ANALYSIS OF ALUMINUM PROTECTIVE EFFECT FOR FEMALE ASTRONAUTS IN SOLAR PARTICLE EVENTS

by

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In order to ensure the health and safety of female astronauts in space, the risks of space radiation should be evaluated, and effective methods for protecting against space radiation should be investigated. In this paper, a dose calculation model is established for Chinese female astronauts. The absorbed doses of some organs in two historical solar particle events are calculated using Monte Carlo methods, and the shielding conditions are 0 gcm^{-2} and 5 gcm^{-2} aluminum, respectively. The calculated results are analysed, compared, and discussed. The results show that 5 gcm^{-2} aluminum cannot afford enough effective protection in solar particle events. Hence, once encountering solar particle events in manned spaceflight missions, in order to ensure the health and safety of female astronauts, they are not allowed to stay in the pressure vessel, and must enter into the thicker shielding location such as food and water storage cabin.

Key words: radiation protection, female astronaut, space radiation, Monte Carlo method, organ dose

INTRODUCTION

Radiation is one of the most harmful environmental factors to astronauts in space, and cannot be avoided in manned spaceflight missions. In this context, radiation derives from particles such as protons, α particles, heavy ions, electrons and neutrons. The degree of radiation damage depends on the doses absorbed by various organs or tissues and the radiation type [1].

In the National Aeronautics and Space Administration space flight human system standard (NASA-STD-3001) [2], five organ-dose limits, which pertain to the eye lenses, skin, blood-forming organs (BFO), heart and central nervous system, are defined to protect astronauts against space radiation. At the same time, the career effective dose limits for one year missions and average life-loss for an exposure-induced death for radiation carcinogenesis are also listed, showing the dose limits for women are less than those for men and the average life-loss for women are higher than that for men. Hence, generally speaking, the radiation resistance of women is lower than that of men. Despite this asymmetry, Chinese female astronauts have already entered space. In the future, more females will explore the universe. Therefore, in order to ensure the safety of space exploration as it pertains to female astronauts, the requirements of space radiation protection for female astronauts must be thoroughly analyzed [3, 4].

In this paper, a Chinese female astronaut radiation dose calculation model is developed, and in combination with Monte Carlo methods, the organ doses of Chinese female astronauts are estimated. The isotropic incident particles of interest are protons with an energy range of 10-20 000 MeV. The shielding areal densities investigated are 0 gcm^{-2} and 5 gcm^{-2} aluminum. Finally, considering the characteristics of the solar particle event (SPE) spectrum, the calculated results were analysed, compared, and discussed.

MATERIALS AND METHODS

Chinese female astronaut model

Since organ doses cannot be measured in astronauts' bodies directly, computational phantoms, together with Monte Carlo methods, are used to precisely simulate space radiation interacting with the

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human body and energy depositing in the human body. Female astronaut model is the basic and key condition of the research. The original images were taken from the visible chinese human adult female (VCH-F) high-precision data sets with an image resolution of 0.10 mm mm mm [5]. The data were obtained from the successive cryosectioning of a 19-year-old female cadaver (156 cm in height and 46 kg in weight), who died of food poisoning without any organ or tissue damage. In order to eliminate the impact of movement, rotation and deformation in the image acquisition process, image rectification was carried out. Automatic segmentation and interactive manual segmentation were used to identify tissues and organs. Thirty tissues and organs, each labeled with a specific identification number, were identified, and total 50,002 pictures were obtained after segmentation. Using rapid 3-D parallel reconstruction software, based on message passing interface (MPI) parallel libraries and the visualization tool kit (VTK), the 3-D digital reconstruction of the female model was carried out on multi-CPU computer clusters and distributed memory systems.

The non-uniform rational B-spline (NURBS) model is a 3-D surface model that can be adjusted to achieve fairly realistic anatomy and to implement personalized deformation. The adjustments and deformations can be performed by scaling and rotating a few control points. In order to accord with the precise characteristics of Chinese female astronauts, the NURBS model was adjusted and deformed by changing its mathematical physical parameters, such as control grid, control vertices, node vectors and weighting factor. The parameters of organs and tissues were also modified [6, 7]. A comparison of some parameters between the average values of Chinese female astronauts and Chinese female astronaut model (CFAM) is listed in tab. 1, and CFAM is shown in fig. 1.

At last, the CFAM was re-meshed and then transformed into the voxel model with the appropriate resolution for radiation doses calculation. In order to balance calculation precision and calculation time, the voxel size of the model was set as 1 mm × 1 mm × 1 mm. The database includes 370 million items of data information. Each item includes the co-ordinates of the voxel, the identification code of the organ or tissue, the density, and the element category. The total storage capacity of the database is about 6.33 GB.

Table 1. Comparison of some parameters

Parameter	CFAM	Average values of chinese female astronauts
Height [mm]	1642606	1644
Shoulder width [mm]	348.401	350
Chest thickness [mm]	216.704	211
Trunk length [mm]	661.807	670
Weight [kg]	57.980	57

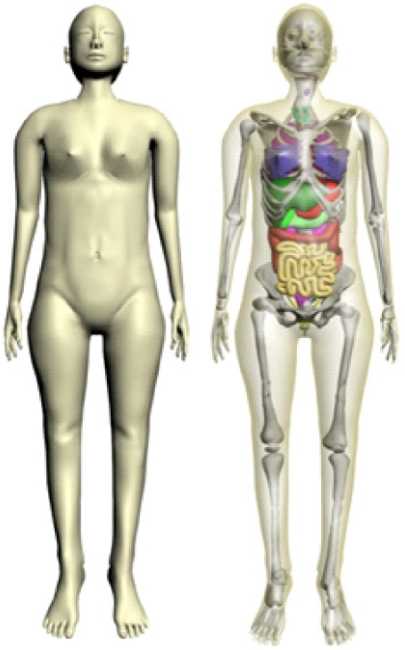

Figure 1. Chinese female astronaut model

Solar particle events

The particles involved in SPE are primarily protons (96 %-99 %), and thus such an event can also be referred to as a solar proton event. During low-Earth orbit flight, owing to the protection afforded by the Earth's magnetic field, SPE affect astronauts only minimally. For manned lunar-landing missions or deep-space exploration, SPE may bring a great threat to health and safety of astronauts.

The August 1972 event has been used in various publications and was also used as a design environment for the NASA Constellation program. The October 1989 event represents a hard spectrum (*i. e.* more intense low energy component) that complicates shielding strategies. The integrated proton fluence spectra of these two historical SPE are shown in fig. 2 [8]. The organ doses during these two SPE were calculated to research the radiation protection effects.

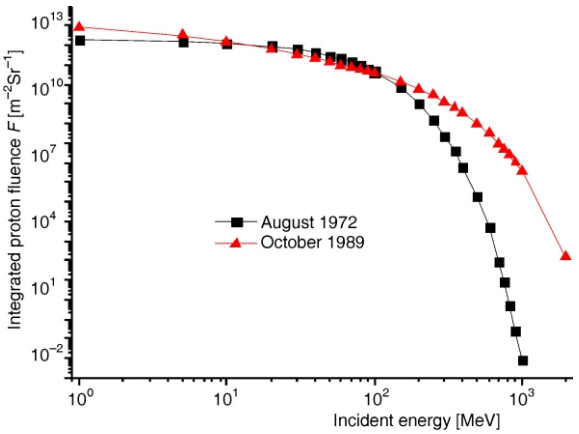

Figure 2. Integrated proton spectra of SPE

Calculation method

In this paper, by making use of Geant4 [9, 10], organ and tissue doses in the CFAM caused by proton were calculated.

Firstly, we calculated the organ doses $D_T(E_0)$ caused by mono-energetic proton with energy E_0, using the following calculation conditions: the energy range investigated was 10-20 000 MeV; the incident direction was isotropic; the shielding areal densities used were 0 gcm^{-2} and 5 gcm^{-2} aluminum (the relative thin shielding location of manned spacecraft, for example the pressure vessel whose average shielding thickness is about 5 gcm^{-2} aluminum).

The proton doses were calculated by integrating the product of each differential proton spectrum $f(E)$ and $D_T(E)$ as

$$D \quad \Phi \quad f(E)D_T(E)\mathrm{d}E \tag{1}$$

where Φ denotes the flux rate through a spherical surface that is the normalization factor related to the spherical source plane used in the Monte Carlo simulation, and E denotes energy.

To perform rapid assessments, the differential proton spectra were represented approximately by their values at discrete points. The doses were then determined as

$$D \quad \Phi \sum_{i\ 1}^{N} f(E_i)D_{T_i}(E_i)\Delta E_i \tag{2}$$

where N denotes the number of discrete points.

RESULTS

Calculation results

In order to satisfy the requirement of calculation error, 10^8 samples at each energy point were set. On this condition, the calculation errors were less than 5 % except at a few low-energy points, and even less than 1 % at almost all high-energy points.

The fluence to organ absorbed dose conversion coefficients, in units of pGy cm^2, were calculated and compared to the corresponding coefficients for the ICRP reference woman [11]. The comparisons of six organs' absorbed doses (skin, red marrow, heart, brain, stomach, and ovary) between CFAM and ICRP reference woman are shown in fig. 3. These six organs are representative: skin and red marrow distribute throughout the body and represent external organ and internal organ, respectively; brain, heart, and, stomach are positioned in head, chest, and abdomen, respectively; ovary is the unique organ of a female.

The absorbed doses of fourteen organs and tissues (skin, red marrow, eyes, heart, brain, colon, lungs, stomach, breast, ovary, urinary bladder, esophagus, livers, and thyroid) on upon two different shielding conditions (0 gcm^{-2} and 5 gcm^{-2} aluminum) are presented in fig. 4. Skin, red marrow, eyes, heart and central nervous system (CNS) are used for space radiation safety evaluations in NASA-STD-3001 [2]. The weighting factors of other eight organs and tissues are relatively large compared to the rest of the organs and tissues. The recommendations for tissue weighting factors (from ICRP publication 103 [12]) are listed in tab. 2.

Table 2. Tissue weighting factors in ICRP publication 103 [12]

Tissue	Tissue weighting factor
Red marrow, colon, lungs, stomach, breast, remainder [a]	0.12
Gonad	0.08
Urinary bladder, esophagus, livers, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01

[a] Component organs for remainder in ICRP 103: adrenals, extra-thoracic airways, gallbladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix

Organ doses in SPE

The proton differential spectra were calculated from fig. 2. The calculated results are shown in fig. 5 and fig. 6.

DISCUSSION

Comparison of calculation results

From figs. 3 and 4, the following characteristics can be identified.

Though there are deviations between calculated and reference coefficients, the variation trend is consistent. At most of the energy points, the deviations are less than 30 %; at some high energy points, the deviations are less than 20 %. These deviations may be caused by two reasons: the first reason is the differences between CFAM and ICRP reference woman; the second reason is the differences between Geant4 and PHITS (the Monte Carlo transport code used to calculate the corresponding coefficients in ICRP Publication 123) [11].

For red marrow, there are large differences between the calculated coefficients and those of the ICRP reference woman, and at low energy points the differences are even in magnitude. The reason for these discrepancies could be that because red marrow is distributed differently in different regions of the human body, minor changes in the models could have strongly affected the calculation results, especially at low energy points.

When the incident energy is approximately below 100 MeV, most of organ doses decrease obviously on 5 gcm^{-2} aluminum shielding condition compared to

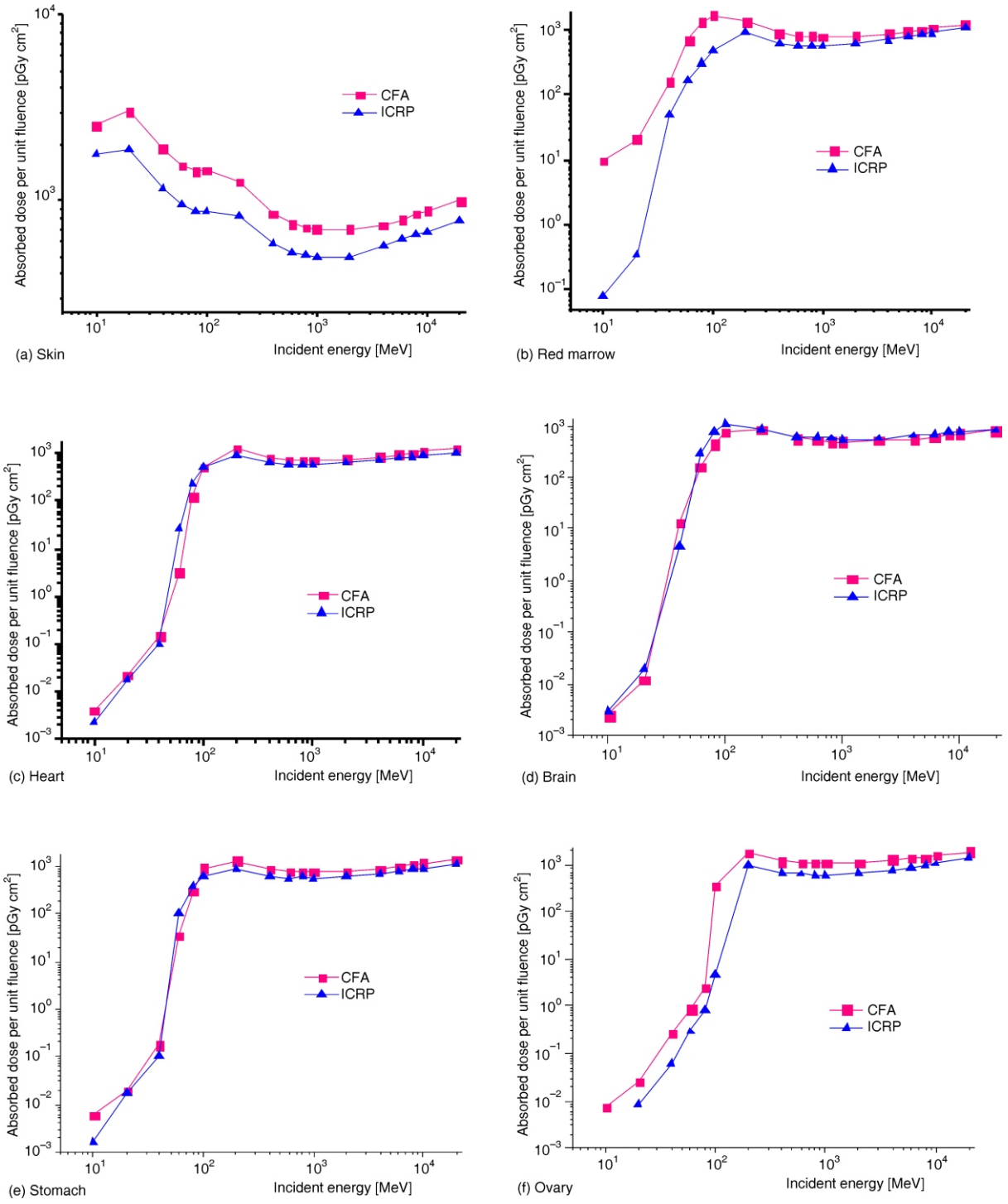

Figure 3. Comparison of the absorbed dose between CFAM and ICRP reference woman

0 gcm^{-2} shielding condition. Taking skin for example, the skin dose decreases to about 30 %-35 % at the energy range 10-60 MeV.

When the incident energy is about 100-1000 MeV, the organ doses exhibit no obvious differences on two shielding conditions (5 gcm^{-2} aluminum and 0 gcm^{-2}), and the deviations are almost all less than 10 %.

When the incident energy is 1000 MeV, the organ doses increase on 5 gcm^{-2} aluminum shielding condition compared to 0 gcm^{-2} shielding condition, and the increment become large with the increase of incident proton energy. Taking skin for example, the skin dose increases by 17 %-34 % at the energy range 2000-20000 MeV.

For some organs, even when the incident energy is below 100 MeV, the organ doses increase on 5 gcm^{-2} aluminum shielding condition compared to 0 gcm^{-2} shielding condition. Taking ovary for example, the ovary dose increases by 37 % at 10 MeV and 34 % at 60 MeV.

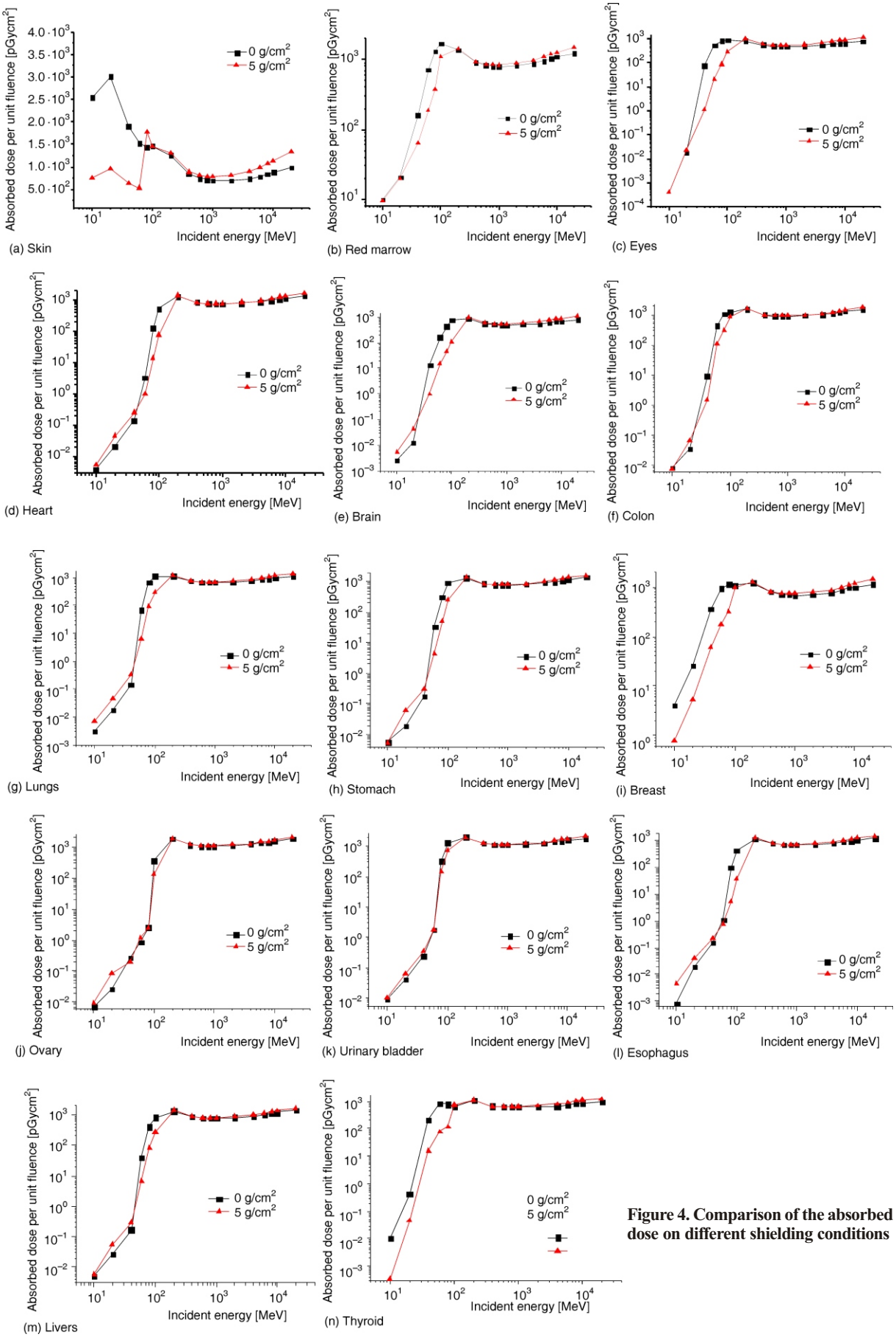

Figure 4. Comparison of the absorbed dose on different shielding conditions

Based on the above-mentioned observations, it is evident that the organ dose variations on two shielding conditions are complex. To clarify the radiation protection effect of 5 gcm^{-2} aluminum, the organ doses on these two different shielding conditions during two historical SPE were calculated.

Extent of protection against SPE

From figs. 5 and 6, the following observations can be made.

The skin dose in the October 1989 SPE is higher than that in August 1972 SPE, because the low energy proton flux is greater for the former SPE.

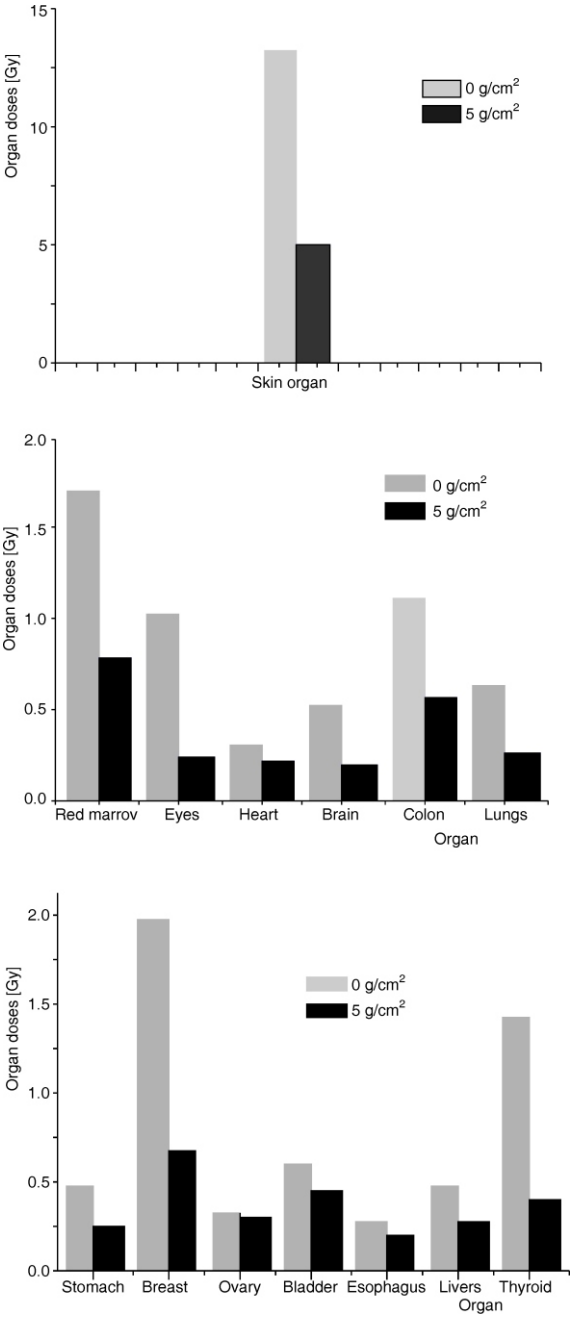

Figure 5. Organ doses during August 1972 SPE

The internal organ doses resulting from October 1989 SPE are lower than those from August 1972 SPE. These differences are present because the maximum internal organ absorbed dose conversion coefficients appear around 100 MeV. Hence, the internal organ doses' orders of magnitude depend upon the fluence of incident protons with energies around 100 MeV. Although the fluence of protons with energies below 30 MeV is higher for October 1989 SPE than for August 1972 SPE, the fluence of protons with energies 30-100 MeV is lower for October 1989 SPE than for

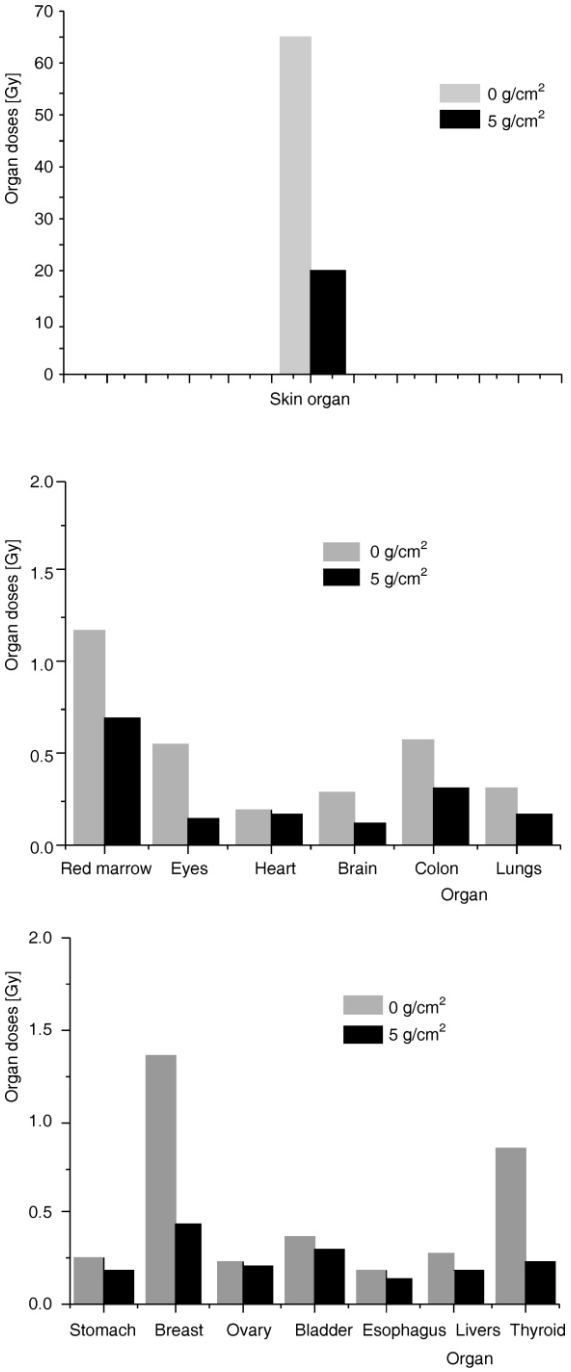

Figure 6. Organ doses during October 1989 SPE

August 1972 SPE. Therefore, the internal organ doses caused by October 1989 SPE are lower than those caused by the August 1972 SPE.

The organ dose variations with shielding condition range from 0.22 to 0.91 in August 1972 SPE and from 0.27 to 0.96 in the October 1989 SPE. Hence, some of the organ doses clearly decrease due to 5 gcm^{-2} aluminum shielding condition, while others do not. The detailed discussions are as follows.

In general, the shielding effect of 5 gcm^{-2} aluminum is better for August 1972 SPE than for October 1989 SPE.

On 5 gcm^{-2} aluminum shielding condition, the skin, eyes, breast, and thyroid doses decrease to below 40 % in both SPE, consequently for these organs, the shielding effect of 5 gcm^{-2} aluminum is evident.

On 5 gcm^{-2} aluminum shielding condition, the heart, ovary, urinary bladder and esophagus doses decrease to above 70 % in both SPE, consequently for these organs especially for ovary, the shielding effect of 5 gcm^{-2} aluminum is not evidently.

For the other organs, the shielding effect of 5 gcm^{-2} aluminum is in the middle level in both SPE.

CONCLUSIONS

In this study, Chinese female astronaut model (CFAM) was developed. The radiation doses received by some organs in CFAM due to protons were calculated using the Monte Carlo method. Finally, the organ dose variations on different shielding conditions in two historical SPE, were analyzed. The conclusions are as follows.

For manned lunar-landing mission or deep-space exploration, the radiation risk is significant due to the lack of protection afforded by the Earth's magnetic field [13]. For different organ or tissue, the shielding effect of 5 gcm^{-2} aluminum varies in SPE. Some organ doses obviously decrease on 5 gcm^{-2} aluminum shielding condition, while others do not. Taking some organs for example, the decrease of eyes dose and thyroid dose is more than 70 %, whereas the decrease of ovary dose is less than 10 %. Hence, though 5 gcm^{-2} aluminum can afford some protection for female astronauts in SPE, however it cannot ensure female astronauts' safety once encountering SPE. For instance, on 5 gcm^{-2} aluminum shielding condition, skin dose is still over 20 Gy and the red marrow dose is approximate 0.7 Gy in October 1989 SPE. Therefore, once encountering SPE in manned spaceflight missions, in order to ensure the health and safety of female astronauts, they are not allowed to stay in the pressure vessel whose average shielding thickness is about 5 gcm^{-2} aluminum, and must enter into the thicker shielding location such as food and water storage cabin.

AUTHORS' CONTRIBUTIONS

The idea of this paper was put forward by F. Xu and C. Yang. The calculations were done by F. Xu. The analysis and discussion was carried out by F. Xu, X. Jia, and W. Lu. The Chinese female astronaut model was developed by F. Xu, Q. Liu, and Z. Pan. The manuscript and figures were prepared by F. Xu and C. Yang.

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REFERENCES

[1] Cucinotta, F. A., Durante, M., Cancer Risk from Exposure to Galactic Cosmic Rays: Implications for Space Exploration by Human Beings, *Lancet Oncol., 7* (2006), 5, pp. 431-435
[2] Williams, R. S., *et al.*, NASA Space Flight Human System Standard Volume 1: Crew Health (Nasa Technical Standard), Washington, D. C., USA, 2012
[3] Townsend, L. W., *et al*., Information Needed to Make Radiation Protection Recommendations for Space Missions beyond Low-Earth Orbit (NCRP Report 153) , Bethesda, Md., USA, 2006
[4] Qi, Z. N., Radiation Protection and Monitoring for Manned Spaceflight, National Defense Industry Press, Beijing, China, 2003
[5] Tang, L., *et al*., Color Atlas of Chinese Digital Human (Female), People's Military Medical Press, Beijing, China, 2006
[6] Sun, W. J., *et al*., Construction of Boundary-Surface-Based Chinese Female Astronaut Computational Phantom and Proton Dose Estimation, *Journal of Radiation Research, 54* (2012), 2, pp. 383-397
[7] Richmond, C. R., *et al*., Basic Anatomic and Physiological Data for Use in Radiological Protection Reference Values (ICRP Publication 89), Pergamon Press, Oxford, UK, 2001
[8] Zhuang, H. C., The Manual of Space Environment, Press of Science and Technology of China, Beijing, China, 2000
[9] Xu, F., *et al*., Comparison of Organ Doses in Human Phantoms: Variations Due to Body Size and Posture, *Radiation Protection Dosimetry, 174* (2016), 1, pp. 21-34
[10] Jia, X. H., *et al*., Estimates of Space Radiation Exposure to Astronauts Using Male Voxel Model Based on MRI, *Space. Med. Med. Eng., 21* (2008), 4, pp. 299-303
[11] Clement, C. H., *et al*., Assessment of Radiation Exposure of Astronauts in Space (ICRP Publication 123), Exeter, UK, 2013
[12] Clarke, R. H., *et al*., The 2007 Recommendations of the International Commission on Radiological Protection (ICRP Publication 103), Exeter, UK, 2007
[13] Jia, X. H., *et al*., Study of Magnetic Field Expansion Using a Plasma Generator for Space Radiation Active Protection, *Chinese Physics C, 37* (2013), 9, pp. 126-131

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АНАЛИЗА ЗАШТИТНИХ МОГУЋНОСТИ АЛУМИНИЈУМА ОД СОЛАРНИХ ЧЕСТИЦА ЗА ЖЕНА АСТРОНАУТЕ

Да би се обезбедила заштита здравља и сигурност жена астронаута у свемиру, потребно је проценити ризик услед излагања зрачењу и испитати делотворност метода за заштиту од космичког зрачења. У овом раду приказан је модел прорачуна дозе за кинеске жене астронауте. Применом Монте Карло методе прорачунате су апсорбоване дозе у органима за два соларна догађаја из прошлости, при чему је употребљена заштита износила 0 gcm^{-2} и 5 gcm^{-2} алуминијума. Анализом и упоређивањем добијених резултата утврђено је да 5 gcm^{-2} алуминијума није довољна заштита од зрачења током соларних догађаја. Стога, уколико дође до соларних догађаја током мисија са људском посадом, женама астронаутима не треба допустити да остану у кабини под притиском већ се морају померити на места са бољом заштитом, као што су оставе за складиштење воде и хране.

Кључне речи: заштита од зрачења, жена астронаут, космичко зрачење, Монте Карло метода, доза за орган