[6] while reporting an increased risk of acute myeloid leukaemia in one subgroup of the cohort, conclude "we are confident in excluding a major cancer related effect of the exposure to cosmic radiation in today's aviation". Similarly, Irvine and Davies[5] conclude that "flightdeck crew live longer than the England and Wales population and do not exhibit patterns of death that could be directly attributable to occupation". A number of authors conclude that the risk factor for skin cancer was likely to be related to the lifestyle of aircrew and their presumed greater opportunity to spend more time sunbathing than the general population.[5–7]

The paper refers to studies of cancer in female cabin attendants.[9 10] Stewart and Stewart[10] concluded that none of the potential risk factors identified among the cohort, including radiation exposure, was thought sufficient to explain the increased incidence of breast cancer.

The possibility of difference in interpretation of these studies of flight crew and cabin attendants supports Lim's advocating the need for further research.

The credibility of Lim's paper is not enhanced by reference to media news sites as authoritative sources. For example, he quotes the BBC News Online network in stating that "frequent flyers on transatlantic flights are exposed to the equivalent of 170 chest *x* rays a year, putting them at increased risk of cancer".[11] This statement carries little scientific validity, and takes no account of the time/dose characteristics of the radiation exposure. A chest *x* ray delivers a concentrated dose of radiation in a short time period, whereas a transatlantic flight exposes the traveller to a whole body exposure diluted over several hours; the radiobiological effects are hardly comparable.

Professor Lim shows admirable ingenuity in suggesting a comparison between the deleterious effects of cosmic radiation on electronic microchips and on human chromosomes. It is well accepted that there is a dose response relation modelling the number of "hard" and "soft" errors in microchips against the intensity of radiation exposure, but the microchip is incapable of self repair. The relevance of this to the human cell is not so obvious, particularly in view of the self repairing capacity of the human cell. It is of course accepted that chromosome aberration may occur due to DNA translocation and other errors during the repair process. However, to date there has been no published evidence linking the type of chromosomal aberrations observed with the process of carcinogenesis.

This paper raises a number of important issues. However, the blurring between good scientific evidence and speculation prevents the derivation of a satisfactory answer to the question posed by its title.

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## AUTHOR'S RESPONSE

I appreciate Dr Bagshaw's insightful comments and agree with him that many questions remain unanswered. While we do not know the extent of the risk, we nevertheless know, on non-epidemiological grounds, there is a small but extant risk. As Bagshaw concedes, the "evidence indicates a low probability of flight crew suffering health effects as a result of occupational exposure to cosmic radiation".

Bagshaw is right about the difficulty in interpreting any finding of increased cancer incidence among aircrew. He cites Gundestrup and Storm who, despite finding significantly increased risks of acute myeloid leukaemia, skin cancer, and total cancer among aircrew, dismissed their finding of excess skin cancer as a major cancer related effect of exposure to cosmic radiation, attributing it probably to other lifestyle factors such as sunbathing. He omits, however, to mention that the authors' overall conclusion was not entirely equivocal: "Our study showed increased risks of acute myeloid leukaemia and total cancer among Danish male jet cockpit crew members flying more than 5000 hours. This finding could be related to cosmic radiation, in as much as the risk is seen in the most exposed group—those flying high (jet) and for many hours. Such crew receive up to 9 mSv annually".[1]

On balance, however, it is fair to say that the epidemiological evidence remains inconclusive. But will it *ever* be conclusive? We must recognise the limitations of relying on the epidemiological approach to quantify health risks due to small effects such as the cumulative exposure to low intensity ionising radiation. If we are serious about answering the unanswered questions, we must embark on additional, intersecting lines of scientific inquiry—such as a biologically founded, laboratory based model showing a cause–effect relation. I have suggested replicating the IBM memory chip study[2] with biological tissues to see if there is a dose–response relation between chromosomal aberrations and increasing altitude, as an example of the kind of cross disciplinary comparison of notes and collaboration that should take place more often.

With regard to the media websites cited in my paper, it should be quite obvious that I was not endorsing the messages (indeed, I was careful to preface that the headlines were "somewhat sensational") but merely pointing to the fact that in the age of instant information access, aircrew and the travelling public alerted to the possible health hazards will not be easily assuaged by pat answers like "no need to worry—there's no conclusive evidence yet". Concern over cosmic radiation exposure has been around for some time, albeit largely confined to a small circle of experts in aerospace medicine and radiation biology. The internet is fast changing that. Unless the scientific community becomes more media responsive, it will increasingly find itself trailing behind public debate and policy, and as the European Union experience shows, even the legislative process.

Hence, the two pressing issues that need to be addressed are: (1) whether current research directions are adequate; and (2) how to handle the legitimate concerns of aircrew and the travelling public. My own recommendations are: (1) be strategic and pursue lines of inquiry that are likely to intersect and lead to a conclusion; and (2) provide information based on current knowledge so that informed choices can be made.

**M K Lim**

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