



Radiation Dosimetry in Space: A Systematic Review

Peer review status:

No

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Article ID: WMC004578

Article Type: Review articles

Submitted on: 08-Mar-2014, 08:39:00 PM GMT **Published on:** 10-Mar-2014, 05:16:35 AM GMT

Article URL: http://www.webmedcentral.com/article_view/4578

Subject Categories: ENVIRONMENTAL MEDICINE

Keywords: Radiation, dosimetry, space, extraterrestrial

How to cite the article: Reynolds RJ, Delclos GL, Cooper SP, Rahbar MH. Radiation Dosimetry in Space: A Systematic Review. WebmedCentral ENVIRONMENTAL MEDICINE 2014;5(3):WMC004578

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Source(s) of Funding:

No funding.

Competing Interests:

None to declare.

Radiation Dosimetry in Space: A Systematic Review

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Abstract

This article presents the results of a systematic literature review to locate peer-reviewed journal articles that offer equivalent or absorbed radiation dose measurements for locations in outer space.

The review utilized three separate keyword searches, one using MEDLINE and 2 using Google Scholar. The queries returned a total of 3,779 potential source documents, 819 of which were screened for inclusion. The final article set contained 43 articles.

The articles were all in English though they were contributed by authors from 10 different nations. The United States was the most frequent contributor followed by Germany. The articles provided data from every manned US space program except Project Mercury, as well as from 3 Soviet space stations.

The article pool displayed recency in publication, with a majority of the articles published in 1990 or later. It is speculated that this is due to a preference for reporting results in technical reports and conference abstracts in the 1960s and 1970s. The shift from research conducted by contractors to the National Aeronautics and Space Administration (NASA) to partnerships with civilian scientists at universities may be responsible for the increased frequency of publication in peer-reviewed journals.

The collection of articles provides more than 550 dose measurements for spacecraft and extra-vehicular activity in 42 combinations of inclination and altitude in low Earth orbit. The articles also provide 57 measurements for lunar missions. The most often sampled locations were those that had space stations, followed by measurements taken aboard the Gemini capsules and the Space Shuttle fleet.

This review demonstrates that dosimetric data exist in sufficient abundance that they might be further synthesized into useful dose estimation models and tools. Such tools could be of great utility in mission planning and epidemiological studies of the effects of space radiation on human health.

Introduction

Radiation exposure in outer space was identified as a major hazard to human health before the first manned

spacecraft entered orbit in 1961. Ionizing radiation remains the most ubiquitous if not the most serious exposure in spaceflight and has therefore remained of prime concern in mission planning. Ionizing radiation is known to have a number of deleterious effects on the human body, such as development of cancers, cataracts, and even the potential for shortened longevity independent of the development of any specific diseases (1-3).

As an exposure of continual concern in space exploration, ionizing radiation has been measured repeatedly on both manned and unmanned space missions, and in collaboration with scientists from many nations. As a result, there is a large body of peer reviewed literature on radiation dosimetry from numerous extraterrestrial locations, recorded using an array of detection technologies. Taken together, these articles could be of great use in further characterizing the radiation doses space travelers may expect while on missions. However, a systematic literature review approach is needed to efficiently locate relevant articles, select those of high quality, and then catalog and describe the locations for which sufficient data exist to conduct further research on ionizing radiation in space.

The objective of this paper is to describe a systematic review of the peer-reviewed scientific literature concerning dosimetry of various types of ionizing radiation in extraterrestrial environments, and to explicitly identify the extraterrestrial locations for which radiation estimates may be formed. Assessment is made of the availability of data at each of these locations, such as the number of sources and the number of available measurements.

Methods

A computerized database search was conducted by searching for all journal articles reporting radiation dosimetry in extraterrestrial environments. To qualify, an article was required to report either absorbed dose or equivalent dose in a numerical format (rather than just as a figure). The search was restricted to articles published between October 1, 1957 and July 1, 2012. October of 1957 represents the earliest date in which direct measurements of radiation could have been made in extraterrestrial environments since that is when the first artificial satellite, Sputnik 1, was

launched into orbit. Because the United States and the Soviet Union (and now Russia) have been the dominant explorers of outer space, the search was limited to articles in English and Russian languages.

Two electronic databases were queried for the review: MEDLINE and Google Scholar. These sources were selected so as to achieve the best possible coverage from the scientific literature. MEDLINE is an extensive and detailed index of the major medical literature while Google Scholar indexes articles and documents from a wide variety of fields and sources. Pairing these databases gives focused coverage to the medical literature, while simultaneously expanding the search to include alternative sources such as engineering and earth science journals.

The MEDLINE search was limited in date, source, and language as described above. It was also set to retrieve citations in two keyword groupings chosen from the MEDLINE subject headings. The first grouping contained exposure-related keywords: radiation; radiation, ionizing; radiation monitoring; cosmic radiation. A second set of keywords related to location: space; extraterrestrial environment; Earth (planet); Moon. The keywords were joined within groups by the "OR" operator and the two keyword groups were joined with an "AND" operator. As a result of this join strategy, all citations that fit at least one of the keywords in the exposure-related group and at least one of the keywords in the location group were selected.

The first query using Google Scholar searched for citations that contained all of the following keywords: radiation, ionizing, galactic, cosmic, dosimetry. This set was crossed with a set that returned at least one of the words from the following list: moon, space, LEO (short for low-earth orbit), low-earth, orbit, extraterrestrial. To ensure adequate coverage for missions conducted by the US National Aeronautics and Space Administration (NASA) from the 1960s and 1970s, a second search was conducted using Google Scholar which combined the term "dosimetry" with any of the following: Apollo, Gemini, Skylab, or ASTP (short for Apollo-Soyuz Test Project). Even though Project Mercury could have been a source of data in the 1960s, mercury is a chemical element, a standard of measuring barometric pressure, and a standard of measuring comparative temperatures. Searches that included "mercury" as a keyword returned primarily results related to chemical and radiological experiments with elemental mercury. Because of this the term "Mercury" was not included in this second search.

No limitations were placed on either Google Scholar

search as to the citation fields in which keywords could appear, and no citations were excluded based on author name, source, or exclusionary keywords. Like the MEDLINE search, the Google Scholar searches were also restricted to the date range 1957 to 2012. Results in the Google Scholar searches were reviewed in groups of 10 per page until citations became primarily repetitive and/or irrelevant to the search topic.

Once the initial set of citations was formed in each query, the article titles were reviewed for relevance. Any title which explicitly mentioned dosimetry in outer space locations was retained in the collection of articles. Those articles that mentioned radiation issues in space but not dosimetry explicitly were further screened by reading the abstracts. An article in the abstract review stage was retained only if it mentioned dosimetry calculations. Next the retained articles were reviewed in full; those that offered direct measurements of equivalent dose or absorbed dose were retained and omitted were those that offered no equivalent or absorbed dose measurements or presented dose estimates only in graphical form. Omitted articles typically dealt with topics such as characterizing radiation fields without reference to human dose estimation, the reporting of statistical dosimetry models without the presentation of empirically measured data, or the effects of radiation on non-human organisms such as plants or rodents.

Finally, the articles were reviewed by a radiation safety expert, who judged the quality of the articles based on his professional expertise. The expert took into account considerations such as the measurement technique employed (active vs. passive detection), time period of measurements, locations of measurements, dose calculations, and any other technical aspects which may affect the reliability and validity of the measurements. Articles deemed to be of low quality were to be discarded from the article pool and further consideration.

Results

Article Selection

Figure 1 displays the contribution of articles from each query. The MEDLINE search generated 369 potential articles. After screening this set by title and abstract, 55 were retained. After full review, 9 were found to offer dose data in extraterrestrial locations. All 9 articles were reviewed by the expert, and all 9 were judged to be of quality and were retained in the final article set (13, 16, 17, 20, 22, 30-32, 35). The only

article published in Russian was in the set of 55, but was excluded because it could not be obtained from online databases or interlibrary loan services.

The first search of Google Scholar located 1,720 documents and citations. Examining the titles of the first 300 results (30 pages) identified an additional 44 potentially qualifying articles which were not duplicative of those from the MEDLINE search. The search halted at 30 pages because by the 30th page of results the results were largely duplicative. Full review of these 44 led to retention of 28 qualifying journal articles. All of these articles were reviewed by the expert and were retained as high quality articles, bringing the total article set to 37 (7, 10-12, 14, 15, 18, 19, 21, 23-29, 33, 36-41, 43-46).

The second Google Scholar search returned 1,690 results. After examining the first 150 results (15 pages) another 14 distinct relevant journal articles were identified by title. A total of 6 articles were found to be relevant after abstract and full review. All 6 were judged to be of quality and were therefore retained, bringing the article pool to 43 (4-6, 8, 9, 42).

Article Characteristics

Table 1 summarizes key attributes of the final article set. It lists the articles chronologically by year of publication, gives the country of origin for the first author, the measurement method(s) employed in the study (passive, active, or both) and the time period and space craft (or EVA) on which the sampling was performed.

The author origins in the table reveal that there are many authors from the US, though there were contributions by authors from 10 distinct nations. Table 1 also makes evident that there is a variety of spacecraft on which dosimetry measurements have been collected.

Table 2 quantifies some of the article attributes. Scientists from the United States were first authors on 58% of the total article pool. German authors were first authors on 19% of the total, while French and Czech scientists were first authors on 5% each. The remaining contributing countries were Armenia, Austria, Canada, Hungary, Ireland, and Japan, all with 1 article each.

About a third of the articles offered measurements taken on board space shuttles and about a third contained measurements made on Mir. Almost a quarter of the articles (23%) had measurements from the International Space Station (ISS). There were fewer than 10% of the articles offering measurements from Apollo missions, ASTP, Gemini missions, Salyut 6 and Salyut 7 space stations, and Skylab.

Over 40% of the articles reviewed offered measurements made by both passive and active dosimetry. Passive measurements alone were offered in 37% of the articles, and 21% of the articles reviewed used only active methods.

It is apparent from Table 1 that the articles in the set were published between 1968 and 2011. However, Figure 2 reveals that the distribution of articles was not uniform over time: 34 of the 43 (79%) were published in 1990 or later. A single article was published between 1985 and 1989 while 8 articles were published before 1985.

Measurement Locations

Measurements were located for 42 combinations of orbital inclination and apogee altitude, taken on board (or outside of) 8 different models of spacecraft (Table 3). The 51.5° inclination – that of the Salyut 6, Salyut 7, Mir, and ISS space stations – contained both the largest number of articles and the most measurements in the article pool, with 21 articles offering 413 measurements. Measurements taken during Gemini missions were well-represented in general, with 127 measurements taken in 2 distinct inclinations. Finally, a small number of articles reported on data obtained from Apollo capsules in LEO (the Apollo 7 and the ASTP missions) and Skylab. Other orbits visited infrequently by the space shuttle were sparsely represented.

Data were also located for 10 manned Apollo missions outside of LEO as well; these are not reflected in Table 3. In total the review located 3 articles (6, 7, 9) and 69 measurements for the manned Apollo missions.

Discussion

The results of this literature search demonstrate that research into the dosimetry of extraterrestrial radiation is abundant in the peer-reviewed scientific literature. In one sense this is unsurprising as NASA has studied radiation exposures to astronauts since the first suborbital flights of project Mercury. What is surprising is how recent many of the articles are: even after a targeted search for dosimetry studies from missions in the 1960s and 1970s, 79% of the articles reviewed here were published since 1990 and 56% were published since 1999. On the other hand, there were no published articles meeting the eligibility criteria during the first 10 years or so of interest, late 1957 to 1967. This recency does not necessarily imply a lack of research on space radiation during that time but may instead reflect preference for the types of information collected and report and/or the media in

which they were published. In the 1960s and 1970s much of the scientific studies in space were designed by NASA but conducted by contractors. The start of the Space Shuttle missions in the early 1980s marked the beginning of more than 30 years of space exploration focused on civilian science experiments, such as those conducted as part of the Spacelab and the Long Duration Exposure Facility programs. This change alone could explain the sudden increase in peer-reviewed journal publications reporting dosimetric data rather than technical reports or internal NASA memos. Indeed, a search of the NASA Technical Reports Server supports this idea. (47) A simple search for the keyword "dosimetry" returns nearly 900 technical reports published between 1957 and 1979.

While a variety of measurement devices were used in the reviewed articles, the detection of radiation may be divided into one of two broad categories: passive methods or active methods. Passive methods include devices such as thermo-luminescent detectors and plastic nuclear track detectors, while active devices include ionizing chambers and tissue-equivalent proportional counters. Active methods measure and track the instantaneous radiation dose at any given point in time, while passive detectors measure the cumulative dose over the total time they are exposed. These methods complement each other well in an environment such as an orbital spacecraft; the active methods can demonstrate the pattern in radiation exposure across an orbit, while the passive methods show the overall dose over the course of a whole mission. In the collection of articles reviewed here the majority of the studies used either passive methods alone or a combination of passive and active methods. In light of the fact that passive methods are valid and reliable, easy to deploy, and cost-effective, this may explain the frequency of their use. No matter the reason, these data are plentiful and useful.

One limitation of this literature review is the lack of articles published in Russian. The Soviets had a highly developed space program which has been continued by Russia since the dissolution of the Soviet Union in 1991. This program launched dozens of manned missions to LEO (including the very first manned mission), maintained the Salyut series of orbital stations starting in 1971, inhabited the Mir station for 12 years in the 1980s and 1990s, and has been a major partner in the ISS since 1998. Though this review did find sets of measurements from Mir, Salyut 6, and Salyut 7, scientists from Russia and other nations formerly under control of the Soviet Union are likely to have published their own findings on radiation dosimetry during these and other missions.

Unfortunately, those articles published in Russian were not detected in this review unless they also provided an abstract in English and were indexed in one of the databases searched here. Therefore it seems likely that there is a sizable body of such articles written in Russian and published in Russian and/or Eastern European journals which have been omitted from this review. Data from Russian experiments would be a valuable source of dosimetry data, and a good companion to this review would be a survey of the Russian literature.

In total, the available information on radiation dosimetry in space presents scientists with continuing opportunities for extraterrestrial radiation research. Though several models of radiation dosimetry have been built and published in the last 20 years (48-50) capitalizing on the large amounts of available data in the peer-reviewed literature could allow for more and perhaps more robust dosimetry models to be built which integrate data from multiple sources and provide more accurate estimates amounts of various types of radiation absorbed.

The identified body of articles could also enable the development of simpler dose estimation tools such as Task Exposure Matrices (TEMs). TEMs are matrices which provide task-specific exposure estimates for particular activities or locations (51). In the case of a TEM for radiation exposure in outer space, the matrix would provide estimates of the equivalent dose rate in specific orbital locations such as those identified in Table 3. While potentially less precise and less anatomically specific than parametric dosimetry models, these matrices are advantageous in that they allow researchers and flight surgeons to easily estimate historical total equivalent doses based on work history alone. They can also allow mission planners to quickly project future doses based on proposed mission plans. Still another use is in the validation of individual radiation measurements from completed missions. Such tools could enable epidemiological research on the long-term health of space travelers or simplify feasibility analyses in mission planning. The current review of 43 articles shows that dose data are of sufficient quality and available in sufficient quantity to construct an exposure matrix for several extraterrestrial environments.

There is a particular abundance of dose estimates for LEO thanks to numerous radiation measurement experiments conducted over the last 40 years. The articles provide measurements for Skylab, the Space Shuttle fleet, the ISS, Mir, Salyut stations, and some data for estimating EVA exposures. These measurements cover a variety of orbital inclinations

and altitudes, meaning that robust estimates of dose rate could be computed on various levels of detail. Likewise, articles reviewed here offer data from the Apollo missions, both translunar and lunar landing missions. All together these articles could allow for detailed and reasonably accurate estimation of astronaut extraterrestrial radiation exposures to date, and should form the basis for being able to accurately predict future exposures based on a given set of proposed mission parameters (e.g. location, duration, and spacecraft).

It is an exciting time for space exploration and research. The completion of the ISS and the end of the Space Shuttle program signal new directions for NASA and the space agencies of the world. As all eyes turn towards Mars, deep-space expeditions, and a lunar colony, we have an excellent opportunity to reflect on the first 50 years of human space exploration. Further research making full use of existing data can help transform our current space exploration dreams into realities by aiding in a greater understanding of the space radiation environment and the dangers it may pose on long-term missions of exploration and colonization. From this understanding scientists can better plan and prioritize missions, and develop preventative or curative health interventions. Reviews such as this may aid in that process, as assessment and planning are always the first steps.

Acknowledgements

The authors wish to thank Mr. Ricky Crouch for performing the quality review on the radiation dosimetry articles. Mr. Crouch is a Radiation Safety Consultant with Quantum Technical Services in Webster, TX.

References

1. Little MP. Cancer and non-cancer effects in Japanese atomic bomb survivors. *J Radiol Prot* 2009; 29:A43-59.
2. Anderson RE. Longevity in radiated human populations, with particular reference to the atomic bomb survivors. *Am J Med* 1973; 55:643-56.
3. Todd P. Space radiation health: A brief primer. *Gravit Space Biol Bull* 2003; 16:1-4.
4. Warren CS, Lill JC, Richmond RG, Davis WG. Radiation dosimetry on the Gemini and Apollo missions. *J Spacecraft* 1968; 5:207-10.
5. Janni, J. Spacecraft cabin radiation distributions for the fourth and sixth Gemini flights. *Aerosp Med* 1969; 40:1527-35.
6. Richmond R. A review of Gemini and Apollo astronaut dosimetry data. *Aerosp Med* 1969; 40:1517-27.
7. Schaefer HJ, Benton EV, Henke RP, Sullivan JJ. Nuclear track recordings of the astronauts' radiation exposure on the first lunar landing mission Apollo XI. *Radiat Res* 1972; 49:245-71.
8. Bailey, JV. Dosimetry during space missions. *IEEE Trans Nucl Sci* 1976; NS-23:1379-84.
9. Benton EV. Dosimetric radiation measurements in space. *Nucl Tracks* 1983; 7:1-11.
10. Benton EV. Summary of current radiation dosimetry results on manned spacecraft. *Adv Space Res* 1984; 4:153-60.
11. Benton EV, Almasi J, Cassou R, Frank A, Henke RP, Rowe V, Parnell TA, Schopper E. Radiation measurements aboard Spacelab 1. *Science* 1984; 225:224-6.
12. Benton EV. Summary of current radiation dosimetry results on US and Soviet manned spacecraft. *Adv Space Res* 1986; 6:315-28.
13. Bouisset P, Nguyen VD, Akatov YA, Siegrist M, Parmentier N, Archangelsky VV, et al. Quality factor and dose equivalent investigations aboard the Soviet space station MIR. *Adv Space Res* 1992; 12:363-7.
14. Reitz G, Beaujean R, Heckeley N, Obe G. Dosimetry in the space radiation field. *J of Mol Med* 1993; 71:710-17.
15. Golightly MJ, Hardy AC, Hardy K. Results of time-resolved radiation exposure measurements made during U.S. Shuttle missions with a tissue equivalent proportional counter. *Adv Space Res* 1994; 14:923-6.
16. Golightly MJ, Hardy K, Quam W. Radiation dosimetry measurements during U.S. Space Shuttle missions with the RME-III. *Rad Meas* 1994; 23:25-42.
17. Frank AL, Benton EV, Armstrong TW, Colborn BL. Neutron fluences and dose equivalents measured with passive detectors on LDEF. *Rad Meas* 1996; 26:833-9.
18. Reitz G, Beaujean R, Heilmann C, Kopp J, Leicher M, Strauch K. Dosimetry on the Spacelab missions IML1 and IML2, and D2 and on MIR. *Rad Meas* 1996; 26:979-86.
19. Badhwar GD, Atwell W, Cash B, Petrov VM, Akatov YA, Tchernykh IV, et al. Radiation environment on the Mir orbital station during solar minimum. *Adv Space Res* 1998; 22:501-10.
20. Reitz G, Beaujean R, Heilmann C, Kopp J, Leicher M, Strauch K. Results of dosimetric measurements in space missions. *Adv Space Res* 1998; 22:495-500.
21. Beaujean R, Kopp J, Reitz G. Active Dosimetry on Recent Space Flights. *Radiat Protect Dosimetry* 1999; 85:223-6.
22. Thomson I. EVA dosimetry in manned spacecraft.

- Mutat Res 1999; 430:203-9.
23. Cucinotta FA, Wilson JW, Williams JR, Dicello JF. Analysis of MIR-18 results for physical and biological dosimetry: radiation shielding effectiveness in LEO. *Radiat Meas* 2000; 32:181-191.
 24. Benton ER, Benton EV. Space radiation dosimetry in low-Earth orbit and beyond. *Nucl Instrum Methods Phys Res B* 2001; 184:255-94.
 25. Doke T, Hayashi T, Kikuchi J, Sakaguchi T, Terasawa K, Yoshihira E, et al. Measurements of LET-distribution, dose equivalent and quality factor with the RRMD-III on the Space Shuttle Missions STS-84, -89 and -91. *Radiat Meas* 2001; 33:373-387.
 26. Apáthy I, Deme S, Feher I, Akatov YA, Reitz G, Arkhanguelski VV. Dose measurements in space by the Hungarian Pille TLD system. *Rad Meas* 2002; 35:381-91.
 27. Badhwar GD. Shuttle Radiation Dose Measurements in the International Space Station Orbits. *Radiat Res* 2002; 157:69-75.
 28. Badhwar GD, Atwell W, Badavi WW, Yang TC, Cleghorn TF. Space Radiation Absorbed Dose Distribution in a Human Phantom. *Adv Space Res* 2002; 157:76-91.
 29. Badhwar GD, Atwell W, Reitz G, Beaujean R, Heinrich W. Radiation measurements on the Mir Orbital Station. *Radiat Meas* 2002; 35:393-422
 30. Beaujean R, Kopp J, Burmeister S, Petersen F, Reitz G. Dosimetry inside MIR station using a silicon detector telescope (DOSTEL). *Radiat Meas* 2002; 35:433-8.
 31. Benton ER, Benton EV, Frank AL. Passive dosimetry aboard the Mir Orbital Station: external measurements. *Radiat Meas* 2002; 35:457-71.
 32. Benton ER, Benton EV, Frank AL. Passive dosimetry aboard the Mir Orbital Station: internal measurements. *Radiat Meas* 2002; 35:439-55.
 33. Bottollier-Depois JF, Siegrist M, Petrov VM, Shurshakov VV, Bengin V, Koslova SB. TEPC measurements obtained on the Mir space station. *Radiat Meas* 2002; 35:485-8.
 34. Berger T, Hajek M, Summerer L, Vana N, Akatov Y, Shurshakov V, Arkhangel'sky V. Austrian dose measurements onboard space station MIR and the International Space Station – overview and comparison. *Adv Space Res* 2004; 34:1414-19.
 35. Akopova AB, Manaseryan MM, Melkonyan AA, Tatikyan SS, Potapov Y. Radiation measurement on the International Space Station. *Radiat Meas* 2005; 39:225-8.
 36. Reitz G, Beaujean R, Benton E, Burmeister S, Dachev T, Deme S, et al. Space radiation measurements on-board ISS—the DOSMAP experiment. *Radiat Prot Dosimetry* 2005; 116:374-9.
 37. Spurny F, Jadrnickova I. Some recent measurements onboard spacecraft with passive detector. *Radiat Prot Dosimetry* 2005; 116:228-31.
 38. Zhou D, O'Sullivan D, Semones E, Heinrich W. Radiation field of cosmic rays measured in low Earth orbit by CR-39 detectors. *Adv Space Res* 2006; 37:1764-69.
 39. Zhou D, Semones E, Gaza R, Johnson S, Zapp N, Weyland M. Radiation measured for ISS-Expedition 12 with different dosimeters. *Nucl Instrum Methods Phys Res A* 2007; 580:1283-9.
 40. Zhou D, Semones E, Gaza R, Weyland M. Radiation measured with passive dosimeters in low Earth orbit. *Adv Space Res* 2007; 40:1575-9.
 41. Berger T. Radiation dosimetry onboard the International Space Station ISS. *Z Med Phys* 2008; 18:265-75.
 42. Cucinotta FA, Kim MY, Willingham V, George KA. Physical and biological organ dosimetry analysis for international space station astronauts. *Radiat Res* 2008; 170:127-38.
 43. Reitz G, Berger T, Bilski P, Facius R, Hajek M, Petrov V, et al. Astronaut's Organ Doses Inferred from Measurements in a Human Phantom Outside the International Space Station. *Radiat Res* 2009; 171:225-35.
 44. Zhou D, Semones E, Gaza R, Johnson S, Zapp N, Lee K, et al. Radiation measured during ISS-Expedition 13 with different dosimeters. *Adv Space Res* 2009; 43:1212-19.
 45. Zhou D, Semones E, Gaza R, Johnson S, Zapp N, Weyland M, et al. Radiation measured with different dosimeters during STS-121 space mission. *Acta Astron* 2009; 64:437-47.
 46. Ambrozova I, Brabcova K, Spurny F, Shurshakov VA, Kartsev IS, Tolochev RV. Monitoring on board spacecraft by means of passive detectors. *Radiat Prot Dosimetry* 2011; 144:605-10.
 47. NASA technical report server [Internet]: United States, National Aeronautics and Space Administration; downloaded February 11, 2013. Available from: <http://ntrs.nasa.gov>.
 48. Cucinotta FA, Wu H, Shavers MR, George K. Radiation dosimetry and biophysical models of space radiation effects. *Gravit Space Biol Bull* 2003; 16:11-8.
 49. De Angelis G, Anderson BM, Atwell W, Nealy JE, Qualls GD, Wilson JW. Astronaut EVA exposure estimates from CAD model spacesuit geometry. *J Radiat Res* 2004; 45:1-9.
 50. Smart DF, Shea MA, Golightly MJ, Weyland M, Johnson AS. Evaluation of the dynamic cutoff rigidity model using dosimetry data from the STS-28 flight. *Adv Space Res*. 2003; 31:841-6.
 51. Benke G, Sim M, Lin F, Aldred G. Beyond the Job

Exposure Matrix (JEM): the Task Exposure Matrix (TEM). *Ann of Occup Hyg* 2000; 44:475-82.

Illustrations

Illustration 1

Figure 1: Article Selection Process

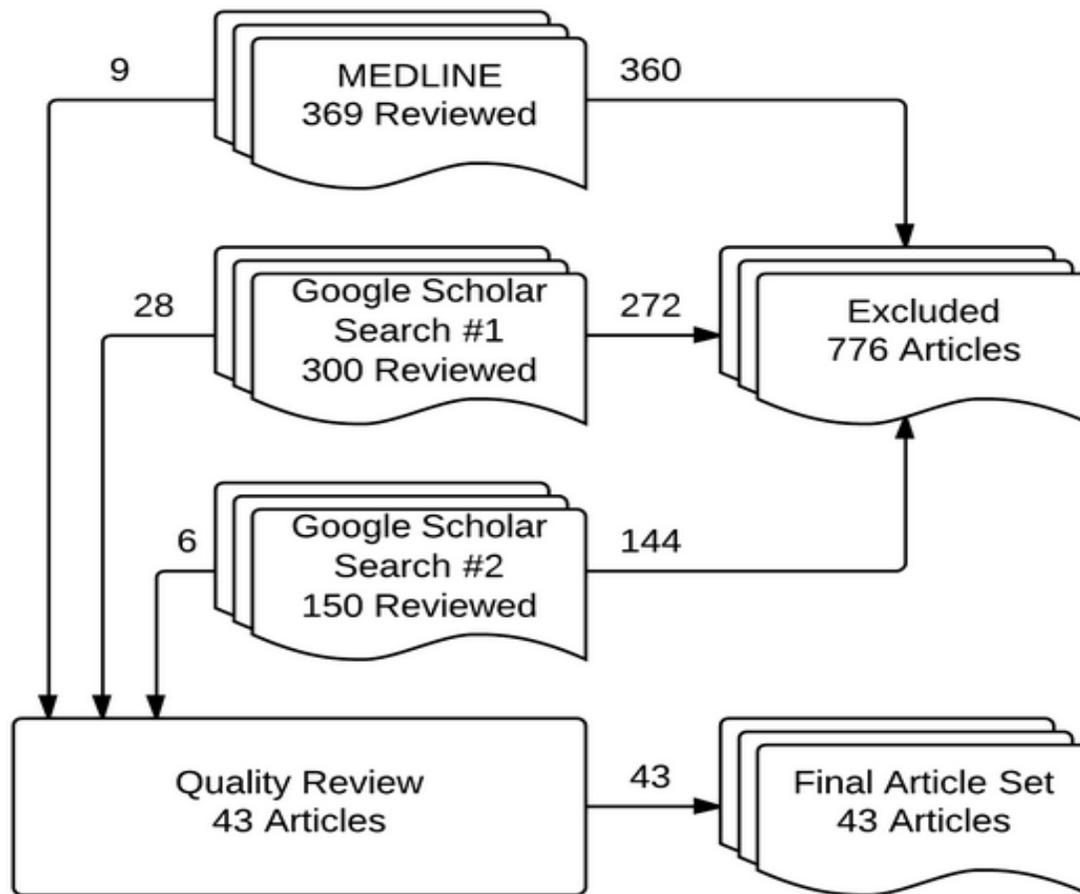


Illustration 2

Table 1: Characteristics of the 43 included articles, ordered by publication date

Article	Country ¹	Measurement Characteristics		
		Method ²	Sample Period	Spacecraft
Warren <i>et al.</i> , 1968 (4)	USA	P	1965-1966	Gemini
Janni, 1969 (5)	USA	A, P	1965	Gemini
Richmond, 1969 (6)	USA	A, P	1965-1969	Gemini and Apollo
Schaefer <i>et al.</i> , 1972 (7)	USA	P	1969	Apollo
Bailey, 1976 (8)	USA	A, P	1968-75	Skylab
Benton, 1983 (9)	USA	A, P	1961-1982	Gemini, Apollo, Skylab, ASTP, STS
Benton, 1984 (10)	USA	A, P	1981-1984	STS
Benton <i>et al.</i> , 1984 (11)	USA	P	1983	STS
Benton, 1986 (12)	USA	A, P	1981-1985	STS
Bouisset <i>et al.</i> , 1992 (13)	France	A	1989	Mir
Reitz <i>et al.</i> , 1993 (14)	Germany	P	1992	Mir
Golightly <i>et al.</i> , 1994 (15)	USA	A	1988-1990	STS
Golightly <i>et al.</i> , 1994 (16)	USA	A	1988-1990	STS
Frank <i>et al.</i> , 1996 (17)	USA	P	1984-1990	EVA
Reitz <i>et al.</i> , 1996 (18)	Germany	A, P	1983, 1985, 1992, 1994, 1996	Mir
Badhwar <i>et al.</i> , 1998 (19)	USA	A, P	1995	Mir
Reitz <i>et al.</i> , 1998 (20)	Germany	A, P	1983, 1985, 1992, 1994	Mir, STS

Article	Country ¹	Measurement Characteristics		
		Method ²	Sample Period	Spacecraft
Beaujean <i>et al.</i> , 1999 (21)	Germany	A	1996, 1997	STS
Thomson, 1999 (22)	Canada	A, P	1992-1993	EVA
Cucinotta, 2000 (23)	USA	A	1995	Mir
Benton and Benton, 2001 (24)	USA	A, P	Various (review)	Mir
Doke <i>et al.</i> , 2001 (25)	Japan	A	1997, 1998	STS
Apáthy <i>et al.</i> , 2002 (26)	Hungary	P	1980, 1983, 1987, 1995-1997	Salyut 6/7, Mir, EVA
Badhwar <i>et al.</i> , 2002 (27)	USA	P	1998	STS
Badhwar <i>et al.</i> , 2002 (28)	USA	A, P	1986-1998	STS
Badhwar, 2002 (29)	USA	A	1995, 1998, 1999, 2000	Mir
Beaujean <i>et al.</i> , 2002 (30)	Germany	A	1997-1998	Mir, STS
Benton <i>et al.</i> , 2002 (31)	USA	P	1991, 1997	EVA
Benton <i>et al.</i> , 2002 (32)	USA	P	1991, 1995, 1996-1997	Mir
Bottollier-Depois <i>et al.</i> , 2002 (33)	France	A	1992	Mir
Berger <i>et al.</i> , 2004 (34)	Austria	P	1997-1999	Mir, ISS
Akopova <i>et al.</i> , 2005 (35)	Armenia	P	Before 2004	ISS
Reitz <i>et al.</i> , 2005 (36)	Germany	A, P	2001	ISS
Spurny and Jadrnickova, 2005 (37)	Czech Rep.	P	1998-2003	ISS, Mir

Article	Country ¹	Measurement Characteristics		
		Method ²	Sample Period	Spacecraft
Zhou <i>et al.</i> , 2006 (38)	Ireland	P	2001-2003	ISS, STS
Zhou <i>et al.</i> , 2007 (39)	USA	A, P	2005-2006	ISS
Zhou <i>et al.</i> , 2007 (40)	USA	P	2005	STS
Berger, 2008 (41)	Germany	A, P	2001	ISS
Cucinotta, 2008 (42)	USA	P	2000-2006	ISS, STS
Reitz <i>et al.</i> , 2009 (43)	Germany	A, P	2004-2005	EVA
Zhou <i>et al.</i> , 2009 (44)	USA	A, P	2006	ISS
Zhou <i>et al.</i> , 2009 (45)	USA	A, P	2006	STS
Ambrozova <i>et al.</i> , 2011 (46)	Czech Rep.	P	2005-2009	ISS

¹Country of origin for first author

²Method of detection: A = Active; P = Passive

Illustration 3

Figure 2: Number of articles selected by period.

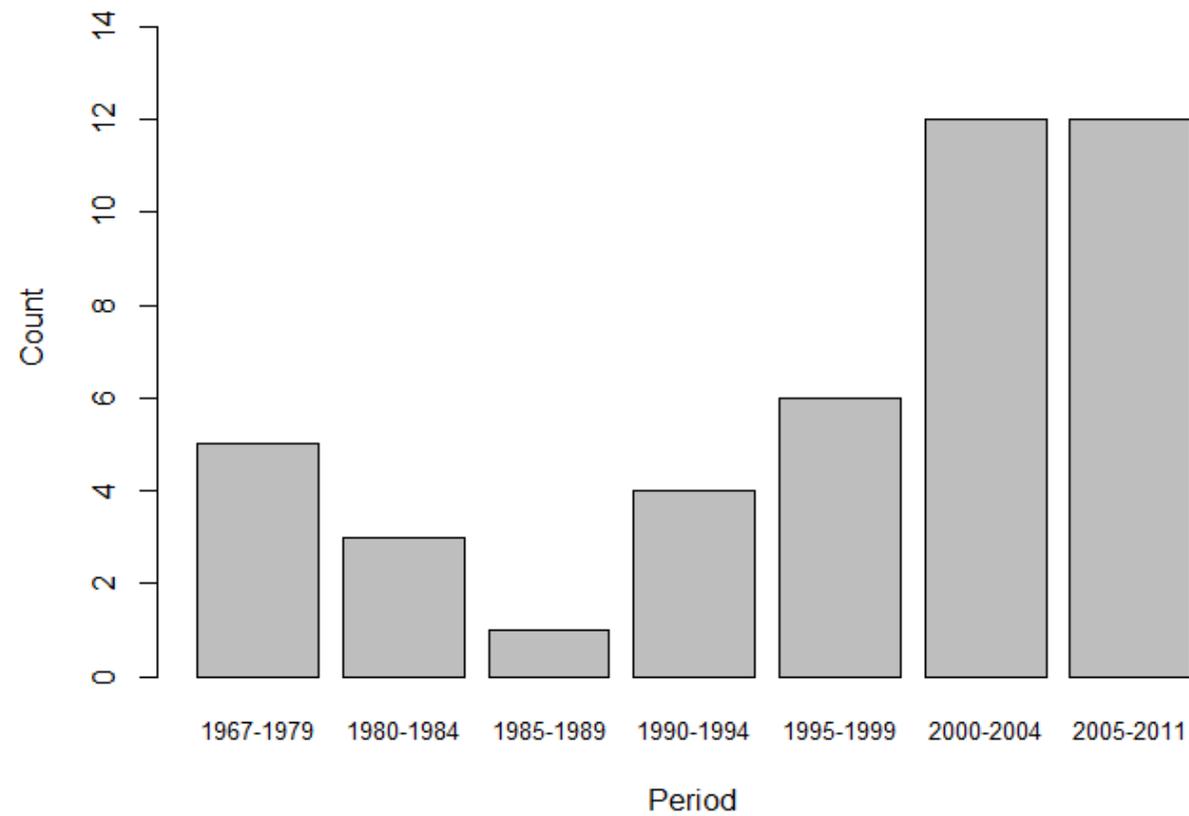


Illustration 4

Table 2: Key article characteristics

Characteristic	n	(%)
National Origin ¹		
United States	25	(58.1)
Germany	8	(18.6)
France	2	(4.7)
Czech Republic	2	(4.7)
All others	6	(14.0)
Data Sources ²		
Apollo	3	(7.0)
ASTP	1	(2.3)
Gemini	4	(9.3)
ISS	10	(23.3)
Mir	14	(32.6)
Salyut 6	1	(2.3)
Salyut 7	1	(2.3)
Skylab	2	(4.7)
STS/Space Shuttle	15	(34.9)
Detection type		
Active only	9	(20.9)
Passive only	16	(37.2)
Both active and passive	18	(41.9)

¹Origin of first author only

²Totals here sum to more than 43 and more than 100% as some articles present data from multiple missions

Illustration 5

Table 3: Low-Earth Orbit locations with radiation measurements in the peer-reviewed literature

Inclination ¹	Apogee Altitudes (km) ²	Spacecraft Types ³	Articles	Obs.
28.5°	190, 300, 330, 340, 345, 350, 365, 410, 520, 540, 610	Space Shuttle	3	15
29.0°	215, 260, 270, 280, 300, 310	Gemini Capsule	3	70
31.5°	300	Apollo Capsule	2	11
32.5°	225, 280, 350	Gemini Capsule	3	57
38.0°	230, 250	Space Shuttle	2	4
40.0°	275	Space Shuttle	1	1
50.0°	440	Skylab	2	30
51.5°	225, 275, 300, 320, 330, 375, 390, 395, 425	Space Shuttle, Mir, ISS, EVA Salyut 6, Salyut 7	21	413
52.0°	231	Apollo Capsule	1	1
57.0°	180, 300, 400, 450, 460	Space Shuttle	3	6
62.0°	240, 250	Space Shuttle	2	2
		TOTAL	--	610

¹ Orbital inclination rounded to nearest 0.5°

² Apogee altitude rounded to nearest 5 km

³ ISS = International Space Station; EVA = Extravehicular Activity