NASA Technical Memorandum 102164

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ABSTRACT

Radiation protection standards for space activities differ substantially from those applied to terrestrial working situations. The levels of radiation and subsequent hazards to which space workers are exposed are quite unlike anything found on earth. In view of these considerations, NASA has adopted a more highly refined system of risk management than that conventionally applied to radiation workers. The refined system involves assessing the risks to each space worker from all sources of radiation (occupational and non-occupational) at the organ level. In this study we applied risk coefficients in the National Council on Radiation Protection and Measurements (NCRP) Report 98, to previous space and medical exposures in order to estimate the radiation-induced lifetime cancer incidence and mortality risks to 19 representative space workers. Results indicate a per capita (n=19) radiation-induced cancer incidence risk from space activities, diagnostic X-ray, and nuclear medicine procedures of 3.1 x 10^{-5}, 37.9 x 10^{-5}, and 6.8 x 10^{-5}, respectively. For radiation-induced cancer mortality, the per capita risks were 2.1 x 10^{-5}, 22.7 x 10^{-5}, and 4.9 x 10^{-5}, respectively. At present, the risk from medical procedures when compared to space activities is 14 times higher for cancer incidence and 13 times higher for cancer mortality; however, this will change as the per capita dose during Space Station Freedom and interplanetary missions increases and more is known about the risks from exposure to high-LET radiation. The per capita effective dose equivalents (H_E) from space activities, diagnostic X-ray, and nuclear medicine procedures were 1.51 mSv (151 mrem), 15.9 mSv (1590 mrem), and 3.6 mSv (360 mrem). Mortality estimates based on risk coefficients in Publication 26 of the International Commission on Radiological Protection (ICRP) underestimated NCRP-based mortality estimates from space activities and diagnostic X-ray by 17% and 28%, respectively, and overestimated mortality risk from nuclear medicine procedures by 3%. Two units, the Incidence Risk Unit (IRU x 10^{-5}) and the Mortality Risk Unit (MRU x 10^{-5}) for radiation protection, are introduced.

INTRODUCTION

Radiation protection standards for space activities are very different form those applied to terrestrial situations. The levels and mixed fields of radiations to which astronauts are exposed are unlike anything found on earth. During low-earth orbit (LEO) missions, such as those previously flown by Mercury, Gemini, and those currently flown by Shuttle, geomagnetically trapped protons with energies on the order of 30 to 500 MeV are of interest. For exploratory class missions, such as the lunar missions of Apollo and future missions to Mars, interest is directed toward galactic cosmic rays (GCR) whose energies range from 30 MeV to 10 GeV. In addition, there is the potential for large solar particle events, during which a large plasma of protons and helium ions is ejected into the near-earth vicinity. Each mission scenario is characterized by a unique level and mixture of radiations. Figure 1 shows an outline of the particulate space radiation environment characterizing the flux and energy of particles. Perhaps as equally important as the above radiations are the secondary particles produced from their interactions with spacecraft materials and body tissues.

Traditionally, the system of dose limitations introduced by the International Commission on Radiological Protection (ICRP) has been a convenient method for limiting the risks to which radiation workers are exposed (1). A fundamental principle on which this system is based is that risk is directly proportional to effective dose equivalent (H_E). As such, H_E serves as a surrogate for risk. We shall not be concerned with this type of approach, but rather one in which individual risks are limited by actual estimates of lifetime risk based on organ doses and the most complete age-, sex-, and site-specific lifetime risk information. In recent years a similar approach has received particular attention, the most notable of which was the development of radioepidemiological tables for use in determining the probability of causation (PC) (2). The PC is defined as the probability that a given dose of radiation will cause cancer at a given age following exposure.

The National Council on Radiation Protection and Measurements (NCRP) in its Report 98 has recommended that NASA adopt a system of risk limitations that is based on a radiation-induced lifetime mortality risk of 3% from occupational radiation exposure (3). The recommended career limits take into account the sex of each individual and their age at first flight. Figure 2 shows the career limit (Sv) as a function of age at first flight for males and females. Also given in Report 98

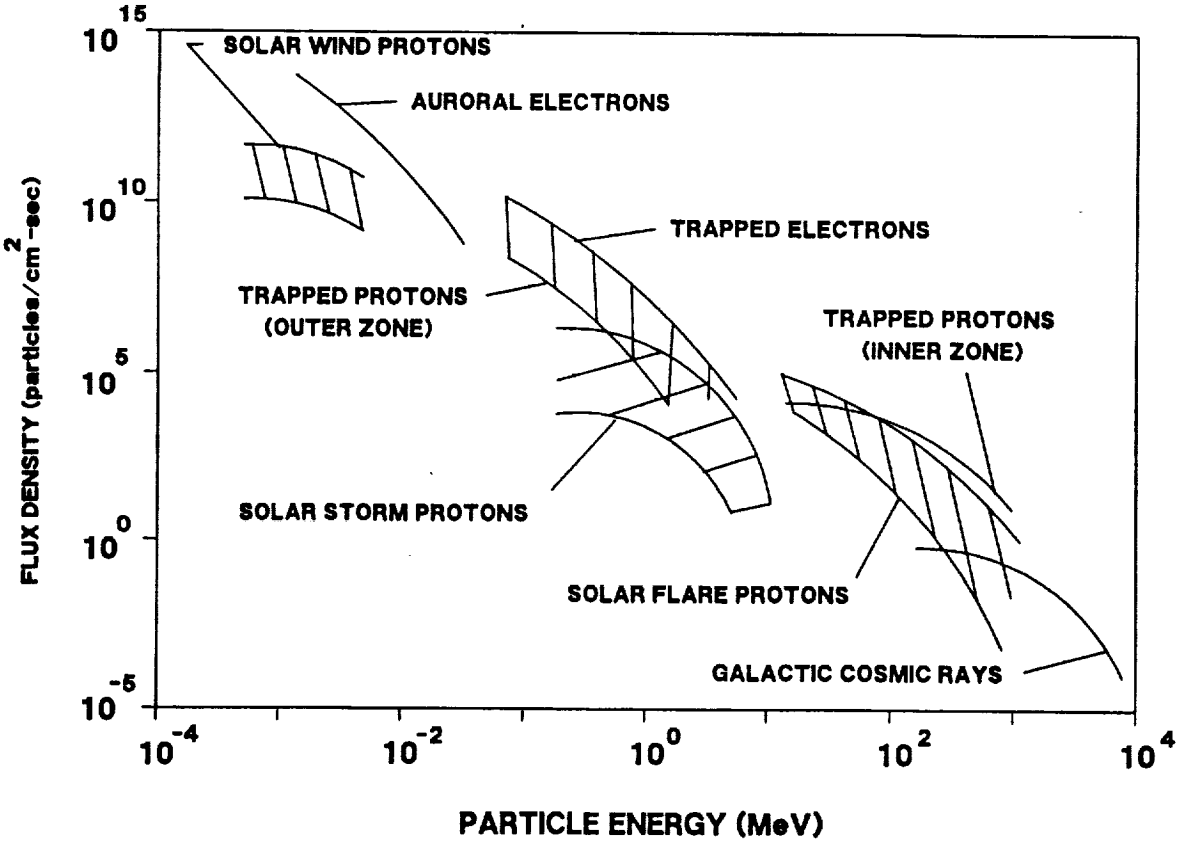

Figure 1. The particulate space radiation environment.

are age- and sex-specific lifetime risk coefficients for cancer incidence and mortality from exposure to low linear energy transfer (LET) radiation for the following sites: lung, breast, thyroid, esophagus, stomach, colon, liver, pancreas, kidney, bladder, acute leukemia, chronic granulocytic leukemia, and an aggregate of "other" tissues consisting of the oral cavity, rectum, gall bladder, uterus, ovaries, brain, bone, prostate, and testes, shown in Tables 1 and 2. The likelihood of radiation-induced lymphoma and Hodgkin's disease was also considered in the "other" tissues. Risk coefficients for all sites were based on the linear-quadratic relationship except for the breast and thyroid for which the linear model was more appropriate. The multiplicative (relative risk) model was used in developing lifetime risk coefficients for all sites except leukemia for which the additive (absolute risk) model provided a better fit.

This paper addresses the projection of radiation-induced lifetime cancer incidence and mortality risks for astronauts who were previously exposed to space radiation and medical procedures using the NCRP risk coefficients in Tables 1 and 2. A comparison is made between the NCRP-based results and mortality risks based on ICRP recommendations. The units for radiation-induced lifetime cancer incidence and mortality risk were the incidence risk unit (IRU x 10^{-5}) and mortality risk unit (MRU x 10^{-5}), respectively. The per capita IRU and MRU from space activities and medical procedures were estimated for astronauts who have previously flown on LEO Shuttle missions and undergone medical radiodiagnoses. Also estimated were the per capita H_E, normalized somatic effective dose equivalent ($H_{E,NS}$), and weighted dose (S_j) for comparison (4,5).

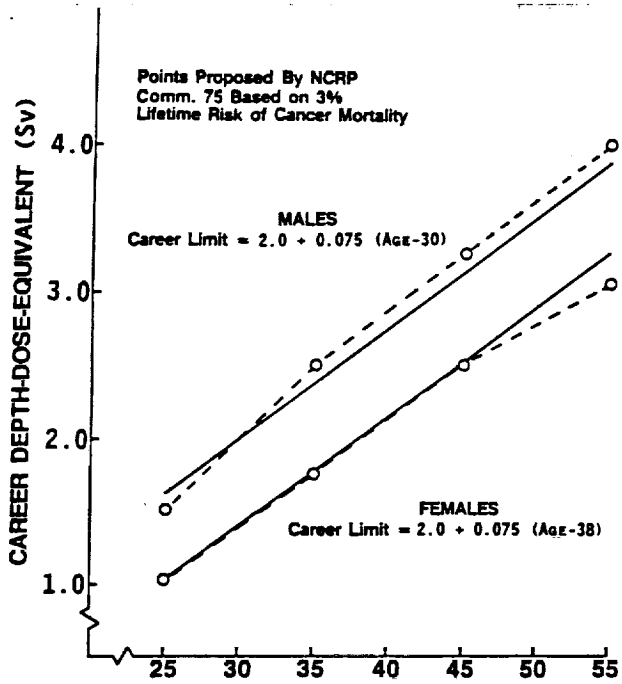

Figure 2. Age- and sex-specific career dose equivalent limits for space activities.

METHODS

EXPOSURE HISTORY DATA BASE

NASA has maintained, as part of its radiation protection program, archives of astronaut radiation exposure histories since Project Mercury (6,7,8,9,10,11,12,13). Exposure records in this computerized data base are divided into several groups representing space activities, diagnostic x-ray examinations, and nuclear medicine procedures. Archived data for space activities include the individual's name, age, sex, age at exposure, launch date, vehicle, mission duration (h), altitude (km), inclination (deg), the radiation absorbed dose (mGy) from thermoluminescent dosimetry (TLD), and organ dose equivalents (mSv) for each mission. Diagnostic x-ray examination data include the individual's name, age, sex, age at exposure, date, type of projection, number of films, projection view (PA, AP, LAT or OBLQ), tube potential (kVp), filament current (mA), skin entrance exposure (mR), half-value layer (mm Al), total filtration (mm Al), source-to-image receptor distance (cm), and horizontal and vertical film size (cm). Records from nuclear medicine studies involving the use of radionuclides include the following data: name, age, sex, age at exposure, date, type of procedure, administered radioactivity (MBq), isotope, and the chemical form of the labelled compound (14).

ORGAN DOSE EQUIVALENTS FROM SPACE ACTIVITIES

The charged-particle radiations of primary interest for LEO missions are protons and GCR. The dose deposition from protons is delivered at a rate that is inversely proportional to particle energy, until a maximum, known as the Bragg peak is reached (15). The dose deposition from GCR is very similar to that of protons; however, due to the much higher energies of GCR, there is more potential for inelastic nuclear interactions resulting in fragments whose LET is greater than that of the incident particle. This combination of incident and secondary radiation results in a polychromatic omnidirectional species of particles, each of which deposit their energy in a manner unique to the geometry, shielding, and organ under consideration. A detailed description of the space radiation environment and relevant dosimetry is given in NCRP Report 98.

Table 1. Predicted lifetime risk of excess cancers among 1000 persons who experienced a protracted exposure of 10 rad within 1 year by age at exposure, sex, and specific organ.

SEX	AGE AT EXPOSURE	LUNG	BREAST	THYROID	ESOPHAG.	STOMACH	COLON	LIVER
MALE	25	0.93		0.25	0.06	0.49	0.40	0.42
	35	0.63		0.16	0.03	0.25	0.19	0.14
	45	0.45		0.11	0.02	0.16	0.11	0.06
	55	0.33		0.06	0.03	0.15	0.10	0.04
FEMALE	25	0.74	3.12	0.77	0.07	0.69	0.48	0.50
	35	0.61	1.92	0.56	0.04	0.40	0.24	0.21
	45	0.55	0.34	0.40	0.03	0.25	0.14	0.10
	55	0.47	0.17	0.27	0.04	0.21	0.14	0.05

SEX	AGE AT EXPOSURE	PANCR.	KIDNEY & BLADDER	ALL ACUTE LEUKEMIA	CHRON. GRANULO. LEUKEMIA	SUM OF NON-CLL LEUKEMIA	ALL OTHER CANCERS	TOTAL CANCER
MALE	25	0.29	0.29	0.14	0.08	0.21	0.69	4.03
	35	0.14	0.16	0.15	0.08	0.23	0.31	2.23
	45	0.09	0.10	0.17	0.08	0.25	0.16	1.51
	55	0.09	0.08	0.17	0.08	0.25	0.13	1.25
FEMALE	25	0.45	0.34	0.09	0.05	0.14	0.44	7.73
	35	0.19	0.20	0.10	0.06	0.16	0.25	4.78
	45	0.12	0.14	0.13	0.06	0.19	0.18	2.45
	55	0.12	0.11	0.15	0.06	0.21	0.18	1.96

EXPOSURE: PROTRACTED (<0.05 Gy/d)
TYPE OF RISK: INCIDENCE
RADIATION DOSE: 0.1 Gy (10 rad)
DURATION: WITHIN 1 YEAR

SOURCE: NCRP Report 98

Table 2. Predicted lifetime risk of excess cancer deaths among 1000 persons who experienced a protracted exposure of 10 rad within 1 year by age at exposure, sex, and specific organ.

SEX	AGE AT EXPOSURE	LUNG	BREAST	THYROID	ESOPHAG.	STOMACH	COLON	LIVER
MALE	25	0.73		0.04	0.06	0.34	0.22	0.41
	35	0.50		0.03	0.03	0.17	0.10	0.14
	45	0.36		0.02	0.02	0.11	0.06	0.06
	55	0.26		0.01	0.02	0.11	0.05	0.03
FEMALE	25	0.53	0.99	0.07	0.06	0.51	0.24	0.48
	35	0.44	0.61	0.05	0.03	0.30	0.12	0.21
	45	0.40	0.11	0.04	0.02	0.18	0.07	0.10
	55	0.34	0.05	0.03	0.03	0.16	0.07	0.05

SEX	AGE AT EXPOSURE	PANCR.	KIDNEY & BLADDER	ALL ACUTE LEUKEMIA	CHRON. GRANULO. LEUKEMIA	SUM OF NON-CLL LEUKEMIA	ALL OTHER CANCERS	TOTAL CANCER
MALE	25	0.27	0.09	0.12	0.05	0.17	0.27	2.59
	35	0.13	0.05	0.13	0.05	0.18	0.12	1.43
	45	0.08	0.03	0.15	0.05	0.20	0.08	1.00
	55	0.08	0.02	0.15	0.05	0.20	0.05	0.84
FEMALE	25	0.42	0.12	0.07	0.03	0.10	0.18	3.70
	35	0.18	0.07	0.09	0.03	0.12	0.10	2.21
	45	0.11	0.05	0.11	0.03	0.14	0.07	1.28
	55	0.11	0.04	0.12	0.03	0.15	0.07	1.09

EXPOSURE: PROTRACTED (<0.05 Gy/d)
TYPE OF RISK: MORTALITY
RADIATION DOSE: 0.1 Gy (10 rad)
DURATION: WITHIN 1 YEAR

SOURCE: NCRP Report 98

Table 3. Organ weighting factors used to estimate H_E, and $H_{E,NS}$ in this study.

Organ	W_T[a]	$W_{T,NS}$[b]
Ovaries	.25	-
Testes	.25	-
Breast	.15	.19
Red Bone Marrow	.12	.16
Lung	.12	.16
Thyroid	.03	.04
Bone Surfaces	.03	.04
Remainder	.30	.40

[a]Weighting factors based on a total stochastic risk of 1.65 x 10^{-2} Sv^{-1}.

[b]Weighting factors based on total somatic risk of 1.25 x 10^{-2} Sv^{-1} normalized to unity.

Estimates of the lifetime risks from cancer incidence and mortality from space activities required the estimation of organ dose equivalents. Within this framework, we used the Computerized Anatomical Man (CAM) model to generate body self-shielding data comprised of information defining the paths traversed by rays traced from internal dose points in the brain, lenses of the eyes, thyroid, esophagus, marrow, lungs, colon, liver, kidneys, spleen, stomach, pancreas, bladder, and testes to the exterior surface for 20 exposures to 19 individuals. For each dose point the mass distribution in the surrounding 4π solid-angle was characterized by systematically tracing 512 rays (16). Ray-tracing results were processed to characterize the equivalent aluminum thickness as areal density at each dose point. Areal densities for each dose point were then coupled with the AP-8 proton environment model (17), CREME GCR model (18), BRYNTRN baryon transport code (19), and the PDOSE proton dose code to yield radiation absorbed dose (20). Dose equivalent was determined by applying ICRP LET-dependent quality factors (1), which are stored within the BRYNTRN and PDOSE codes.

ORGAN DOSE EQUIVALENTS FROM MEDICAL PROCEDURES

Astronauts undergo radiodiagnoses for routine health care and screening during the selection process in order to be medically qualified for space flight. While radiation protection does not typically involve individual monitoring for medical exposures, we considered risk from all sources and thus needed to account for such exposures. Estimates of risk from 364 diagnostic x-ray exposures to the same 19 individuals were based on organ dose equivalents, which were estimated as follows: For diagnostic x-ray examinations performed locally, for which the exposure settings and calibration-obtained beam qualities were known, a computer program (21) was used to estimate the radiation absorbed dose to the following organs: testes, marrow, lung, thyroid, bone, bladder, colon, kidneys, liver, uterus, brain, and lenses of the eyes. The following examination parameters were specified at run-time: projection and view (PA, AP, LAT), x-ray field size at the image receptor, x-ray field location in relation to anatomical landmarks, skin entrance exposure (mR), beam quality (kVp and HVL-1), and source-to-image receptor distance (cm). Skin entrance exposure (mR) and total tube filtration (mm Al) were calculated using published exposure values (22). For x-ray examinations performed at locally referred institutions, we used the the same computer program for estimating organ doses, but derived entrance skin exposure and peak kilovoltage by combining exposure values and beam qualities (HVL-1) for projections common in diagnostic radiology (23). For nuclear medicine procedures, organ dose conversion factors (mGy/MBq) were used to obtain dose equivalent to the adrenals, bladder, bone, stomach, small intestine, upper large intestine, lower large intestine, kidneys, liver, lungs, pancreas, marrow, spleen, testes, thyroid, and other organs for 65 exposures to 4 individuals (24).

ESTIMATION OF H_E, $H_{E,NS}$, S_j, AND LIFETIME RISKS FROM EXPOSURE TO SPACE RADIATIONS, DIAGNOSTIC X-RAY EXAMINATIONS, AND NUCLEAR MEDICINE PROCEDURES

After estimating organ dose equivalents from space activities and medical procedures, several estimators representing the detriment from radiation exposure were calculated. First, the effective dose equivalent (H_E) was estimated to assess the stochastic risk to space workers from medical exposures. The International Commission on Radiological Protection (25) introduced H_E for the protection of workers. H_E includes the genetic and somatic risk for a theoretically age-independent and sex-independent population that is occupationally exposed to radiation; it can be used to equate harm (somatic and genetic risk) from a nonuniform exposure to harm from a uniform whole-body exposure. It does not include the genetic detriment of generations subsequent to the second generation, nor does it include nonfatal malignancies (cancer incidence). For somatic detriment, the normalized somatic effective dose equivalent ($H_{E,NS}$) was used. The $H_{E,NS}$ was introduced to measure somatic detriment to a patient, because the age distribution of patients undergoing radiodiagnostic procedures is not normally distributed and is skewed toward older ages when the birth-rate is low (4,26,27). We have employed this somatic-based derivative as part of a more refined approach to counseling, which involves separate somatic and genetic risk (offspring) assessments. The weighting factors used to estimate H_E and $H_{E,NS}$ are shown in Table 3.

Table 4. Male and female age- and sex-dependent ponderation factors used to calculate S_j.

		Age at irradiation			
Sex	Organ	25	35	45	55
Male	Testes	0.47	0.10	0.02	0.00
	Marrow	0.12	0.12	0.12	0.09
	Lung	0.12	0.10	0.07	0.04
	Thyroid	0.03	0.03	0.02	0.01
	Bone	0.03	0.03	0.02	0.01
	Remainder	0.28	0.24	0.18	0.10
Female	Ovaries	0.30	0.05	0.00	0.00
	Breast	0.33	0.31	0.28	0.22
	Marrow	0.12	0.12	0.12	0.11
	Lung	0.12	0.10	0.07	0.04
	Thyroid	0.03	0.03	0.02	0.01
	Bone	0.03	0.03	0.02	0.01
	Remainder	0.28	0.24	0.18	0.10

* Ponderation factors based on a total stochastic risk of 1.65×10^{-2} Sv^{-1}.

To provide a measure of detriment for space activities and medical procedures based on sex and age, the age- and sex-specific weighted dose (S_j) was used. Beninson and Sowby introduced S_j along with its age- and sex-dependent ponderation factors (Table 4) for weighting detriment from medical irradiation (5). In previous work, Mettler et al. used these age- and sex-dependent ponderation factors to compare H_E to S_j and found that their use results in a reduction in the estimate of detriment by 33% to 50% (28,29).

Lastly, we estimated the per capita lifetime risk of radiation-induced cancer incidence and mortality from exposure to LEO space radiations and medical procedures by multiplying the organ-, age-, and sex-specific risk coefficients in Tables 1 and 2 by the organ dose equivalents from each exposure. This yielded the Incidence Risk Unit (IRU x 10^{-5}) and Mortality Risk Unit (MRU x 10^{-5}) for each organ. To illustrate the refined system, estimates of per capita IRU,

MRU, H_E, $H_{E,NS}$, and S_j were made for 19 males who have flown previously on Shuttle and undergone radiodiagnoses. The Appendix lists the equations used for calculating H_E, $H_{E,NS}$, S_j, IRU, and MRU.

RESULTS AND DISCUSSION

COMPARISON OF DETRIMENT FROM SPACE ACTIVITIES AND MEDICAL EXPOSURES

Table 5 gives the per cent contribution of the weighted dose equivalents to H_E, $H_{E,NS}$, and S_j from space activities, diagnostic X-ray, and nuclear medicine procedures. In all three cases, the remainder tissue contributed to more than 30% of H_E. This corroborates several recent studies on contribution of the remainder to H_E (30,31). Figures 3,4, and 5 depict graphically the contribution of the weighted dose equivalents to H_E, $H_{E,NS}$, and S_j for the three sources in Table 5. It should be noted that the highest per cent contribution to H_E, $H_{E,NS}$, and S_j was from the remainder tissue, followed by the testes for H_E and the marrow for S_j (Fig. 3,4,5). This indicates clearly that the remainder tissues accounted for the largest proportion of mortality risk. It can be argued, therefore, that the concept of an effective dose should not include a remainder organ for which the aggregate of risk from other organs is considered.

Table 5. Per cent contribution of weighted dose equivalents to H_E, $H_{E,NS}$, and S_j from space activities (n=20), diagnostic X-ray (n=364), and nuclear medicine procedures (n=65).

Source	Organ	H_E	$H_{E,NS}$	S_j
Space activities	Testes	29	-	5
	Marrow	14	20	26
	Lung	14	20	16
	Thyroid	4	5	5
	Bone	4	5	6
	Remainder[a]	35	50	42
Diagnostic x-ray examinations	Testes	38	-	27
	Marrow	7	11	10
	Lung	14	23	17
	Thyroid	5	9	8
	Bone	6	9	8
	Remainder[b]	30	48	32
Nuclear medicine procedures	Testes	14	-	2
	Marrow	17	20	26
	Lung	13	15	13
	Thyroid	3	2	3
	Bone	3	3	4
	Remainder[c]	50	60	52

[a] Organs considered in the remainder were bladder, colon, stomach, kidneys, liver, esophagus, pancreas, spleen, brain, and lenses of eyes.

[b] Organs considered in the remainder were bladder, colon, small intestine, kidneys, liver, brain, and lenses of eyes.

[c] Organs considered in the remainder were bladder, upper large intestine, lower large intestine, small intestine, stomach, kidneys, liver, spleen, adrenals, pancreas, brain, and lenses of eyes.

Per capita values for H_E, $H_{E,NS}$, S_j, IRUs, and MRUs for space activities and medical procedures are shown in Table 6, which illustrates that the per capita H_E, $H_{E,NS}$, S_j, IRU, and MRU (NCRP- and ICRP-based) from medical procedures were 12 to 17 times greater than that for space activities. The per capita H_E from space activities, diagnostic X-ray, and nuclear medicine procedures were 1.51 mSv (151 mrem), 15.9 mSv (1590 mrem), and 3.6 mSv (360 mrem), respectively. In particular, H_E from space activities was comparatively higher than the per capita radiation absorbed dose from space activities of 0.95 mGy (95 mrad). Medical procedures, for the 19 individuals under study, contributed on average to 93% of the total risk, which suggests that the risks from medical procedures far outweighed the risks from space activities. The per capita H_E from space activities and diagnostic X-ray (Table 7) was 6% and 17% greater than $H_{E,NS}$ for the same sources. However, an opposite trend was discovered for nuclear medicine procedures (13% lower), which is explained by the small contribution (14%) of the weighted gonad dose equivalent to H_E. For space activities, diagnostic x-ray examinations, and radionuclide procedures, H_E yielded a detriment that was 48%, 31%, and 37% higher than detriment measured by S_j, respectively. This is in good agreement with the findings of Mettler et al. (28).

The ICRP-based risk estimates underestimated NCRP-based mortality estimates from space activities and diagnostic X-ray by 17% and 28%, respectively, and overestimated mortality risk from nuclear medicine procedures by 3%. There were several reasons for this: for space activities and diagnostic X-ray, mortality risk, as defined by the ICRP (ICRP77), is lower than mortality based on NCRP risk coefficients. Further, in the NCRP methodology, the *remainder* or *other* tissue does not contain organs such as the colon, kidneys, bladder, liver, etc., which are included in the ICRP's *remainder*. Since the remainder tissue accounted for 60% of $H_{E,NS}$ from nuclear medicine procedures, the ICRP-based estimates did not underestimate NCRP-based risk.

Table 6. Per capita H_E, $H_{E,NS}$, S_j, IRUs, and MRUs from space activities, diagnostic x-ray examinations, and nuclear medicine procedures.

Source		H_E (mSv)	$H_{E,NS}$ (mSv)	S_j (mSv)	IRU ($\times 10^{-5}$)[a]	MRU ($\times 10^{-5}$)[b]	MRU ($\times 10^{-5}$)[c]
Space activities	$\bar{x}$	1.51[d]	1.42	0.79	3.10	2.10	1.78
	SEM	0.26	0.24	0.13	0.52	0.36	0.30
	n=19						
Diagnostic x-ray examinations	$\bar{x}$	15.86	13.09	10.95	37.94	22.73	16.38
	SEM	4.73	3.76	3.09	9.72	6.70	4.70
	n=19						
Nuclear medicine procedures	$\bar{x}$	3.58	4.05	2.24	6.80	4.92	5.08
	SEM	1.19	1.28	0.69	2.42	1.69	1.59
	n=4						

[a] IRU based on NCRP age- and sex-specific cancer incidence risk coefficients in Table 1 (NCRP89).

[b] MRU based on NCRP age- and sex-specific cancer mortality risk coefficients in Table 2 (NCRP89).

[c] MRU based on ICRP mortality risk coefficients (ICRP77).

[d] Per capita radiation absorbed dose (mGy) from TLD (LiF-100) was 0.95 $\pm$ 0.012 SEM.

Table 7. Per cent differences between various detriment estimators.

Exposure	Estimator	Comparison estimator	Percentage by which estimator differs from comparison estimator
Space activities	$H_{E,NS}$	H_E	-6
	S_j	H_E	-48
	MRU_{NCRP}	IRU_{NCRP}	-32
	MRU_{ICRP}	MRU_{NCRP}	-17
Diagnostic x-ray examinations	$H_{E,NS}$	H_E	-17
	S_j	H_E	-31
	MRU_{NCRP}	IRU_{NCRP}	-40
	MRU_{ICRP}	MRU_{NCRP}	-28
Nuclear medicine procedures	$H_{E,NS}$	H_E	13
	S_j	H_E	-37
	MRU_{NCRP}	IRU_{NCRP}	-28
	MRU_{ICRP}	MRU_{NCRP}	3

Table 8 lists in tabular notation values of the total per capita (n=19) IRUs from space activities, diagnostic X-ray, and nuclear medicine procedures, which were 3.1×10^{-5}, 37.9×10^{-5}, and 6.8×10^{-5}, respectively. The per capita IRU from medical procedures was 14 times greater than IRU from space activities. This finding coincides with the marked difference between the total per capita H_E from medical procedures and H_E from space activities. Per capita values of MRUs from space activities, diagnostic X-ray, and nuclear medicine procedures were 2.1×10^{-5}, 22.7×10^{-5}, and 4.9×10^{-5}, respectively. Similarly, the per capita MRU from medical procedures was 13 times greater than that from space activities. The observed difference between cancer incidence and mortality expressed by IRU and MRU was simply due to the site-specific case-fatality ratios.

Figures 6,7, and 8 illustrate the per cent contributions of cancer incidence and mortality risk from each tissue to the total risk for space activities, diagnostic X-ray, and nuclear medicine procedures listed in Table 8. For uniform whole-body exposures from space activities (Figure 6), the highest proportion of risk was for lung cancer, followed by leukemia, stomach, colon, pancreas, and other organs that contributed approximately the same amount to total risk. Risks for esophageal cancer were the lowest. Risks from diagnostic X-ray (Figure 7) were mainly from cancer of the lung, other tissues, liver, thyroid, leukemia, colon, and kidney and bladder since chest projections were the most frequent (43%). Skull (18%) and kidney-ureter-bladder (12%) projections were the second and third most frequent. The highest contribution of risk from nuclear medicine procedures (Figure 8) was from lung cancer borne out by its high risk (Tables 1 and 2). This was followed by leukemia, liver, and stomach cancer; the rest of the tissues contributed approximately the same amount of risk to the total.

Table 8. Per capita (n=19) IRUs and MRUs from space activities, diagnostic x-ray examinations, and nuclear medicine procedures.

Source	Organ	IRU x 10^{-5} ± SEM	MRU x 10^{-5} ± SEM
Space activities (n=19)	Lung	.84 ± .14	.66 ± .11
	Thyroid	.22 ± .04	.04 ± .01
	Esophagus	.04 ± .01	.03 ± .01
	Stomach	.27 ± .05	.19 ± .03
	Colon	.20 ± .04	.11 ± .02
	Liver	.11 ± .02	.11 ± .02
	Pancreas	.15 ± .03	.14 ± .02
	Kidney & Bladder	.18 ± .03	.06 ± .01
	Acute Leuk.	.29 ± .05	.25 ± .04
	Chron. Gran. Leuk.	.14 ± .02	.08 ± .01
	All other cancers[a]	.21 ± .04	.08 ± .01
	Total	3.10 ± .52	2.10 ± .36
Diagnostic x-ray examinations (n=19)	Lung	12.72 ± 3.76	10.01 ± 2.96
	Thyroid	5.11 ± .78	.82 ± .12
	Colon	2.62 ± 1.00	1.39 ± .53
	Liver	3.16 ± 1.32	3.07 ± 1.27
	Kidney & Bladder	2.50 ± .99	.77 ± .30
	Acute Leuk.	1.4 ± .35	1.22 ± .30
	Chron. Gran. Leuk.	.75 ± .18	.45 ± .11
	All other cancers[b]	7.21 ± 1.44	2.82 ± .55
	Total	37.94 ± 9.72	22.73 ± 6.70
Nuclear medicine procedures (n=4)	Lung	1.86 ± .71	1.45 ± .56
	Thyroid	.28 ± .13	.04 ± .02
	Stomach	.46 ± .17	.31 ± .12
	Colon	.29 ± .12	.16 ± .18
	Liver	.55 ± .18	.55 ± .18
	Pancreas	.24 ± .07	.22 ± .06
	Kidney & Bladder	.32 ± .12	.10 ± .04
	Acute Leuk.	.83 ± .36	.78 ± .31
	Chron. Gran. Leuk.	.41 ± .18	.25 ± .10
	All other cancers[c]	.42 ± .14	.16 ± .06
	Total	6.80 ± 2.42	4.92 ± 1.69

[a] Other organs consisted of the testes, brain, and spleen.
[b] Other organs consisted of the testes, brain, and bone.
[c] Other organs consisted of the testes, bone, and adrenals.

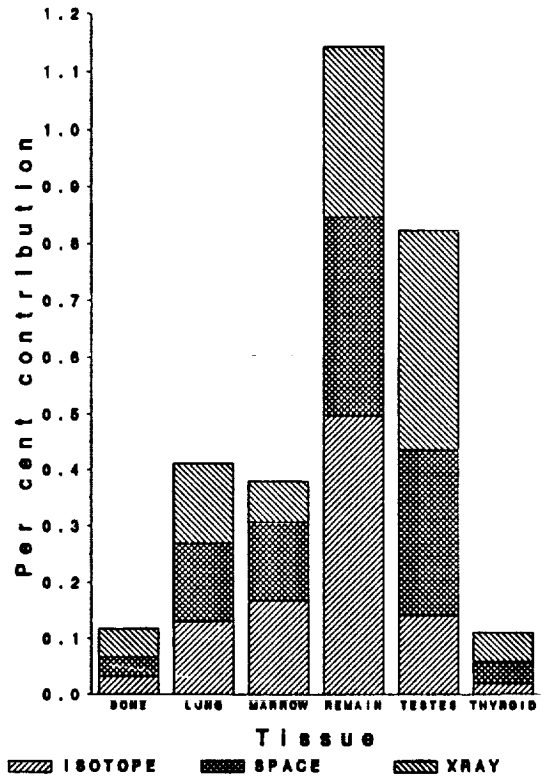

Figure 3. Per cent contribution of weighted dose equivalents to H_E for space activities (n=20), diagnostic X-ray (n=364), and nuclear medicine procedures (n=65).

CONCLUSIONS

EXPOSURES FROM SPACE ACTIVITIES

Over the years, there has been a steady accumulation of radiation-induced risk from space activities. On the other hand, risks from medical procedures have increased at a much higher rate. Notwithstanding this caveat, we consider risks from medical procedures only when dealing with total risk, and accordingly, do not account for risk from medical procedures when comparing an individual's cumulative lifetime risk to the 3% career risk limit. We believe that our approach in using risk coefficients based on low-LET exposures from low-orbit space activities is justified since the majority of dose is attributable to low-LET radiations, whose average quality factor is 1.2.

Manned space activities during Space Station Freedom and interplanetary travel will involve radiation exposures that are much higher than those presently experienced on Shuttle (32). We are vigorously pursuing methods for obtaining refined organ dose equivalents from known space radiation environments in order to estimate the radiation-induced cancer and genetic risks to space workers.

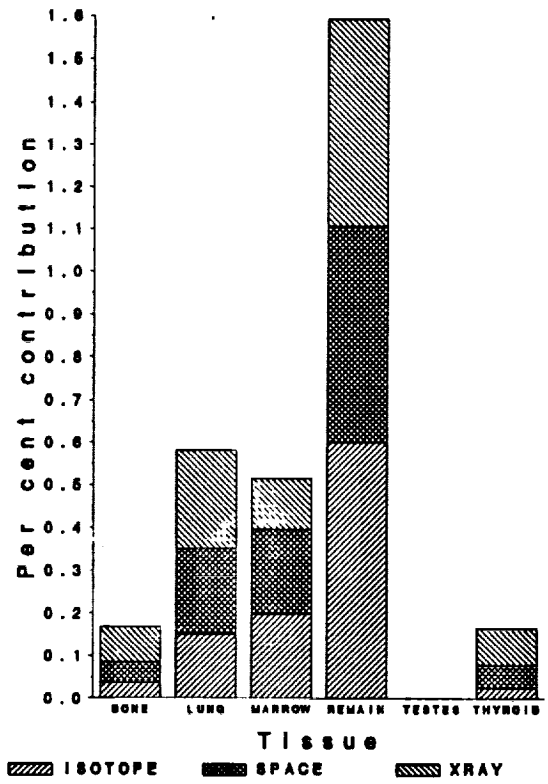

Figure 4. Per cent contribution of weighted dose equivalents to $H_{E,NS}$ for space activities (n=20), diagnostic X-ray (n=364), and nuclear medicine procedures (n=65).

EXPOSURES FROM MEDICAL PROCEDURES

We found that for x-ray examinations and radionuclide studies, H_E overestimated detriment when compared to S_j. Perhaps the most important finding was that $H_{E,NS}$, based on the ICRP somatic risk of 1.25×10^{-2} Sv^{-1}, underestimated the NCRP-based mortality risk for space activities and diagnostic X-ray and overestimated NCRP-based mortality risk from radionuclide studies. The remainder organs contributed the most to H_E from diagnostic x-ray examinations and nuclear medicine procedures.

These estimators, representing harm to an individual, are quantities whose values are affected by several phenomena: (1) the type of exposure, i.e., internal or external, and the irradiation geometry, (2) the sex and age distribution of the population that the individual represents, and (3) the particular application of these quantities. In the present treatment, cause (1) dealt with whole or partial-body exposures from multiple internal and external sources of radiation. Changes due to cause (2) were fully taken into consideration by using ICRP weighting factors which are averaged over sex and age. Cause (3) was also fully considered as we used these quantities to estimate with some degree of accuracy the somatic risks to each space worker. The choice of which parameter to use when assessing stochastic risk to an individual or population should be based on several criteria. For the protection of workers in general, where justification of practice

and optimization of protection are paramount, emphasis is placed on H_E in order to assess the harm incurred by fatal cancers and hereditary damage in the first two generations. When assessing the stochastic somatic risk to an individual, $H_{E,NS}$, which does not account for genetic risk, should be used. When the objective is to determine the lifetime cancer incidence and mortality risks to various organs of an individual, we recommend use of site-specific IRUs and MRUs that are based on age- and sex-specific lifetime incidence and mortality risk coefficients such as those in Tables 1 and 2. In the present work, we found that the different estimators were all within a factor of 2.

COMPARISON OF EXPOSURES FROM MEDICAL PROCEDURES TO SPACE ACTIVITIES

Calculations of the various detriment estimators confirm the impression that the risks to the astronaut population from medical procedures is substantially higher than the risks incurred from space activities. This was no surprise since space workers are more frequently exposed to medical procedures for screening during selection and routine health care. A similar case could be made for career aviators of all types. This trend will undoubtedly change in the future when astronauts are exposed to increased levels of radiation during Space Station Freedom and exploratory missions and more is known about the risks from exposure to high-LET radiation.

ESTIMATION OF LIFETIME RISKS

Risk estimates for human exposure to low doses of radiation in the range 0-.2 Gy (0- 20 rad) are based upon observational data from radioepidemiological studies and are far from precise. An equally important part of radiation risk estimation is the assumption about the underlying dose-response relationship. At low doses, the dose-response assumptions are not known precisely but based on reasonable assumptions given certain biophysical principles. This belief does not recognize the fact that, in humans, radiation-induced cancers are masked by naturally occurring (spontaneous) cancers and by the presence of genetic and host factors in the exposed individual. Radiation risk estimates from low doses of radiation are at best uncertain.

In radiation protection, rationalizations of a dose-response relationship in the low dose region are vital and justifiably used by assuming that, albeit small, there is a probability of induced detectable harm. Unfortunately, several large analytical etiologic studies on cancer mortality in the nuclear industry have found that the standardized mortality ratios (SMR) for leukemia and solid cancers were all below unity, thus indicating that cancer mortality was lower in the exposed population (33,34,35). Furthermore, Land has pointed out that studies on cancer in workers exposed to low doses of radiation are a waste of time and money (36).

Studies on humans exposed to intermediate to very high doses of radiation in the range 0.2 - 5 Gy (20 - 500 rad), such as those of the atomic bomb survivors (37,38,39), persons with anklylosing spondylitis (40), and women undergoing radiation therapy for cervical cancer (41), have shown the signal-to-noise ratio to be much higher allowing for a more reliable measure of risk.

There were additional factors considered in the present analysis. While there is control over the reduction of exposure from medical procedures, there is, aside from the use of time, distance, and shielding, little control over the reduction of exposure from space activities. Further, there are no radioepidemiological data for human exposure to space radiation from which risk can be directly estimated. There are radiobiological data, however.

In view of these shortcomings, we have adopted the NCRP's system of risk limitation for the purpose of establishing radiation protection guidelines for manned space activities. In addition, we have established a program for assessing and monitoring these risks to counsel the astronauts. The Soviets have begun similar work in their space program as required by their government standards (42).

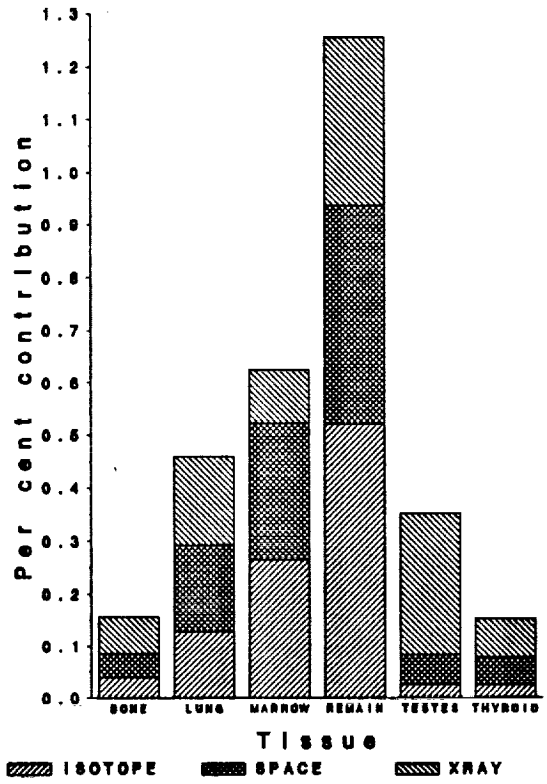

Figure 5. Per cent contribution of weighted dose equivalents to S_j for space activities (n=20), diagnostic X-ray (n=364), and nuclear medicine procedures (n=65).

SUMMARY

Several problems were encountered in the course of this investigation. The first was that we lacked a computerized anthropomorphic female model to estimate the dose to the breasts, ovaries, and uterus from space activities. This imposed serious limitations on our ability to estimate collective and per capita risks to female astronauts. Computerized anthropomorphic male and female models based on more complete geometry data, such as that obtained with computerized tomography or magnetic resonance imaging, need to be developed and maintained.

Finally, we realize that our approach in using the NCRP age- and sex-specific lifetime risk coefficients to assign conservative risk estimates to workers who are exposed occupationally and non-occupationally to low- and high-LET radiations involved the acceptance of some rather grave assumptions. Nevertheless, as the uncertainties surrounding low-dose radiation risk estimates are reduced and radiation risk information becomes more stable and reliable, NASA will be in a position to adopt such information as it becomes available.

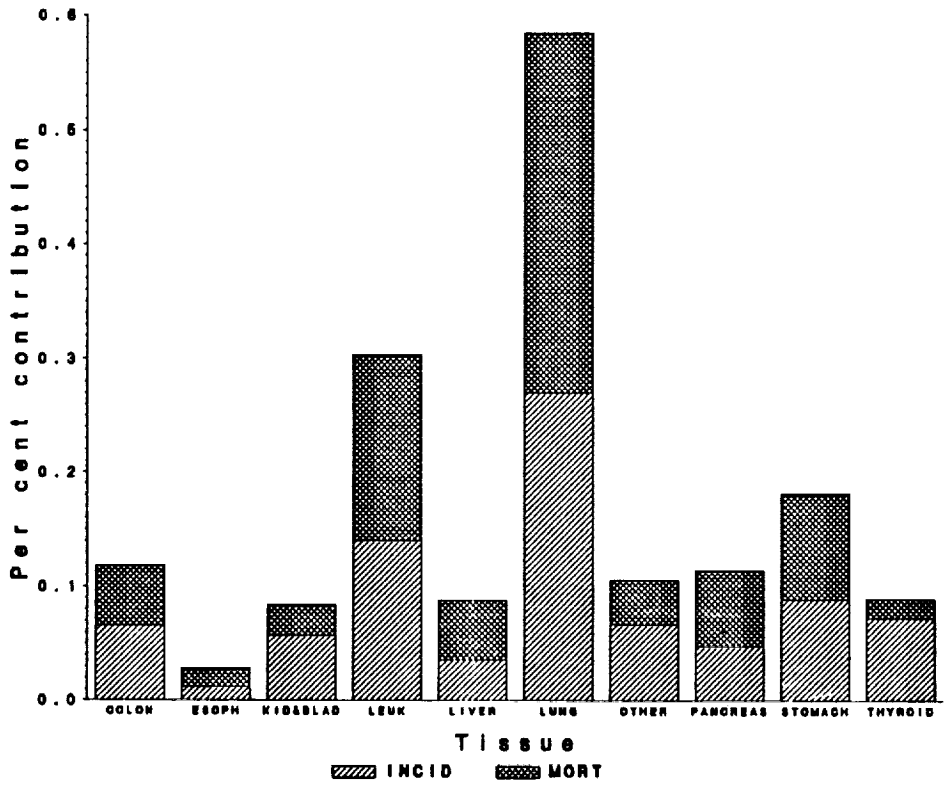

Figure 6. Per cent contribution of individual tissue IRUs and MRUs to total incidence and mortality risk from space activities (n=20).

APPENDIX

ESTIMATION OF INCIDENCE RISK UNITS (x 10^{-5}) AND MORTALITY RISK UNITS (x 10^{-5}) PER mGy EXPOSURE FROM SPACE ACTIVITIES AND MEDICAL PROCEDURES

The following equation was used to calculate lifetime Incidence Risk Units (IRU x 10^{-5}) for organs listed in Table 1:

$$IRU_n = IRU_T\left(\frac{D_n}{D_T}\right) \qquad (1)$$

where IRU_n is the incidence risk unit (x 10-5) for a given organ for new dose, D_n in mGy and IRU_T is the incidence risk unit (x 10-5) associated with dose, D_T in Table 1. Likewise, the the lifetime Mortality Risk Unit from exposure to space radiation and medical procedures was approximated by the equation

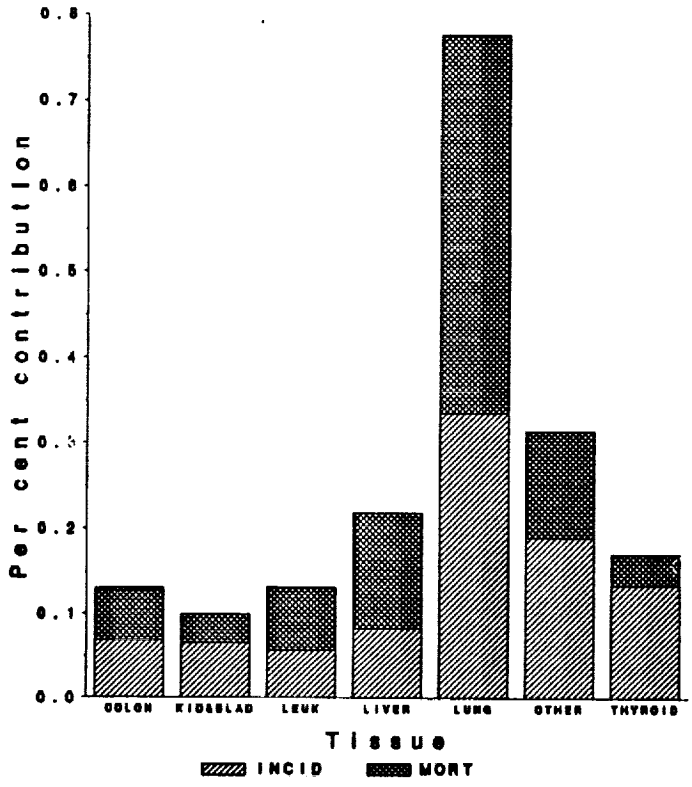

Figure 7. Per cent contribution of individual tissue IRUs and MRUs to total incidence and mortality risk from diagnostic X-ray (n=364).

$$MRU_n = MRU_T\left(\frac{D_n}{D_T}\right) \tag{2}$$

where IRU_n is the mortality risk unit (x 10^{-5}) for a given organ for new dose, D_n in mGy and IRU_T is the mortality risk unit (x 10^{-5}) associated with dose, D_T in Table 2.

CALCULATION OF H_E, $H_{E,NS}$, AND S_j FROM SPACE ACTIVITIES AND MEDICAL PROCEDURES

The H_E from space activities and medical procedures to astronaut k was taken as

$$H_E = \sum_j \sum_i \left(H_{ijk} \cdot W_T\right), \tag{3}$$

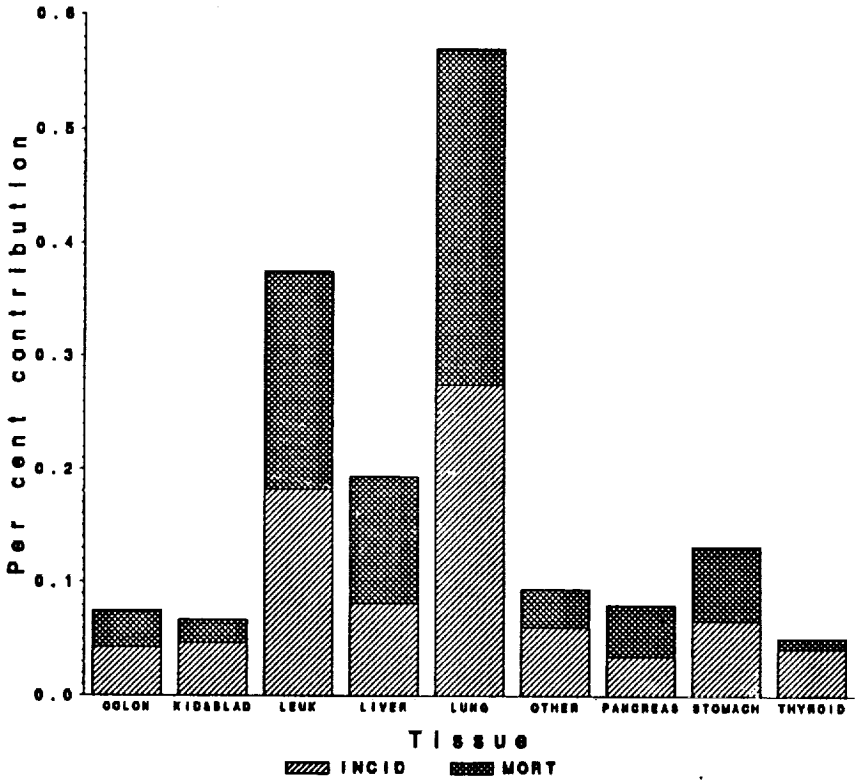

Figure 8. Per cent contribution of individual tissue IRUs and MRUs to total incidence and mortality risk from nuclear medicine procedures (n=65).

where H_E is the lifetime cumulative effective dose equivalent from space activities and medical procedures for astronaut k, H_{ijk} is the dose equivalent to organ j from i exposures to medical procedures for astronaut k, and W_T is the ICRP weighting factor for organ j. Table 3 lists the weighting factors used in Eq. 3.

The equation used for calculating the normalized somatic effective dose equivalent $H_{E,NS}$ from space activities and medical procedures was

$$H_{E,NS} = \sum_j \sum_i \left(H_{ijk} \cdot W_{T,NS} \right), \tag{4}$$

where $H_{E,NS}$ is the somatic effective dose equivalent (normalized to 100% of the total somatic risk) from space activities and medical exposures for astronaut k, H_{ijk} is the dose equivalent to organ j from i exposures to space activities and medical procedures for astronaut k, and $W_{T,NS}$ is the normalized somatic weighting factor for organ j, which are listed in Table 3.

The weighted dose S_j from space activities and medical procedures is defined by the form:

$$S_j = \sum_j \sum_i \left(\frac{r_{iT}}{R} \right) H_{Tijk} \qquad (5)$$

where r_{iT}/R are the ponderation factors listed in Table 4, H_{Tijk} is the dose equivalent to organ T in the i age stratum for examination j, for astronaut k.

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REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA-TM 102164		

4. Title and Subtitle	5. Report Date
Radiological Health Risks to Astronauts from Space Activities and Medical Procedures	June 1990
	6. Performing Organization Code: SD23
7. Author(s)	8. Performing Organization Report No.
Leif E. Peterson, D. Stuart Nachtwey*	S-610
9. Performing Organization Name and Address	10. Work Unit No.
NASA Lyndon B. Johnson Space Center Houston, TX 77058	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546-0001	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

*Deceased, March 1990

16. Abstract

Radiation protection standards for space activities differ substantially from those applied to terrestrial working situations. The levels of radiation and subsequent hazards to which space workers are exposed are quite unlike anything found on Earth. In view of these considerations, NASA has adopted a more highly refined system of risk management than that conventionally applied to radiation workers. The refined system involves assessing the risks to each space worker from all sources of radiation (occupational and non-occupational) at the organ level. In this study we applied risk coefficients in the National Council on Radiation Protection and Measurements (NCRP) Report 98, to previous space and medical exposures in order to estimate the radiation-induced lifetime cancer incidence and mortality risks to 19 representative space workers. Results indicate a per capita (n=19) radiation-induced cancer incidence risk from space activities, diagnostic X-ray, and nuclear medicine procedures of 3.1 x 10^{-5}, 37.9 x 10^{-5}, and 6.8 x 10^{-5}, respectively. For radiation-induced cancer mortality, the per capita risks were 2.1 x 10^{-5}, 22.7 x 10^{-5}, and 4.9 x 10^{-5}, respectively. At present, the risk from medical procedures when compared to space activities is 14 times higher for cancer incidence and 13 times higher for cancer mortality; however, this will change as the per capita dose during Space Station Freedom and interplanetary missions increases and more is known about the risks from exposure to high-LET radiation. The per capita effective dose equivalents (H_E) from space activities, diagnostic X-ray, and nuclear medicine procedures were 1.51 mSv (151 mrem), 15.9 mSv (1590 mrem), and 3.6 mSv (360 mrem). Mortality estimates based on risk coefficients in Publication 26 of the International Commission on Radiological Protection (ICRP) underestimated NCRP-based mortality estimates from space activities and diagnostic X-ray by 17% and 28%, respectively, and overestimated mortality risk from nuclear medicine procedures by 3%. Two units, the Incidence Risk Unit (IRU x 10^{-5}) and the Mortality Risk Unit (MRU x 10^{-5}) for radiation protection, are introduced.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space radiation Diagnostic X-rays Nuclear medicine Organ doses	Unclassified - Unlimited Subject Category - 52

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	21	

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