Space Radiation Protection: Comparison of Effective Dose to Bone Marrow Dose Equivalent

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Effective dose / Solar particle events / Galactic cosmic rays

In many instances, bone marrow dose equivalents averaged over the entire body have been used as a surrogate for whole-body dose equivalents in space radiation protection studies. However, career radiation limits for space missions are expressed as effective doses. This study compares calculations of effective doses to average bone marrow dose equivalents for several large solar particle events (SPEs) and annual galactic cosmic ray (GCR) spectra, in order to examine the suitability of substituting bone marrow dose equivalents for effective doses. Organ dose equivalents are computed for all radiosensitive organs listed in NCRP Report 116 using the BRYNTRN and HZETRN space radiation transport codes and the Computerized Anatomical Man (CAM) model. These organ dose equivalents are then weighted with the appropriate tissue weighting factors to obtain effective doses. Various thicknesses of aluminum shielding, which are representative of nominal spacecraft and SPE storm shelter configurations, are used in the analyses. For all SPE configurations, the average bone marrow dose equivalent is considerably less than the calculated effective dose. For comparisons of the GCR, there is less than a ten percent difference between the two methods. In all cases, the gonads made up the largest percentage of the effective dose.

INTRODUCTION

Risks to flight crews from energetic solar particle events (SPEs) and galactic cosmic rays (GCR) are a major concern when planning for long-duration manned missions. Bone marrow dose equivalents are frequently used to represent whole-body dose equivalents; however, career space radiation limits require the use of effective doses. During the events during the latter part of 1989, the average bone marrow dose equivalent ranged from 0.12 to 43.7 cGy\(^{1}\). Based on these results, career limits\(^2\) would not have been exceeded. However, since the limits are not based on average bone marrow dose equivalent, it is important to calculate effective dose to determine if the limits would have actually been exceeded. The relevance of this work is not only important for flight crews in space but also for airline flight crews who come into contact with cosmic radiation while working during long international flights\(^3\).

In this work, the average bone marrow dose equivalent and the radiosensitive organ dose equivalents are estimated through the use of the BRYNTRN\(^4\) and HZETRN\(^5\) space radiation transport codes and the computerized anatomical man (CAM) model\(^6\). These estimates are for several large SPEs and several annual GCR spectra from throughout the space era. These specific SPEs and GCR are selected because previous analyses indicate that they are representative of high dose and dose equivalent events for manned interplanetary missions\(^1,7,8\). In this analysis, various thicknesses of aluminum shielding, which are representative of nominal spacesuit, spacecraft and SPE “storm shelter” designs, are looked at for each organ.

MATERIALS AND METHODS

Transport Calculations

The calculations for bone marrow dose equivalents and radiosensitive organ dose equivalents are made using the space radiation transport computer codes, BRYNTRN and HZETRN, and a realistic, detailed CAM model to represent the actual organ distributions.
The BRYNTRN computer code transports incident protons and their reaction secondaries (protons, neutrons, 3H, 3He and 4He) through aluminum shield material and then through an additional quantity of water. In the same way, the HZETRN computer code transports incident heavy ions (from protons through nickel) and their reactions secondaries. This additional quantity of water is assumed to be equivalent to soft tissue. The thicknesses of aluminum shielding are 1, 2, 5 and 10 g/cm², which are representative of a spacesuit, a thin spacecraft, a nominal spacecraft and a SPE “storm shelter,” respectively.

The calculated dose equivalents as a function of water depth, at the conclusion of each event, are then folded with the body organ self-shielding depth distributions computed from the CAM model to yield dose equivalent estimates for each organ location. The CAM model is based on a 50th percentile United States Air Force male. The model includes material densities of organs, bones and other body constituents encountered by a particle as it traverses one of the 512 rays, covering the entire 4 solid angle about the organ site. In the version of the CAM model used for this analysis, the average bone marrow distribution is one that is an average of 33 different site distributions.

Effective Dose

The effective dose is calculated by summing the dose equivalent for each of the radiosensitive organs given in NCRP Report 116, which has been multiplied by the appropriate tissue weighting factor given in the same report. The dose equivalent is determined at the center of mass of the organ of interest. Of the organs given in the report, a few had some restraints placed on them in order to simplify the transport code calculations. The bone surface is limited to one point on the surface of the pelvic bone. The skin is an average of 32 different site distributions. The breast is a single point in the muscle of the upper chest. As stated in the previous section, the bone marrow is an average of 33 different site distributions. The adrenal gland is a point directly above the kidney. The small and large intestine are combined under one point because the CAM model does not distinguish between the two organs. The muscle is a point in the upper leg since this muscle is one of the largest in the body. The thymus is neglected because it atrophies after puberty and is subsequently replaced by fatty tissue. The uterus is also neglected because this study focuses only on the male anatomy.

SPEs and GCR

The solar particle events included in this study are historically some of the largest that have been analyzed. Included are the February 1956 SPE, which had the hardest spectrum, the November 1960 SPE, which had the largest alpha component, the August 1972 SPE, which provided the largest dose, the October 1989 SPE, which had the largest fluence of particles, and two of the recent SPEs (July 2000 and November 2001). The GCR spectra included in this study are representative of both solar minimum and solar maximum periods. Those chosen are the 1970–1971 and 1989 solar maximum periods and the 1977 and 1986–1987 solar minimum periods. Of the spectra chosen, the 1977 spectra had the maximum GCR activity.

RESULTS AND DISCUSSION

The results of this analysis are given in Table 1. For each separately listed event, the following results are given: Al – the aluminum shield thickness (g/cm²), E – the effective dose (cSv), E* – the effective dose without the gonads contributions (cSv), H – the average bone marrow dose equivalent (cSv), 5-cm – the dose equivalent at 5-cm depth in water (cSv) and % – the percent difference between E and H, which is equal to (E-H)/H. The 5-cm depth dose equivalent corresponds to an approximation often used in space radiation protection to estimate bone marrow dose equivalents.

When looking at each event, it can be seen that the average bone marrow dose equivalent is quite different from the effective dose. In all cases, the average bone marrow dose equivalent is less than the effective dose. As can be seen from the table, all of the SPEs, except the February 1956 event, have large percentage differences, especially for the 1.2 and 5 g/cm² aluminum shield thicknesses. The gonads make up an extremely large fraction of the effective dose. By not including this contribution, the effective dose is much closer to the average bone marrow dose equivalent.

The new space radiation career limits, based on a lifetime excess risk of cancer mortality of three percent, range from 50 to 300 cSv for the bone marrow depending on age at first exposure and sex. Although they are strictly to be used for low-Earth orbit missions, they are useful as a benchmark for this study. Based on the effective dose calculations, almost all of the SPEs, especially behind 1 and 2
COMPARISON OF EFF. DOSE TO BFO DOSE EQ.

Table 1. Effective Dose and Dose Equivalent Summary – Al (aluminum shield thickness in g/cm²), E (effective dose in cSv), E* (effective dose without gonads in cSv), H (average bone marrow dose equivalent in cSv), 5-cm (5-cm depth dose equivalent in water in cSv), % (percent difference between E and H, which is equal to (E-H)/H).

| February 1956:       | November 1960:       |
|----------------------|----------------------|
| Al       | E       | E*      | H       | 5-cm | %       | Al       | E       | E*      | H       | 5-cm | %       |
| 1        | 67.5    | 41.4    | 46.6    | 76.0  | 44.9  | 1        | 124.9   | 55.0    | 52.0    | 112.6 | 140.2  |
| 2        | 55.8    | 37.7    | 44.1    | 68.3  | 26.6  | 2        | 75.1    | 43.2    | 47.0    | 99.3  | 60.0   |
| 5        | 43.2    | 32.4    | 39.3    | 54.6  | 9.9   | 5        | 44.2    | 31.3    | 36.8    | 73.3  | 20.2   |
| 10       | 36.1    | 28.2    | 34.9    | 44.4  | 3.6   | 10       | 29.7    | 22.1    | 26.5    | 49.6  | 12.1   |

| August 1972:        | October 1989:        |
|---------------------|----------------------|
| Al       | E       | E*      | H       | 5-cm | %       | Al       | E       | E*      | H       | 5-cm | %       |
| 1        | 337.5   | 130.7   | 111.0   | 337.2 | 203.9 | 1        | 192.8   | 78.2    | 68.9    | 204.7 | 179.7  |
| 2        | 200.2   | 94.2    | 91.3    | 271.0 | 119.3 | 2        | 118.5   | 57.8    | 57.3    | 166.1 | 106.9  |
| 5        | 88.5    | 51.9    | 56.3    | 155.3 | 57.3  | 5        | 55.2    | 33.1    | 36.3    | 97.6  | 52.2   |
| 10       | 40.2    | 26.7    | 30.5    | 75.3  | 31.7  | 10       | 26.2    | 17.7    | 20.3    | 48.9  | 29.2   |

| July 2000:          | November 2001:       |
|---------------------|----------------------|
| Al       | E       | E*      | H       | 5-cm | %       | Al       | E       | E*      | H       | 5-cm | %       |
| 1        | 170.6   | 52.9    | 35.9    | 118.1 | 375.3 | 1        | 133.5   | 36.7    | 20.9    | 70.5  | 538.4  |
| 2        | 83.8    | 32.7    | 27.8    | 90.4  | 201.5 | 2        | 58.0    | 20.3    | 15.6    | 52.3  | 272.6  |
| 5        | 28.0    | 14.5    | 14.9    | 45.7  | 88.3  | 5        | 16.2    | 7.8     | 7.6     | 24.5  | 112.3  |
| 10       | 10.0    | 6.2     | 6.9     | 18.9  | 45.5  | 10       | 5.0     | 3.0     | 3.2     | 9.2   | 54.7   |

| 1970–71 Solar Maximum: | 1977 Solar Minimum: |
|------------------------|---------------------|
| Al         | E       | E*      | H       | 5-cm | %       | Al         | E       | E*      | H       | 5-cm | %       |
| 1          | 17.9    | 13.7    | 16.7    | 26.1  | 7.7   | 1          | 48.8    | 36.8    | 44.5    | 72.0  | 9.6    |
| 2          | 17.6    | 13.4    | 16.4    | 25.4  | 7.6   | 2          | 47.3    | 35.8    | 43.4    | 69.0  | 9.1    |
| 5          | 16.7    | 12.8    | 15.6    | 23.4  | 6.9   | 5          | 43.7    | 33.3    | 40.5    | 61.6  | 7.8    |
| 10         | 15.4    | 11.9    | 14.6    | 20.7  | 5.8   | 10         | 39.3    | 30.3    | 37.1    | 52.6  | 6.1    |

| 1986–87 Solar Minimum: | 1989 Solar Maximum: |
|------------------------|---------------------|
| Al         | E       | E*      | H       | 5-cm | %       | Al         | E       | E*      | H       | 5-cm | %       |
| 1          | 48.8    | 36.8    | 44.5    | 72.0  | 9.6   | 1          | 13.9    | 10.6    | 12.9    | 20.2  | 7.4    |
| 2          | 47.3    | 35.8    | 43.4    | 69.0  | 9.1   | 2          | 13.7    | 10.5    | 12.7    | 19.6  | 7.3    |
| 5          | 43.7    | 33.3    | 40.5    | 61.6  | 7.8   | 5          | 13.0    | 10.0    | 12.2    | 18.2  | 6.7    |
| 10         | 39.3    | 30.3    | 37.1    | 52.6  | 6.1   | 10         | 12.1    | 9.3     | 11.4    | 16.3  | 5.8    |

g/cm² aluminum shielding, would reach or exceed the career limits. However, based on the average bone marrow dose equivalent, most would not exceed the limits. For all of the GCR spectra, whether effective dose or average bone marrow dose equivalent is used, these limits would not be exceeded.

The other result of interest is the difference between the 5-cm depth dose equivalent and either the effective dose or the average bone marrow dose equivalent. In all cases, there is a large discrepancy between the results with the 5-cm depth dose equivalent and the average bone marrow dose equivalent. As can be seen from the table, the 5-cm depth dose equivalent is often much closer or even larger than the effective dose. Although the average bone marrow dose equivalent is smaller than the 5-cm depth dose equivalent, it is much more realistic since it incorporates many points rather than just one and includes body organ self-shielding effects from the CAM model.
CONCLUSIONS

As can be seen from the results, there is a substantial difference between the average bone marrow dose equivalent and the effective dose. For every spectrum included in this study, the calculated average bone marrow dose equivalent is smaller than the effective dose. However, in every case, the dose equivalent contribution to the gonads makes up a significant portion of the effective dose. For all of the SPEs, except for the February 1956 SPE, there is an extremely large difference between the effective dose and the average bone marrow dose equivalent. This is especially noticeable for the 1, 2 and 5 g/cm² Al shielding thicknesses. For the annual GCR spectra considered, there is a less than ten percent difference between the two methods for all of the shielding cases. This study shows the necessity of calculating the effective dose rather than relying only on the average bone marrow dose equivalent when comparing with limits and estimating shielding requirements for space missions.

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