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# Comparison of organ dose and dose equivalent for human phantoms of CAM vs. MAX

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**Abstract**

For the evaluation of organ dose and dose equivalent of astronauts on space shuttle and the International Space Station (ISS) missions, the CAMERA models of CAM (Computerized Anatomical Male) and CAF (Computerized Anatomical Female) of human tissue shielding have been implemented and used in radiation transport model calculations at NASA. One of new human geometry models to meet the "reference person" of International Commission on Radiological Protection (ICRP) is based on detailed Voxel (volumetric and pixel) phantom models denoted for male and female as MAX (Male Adult voXel) and FAX (Female Adult voXel), respectively. We compared the CAM model predictions of organ doses to those of MAX model, since the MAX model represents the male adult body with much higher fidelity than the CAM model currently used at NASA. Directional body-shielding mass was evaluated for over 1500 target points of MAX for specified organs considered to be sensitive to the induction of stochastic effects. Radiation exposures to solar particle event (SPE), trapped protons, and galactic cosmic ray (GCR) were assessed at the specific sites in the MAX phantom by coupling space radiation transport models with the relevant body-shielding mass. The development of multiple-point body-shielding distributions at each organ made it possible to estimate the mean and variance of organ doses at the specific organ. For the estimate of doses to the blood forming organs (BFOs), data on active marrow distributions in adult were used to weight the bone marrow sites over the human body. The discrete number of target points of MAX organs resulted in a reduced organ dose and dose equivalent compared to the results of CAM organs especially for SPE, and should be further investigated. Differences of effective doses between the two approaches were found to be small (<5%) for GCR.


*Keywords:* Organ dose and dose equivalent; Human tissue models; Risk assessment; Solar particle events; Galactic cosmic ray; Radiation protection

## 1. Introduction

Exposure to space radiation is an occupational hazard for astronauts in space missions such as the International Space Station (ISS) and future missions to Moon and Mars. Astronauts may participate in more than one ISS mission, space shuttle mission, or future lunar missions. The cumulative risk across several missions, and the lifetime risks for cancer, cataract, and other diseases from space radiation exposures are a major concern (Cucinotta and Durante, 2006; Cucinotta et al. 2001a, 2001b; NCRP, 2000; NRC, 2005; Schimmerling et al. 2003; White and Averner, 2001). The large uncertainties in the estimations of these risks have led to a rigorous radiobiological research program at NASA.

A major focus of NASA's radiation protection program is to monitor career effective doses for individual astronauts and best efforts are used to keep the risk as low as reasonably

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achievable (ALARA) (NCRP, 2002; Cucinotta et al. 2008). The equivalent dose in an organ or tissue is the product of the average absorbed dose over the tissue or organ and the defined radiation weighting factor for a given type and energy of the radiation incident and it is summed over all radiations causing the dose. The effective dose is defined as the sum of weighted equivalent doses in the specified tissues and organs of the body (ICRP, 2007) for cancer risks in radiation protection practices. Radiation exposure limits for astronauts corresponding to a 3% risk of exposure-induced death (REID) from fatal cancer calculated from the effective dose are given as career limits for missions in low Earth orbit (LEO) (NCRP, 2000, 2002) and recommended for lunar and Mars missions (NCRP, 2006).

Numerous measurements of space radiation exposures were performed with crew personal dosimeters using thermoluminescence detectors (TLDs) and nuclear track detectors (CR39) and with environmental dosimeters employing in addition instruments, such as tissue equivalent proportional counters (TEPC) and particle spectrometers. However, such measurements have not yet been used for the evaluation of crew organ dose equivalents but used for the consistency checks of the transport models. Because crew personnel dosimeters of TLDs do not account for radiation quality or organ shielding by body tissue, the radiation shielding by body tissue at specific organ sites were accounted for by using ray tracing in the human phantom models of CAM and CAF (Billings et al. 1973). Individual organ dose equivalents were determined by scaling the calculated doses to the measurements of the area together with the astronaut dosimeter results (Cucinotta et al. 2008). Organ doses were measured in some phantom experiments (Badhwar et al. 2002) and Cucinotta et al. (2008) published a comparison between measurements and calculations. NASA's space radiation transport models of organ dose equivalents, BRYNTRN (Cucinotta et al. 1994; Wilson et al. 1989) and HZETRN (Wilson et al., 1991) with QMSFRG (Cucinotta et al. 2006), were used to estimate the effective dose for astronauts upon their return from space missions.

For accurate organ dose and dose equivalent assessments, an anatomically correct geometric model of the different tissues is considered important, because the characteristic primary radiation environment at a specific organ site varies considerably in traversing tissue within the human body. The body geometry models of CAM and CAF represent the 50th percentile Air Force male and female bodies, respectively (Billings et al. 1973). In recent years, several new human phantoms have been developed for risk analysis. New models are designed to address possible shortcomings of the older models, and to reflect the analysis recommendations of national and international committees. New human geometry models denoted for male and female as MAX (Male Adult voXel) (Kramer et al. 2003) and FAX (Female Adult voXel) (Kramer et al. 2004), respectively, are based upon Computed Tomography (CT) scans of human bodies and closely resemble the "Reference Adults" of the International Commission on Radiological Protection (ICRP). A new tissue model of MAX was implemented for the evaluation of directional body-shielding mass at evenly distributed target points throughout each major organ.

Radiation doses due to solar particle event (SPE), trapped protons, and galactic cosmic ray (GCR) were assessed at numerous sites in the human body by coupling space radiation transport models with the detailed body shielding masses of the phantom models of CAM and MAX. From the multiple-point body-shielding distributions at each organ of MAX, the mean and variance of the organ dose was estimated, by which the dose–response relationship can be assessed for the acute risk. For the estimate of the blood forming organ (BFO) dose, the detailed distributions of active marrow in adults (Cristy, 1981) were implemented at bone marrow sites over the human body. We report the detailed comparison between CAM and MAX models in terms of organ dose (in Gy-Eq) and the effective dose (in Sv) obtained from the organ dose equivalents, for various radiation environments, including those at ISS orbit.

The discrete number of target points used at the MAX organ in the current study resulted in the underestimating of the organ dose and dose equivalent compared to the results of CAM. Assessments of organ averaged dose and dose equivalent of MAX were dependent on the number of target points at the organ (Slaba et al. 2009). Because the ICRP reference male values of density, mass, and volume for major organs are represented very well by MAX, the dose assessment is expected to be accurate at the specific site. However, for the convergence of organ averaged dose equivalent of MAX phantom, more target points are necessary than are currently considered points of over 1500 sites as discussed in the mass averaged error analysis by Slaba et al. (2009). In the current study, the difference between CAM and MAX for the effective dose calculations from GCR exposure was less than 5%, with little dependence on spacecraft thickness; while relatively large differences were observed for thin spacecraft thicknesses due to solar- and trapped-protons. However, for a moderately-thick spacecraft, the difference was reduced to within the error range of 10% for the exposure to those protons. The resultant effective dose from the converged organ dose equivalents of MAX phantom would narrow the difference between CAM and MAX for the cancer risk of exposure to various space radiation environments.

## 2. Model description for the evaluation of space radiation risk

### *2.1. NASA operational procedure for the space radiation at LEO*

As an effective operational radiation safety program for astronauts in LEO (Cucinotta et al. 2008), the radiation cancer risk and organ doses have been assessed and recorded at NASA. Based on crew personnel dosimeters