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Abstract

No regulatory dose limits are specifically assigned for the radiation exposure of female breasts during manned spaceflight. However, the relatively high radiosensitivity of the glandular tissue of the breasts and its potential exposure to solar-flare protons on short- and long-term missions mandate a priori estimation of the associated risks. In this report, a model for estimating exposure within the breast is developed for use in future NASA missions.

The female breast and torso geometry is represented by a simple interim model. A recently developed proton dose-buildup procedure is used for estimating doses. The model considers geomagnetic shielding, magnetic-storm conditions, spacecraft shielding, and body self-shielding. Inputs to the model include proton energy spectra, spacecraft orbital parameters, STS orbiter-shielding distribution at a given position, and a single parameter allowing for variation in breast size.

Introduction

Career total body dose limits proposed by the National Council on Radiation Protection and Measurements (ref. 1) have been adopted by NASA for astronauts on any nonexploratory class missions. These limits depend upon the age at first exposure, are gender specific, and are based on a 3-percent increased lifetime risk of cancer mortality. Annual dose limits to the lens of the eye, skin, and blood-forming organs (BFO) also exist, and preliminary dose estimates to these tissues have been made (ref. 2) for exposure to cosmic radiation during low Earth orbit and other space missions. No annual dose limit is currently imposed specifically upon the female breast tissue. However, analyses suggest that the female breast is one of the most sensitive organs to the carcinogenic effects of ionizing radiation. The relatively high radiosensitivity of this tissue is partially responsible for the fact that female career dose limits are only 65 to 85 percent of the corresponding career limit to males (ref. 1).

Solar proton events (solar flares) present a potential source of high-energy proton exposure during space activities except in low Earth orbit at low inclination. The high penetrability of the most energetic protons makes them particularly difficult to shield against. Although the geomagnetic field of the Earth provides some protection to crewmembers in low Earth orbit, unacceptable exposure levels may occur during magnetic-storm conditions. Such events can be lethal if adequate protection is not provided in free space. The statistical nature of these events is such that the prediction of exposure is impossible. Rather, a worst-case scenario is usually described as some spectrum that has an estimated probability of occurring for a given time interval. In addition to cosmic radiations, protons of the trapped radiations are usually unavoidable in low Earth orbit.

Virtually all breast cancers arise from the 15 to 20 glandular tissue lobes which exist within the connective tissue stroma. The stroma lies beneath a thin outer layer of skin and a subdermal layer of adipose tissue that is several millimeters to about 1 centimeter thick. Most breast cancers occur centrally and laterally in proportion to the amount of glandular tissue in these volumes (ref. 3). The masses of the various types of tissue in the breast vary widely between individuals and with age.

A mathematical model of an "average" adult male was developed by Snyder, Ford, Warner, and Watson (ref. 4). Cristy and Eckerman (ref. 5) used this model to derive infant, child, 15-year-old, and adult male models. Following the observation that the body weight and dimensions of an adult female are approximately those of the 15-year-old male model, modifications were made to that model to simulate the adult female. Breasts, ovaries, and uterus were added. This "hermaphroditing" of a male model is a common method in studies of internally deposited radionuclides in women and should be equally acceptable for future consideration of external irradiation. However, data for use with external radiation are not currently available.

As an interim measure, a simplified geometry is developed in this study to simulate the self-shielding of the female body. A tissue-equivalent truncated sphere placed on a finite-tissue equivalent slab is used. The slab dimensions are somewhat larger than the average female torso to compensate for the shielding provided by the arms, legs, and head.

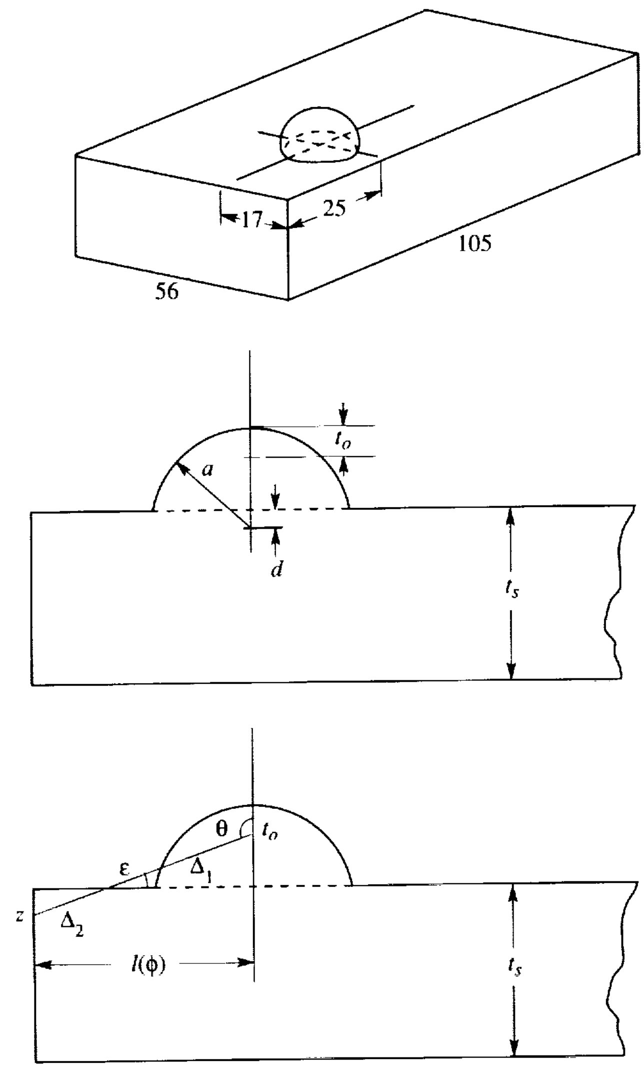

Figure 1. Breast geometry in meridian plane showing basic variables. All dimensions are in centimeters; a = 7, 10, and 13 cm; t_o = 0.5, 2, 4, and 7 cm; d = 2 cm; t_s = 25 cm.

Simplified Breast Geometry

We take as an interim geometry a tissue-equivalent truncated sphere placed on a finite-tissue equivalent slab (fig. 1). The slab dimensions are taken as the mean dimensions of the trunk, and the dimension for the truncated spheres is to be in accordance to individual geometry. Herein we consider a small, medium, and large breast size by taking the sphere radius a to be a parameter 7, 10, and 13 cm, respectively, with a base after truncation of 13.4, 19.6, and 25 cm, respectively; the 0g height $(a-d)$ is then 5, 8, and 11 cm, respectively. The sensitive sites are assumed distributed. The average exposure for the sites is calculated along the axis of symmetry as a mean dose at depths of 0.5, 2, 4, and 7 cm. For convenience, we establish a spherical-coordinate system centered at each dose point t_o and zenith outward along the axis of symmetry. The general geometry in any meridian plane is shown in figure 1. The length l is a function of the azimuth angle ϕ. We neglect the shielding provided by the second breast. The chord length in the breast tissue is

$$\Delta_1(\theta) = \left[(a-t_o)^2 \cos^2\theta + t_o(2a-t_o)\right]^{1/2} - (a-t_o)\cos\theta \quad (1)$$

and the total chord length is

$$t(\theta) = \Delta_1(\theta) \qquad \left(0 \le \theta \le \frac{\pi}{2} + \epsilon_1\right) \quad (2)$$

where

$$\tan\epsilon_1 = \frac{a-t_o-d}{l}$$

and θ is the polar angle. Defining

$$\epsilon = \theta - \frac{\pi}{2}$$

the trunk chord length may be written in terms of the following function:

$$Z = l\tan\epsilon - (a-d-t_o) \quad (3)$$

as

$$\Delta_2(\theta) = \begin{Bmatrix} 0 & (Z \le 0) \\ \dfrac{Z}{\sin\epsilon} & (0 \le Z \le t) \\ \dfrac{t}{\sin\epsilon} & (\text{Otherwise}) \end{Bmatrix} \quad (4)$$

The total thickness function is then

$$t(\theta) = \Delta_1(\theta) + \Delta_2(\theta) \qquad \left(0 \le \theta \le \frac{\pi}{2} + \epsilon_2\right) \quad (5)$$

where

$$\tan\epsilon_2 = \frac{a-t_o-d}{\sqrt{a^2-d^2}}$$

For larger values of θ,

$$t(\theta) = \begin{Bmatrix} \dfrac{Z+a-d-t_o}{\sin\epsilon} & (0 \le Z \le t) \\ \dfrac{t+a-d-t_o}{\sin\epsilon} & (t \le Z) \end{Bmatrix} \quad (6)$$

The azimuth values of l will have local minima at $\phi = 0$, $\frac{\pi}{2}$, π, and $\frac{3}{2}\pi$ corresponding to l_1, l_2, l_3, and l_4.

There are four boundaries in ϕ separating the local minima and related through

$$\frac{l_1}{\cos \phi_1} = \frac{l_2}{\cos\left(\frac{\pi}{2} - \phi_1\right)} \tag{7}$$

$$\frac{l_2}{\cos\left(\phi_2 - \frac{\pi}{2}\right)} = \frac{l_3}{\cos\left(\pi - \phi_2\right)} \tag{8}$$

$$\frac{l_3}{\cos\left(\phi_3 - \pi\right)} = \frac{l_4}{\cos\left(\frac{3}{2}\pi - \phi_3\right)} \tag{9}$$

$$\frac{l_4}{\cos\left(\phi_4 - \frac{3}{2}\pi\right)} = \frac{l_1}{\cos\left(2\pi - \phi_4\right)} \tag{10}$$

Then l as a function of azimuth is

$$l(\phi) = \frac{l_i}{\cos\left[\phi - (i-1)\frac{\pi}{2}\right]} \qquad (\phi_{i-1} \leq \phi \leq \phi_i) \tag{11}$$

where $\phi_o \equiv \phi_4 - 2\pi$. The total chord length is then given by $t(\theta, \phi)$ or $t(\Omega)$, where numerical values are given by equations (1) through (11). Approximate values of l_i are 17, 80, 39, and 25 cm, respectively, for which

$$\phi_1 \rightarrow \phi_4 = \{78°,\ 116°,\ 212.7°,\ 304.2°\}$$

The thickness t_s is taken as 25 cm. The dose response is given as usual by

$$R_B(E) = \int d\Omega\ R[E, t(\Omega)] \tag{12}$$

The present method has been incorporated into a computer code written for the Shuttle geometry (ref. 6) for use in future mission analysis.

Results

The solar event of February 1956 was a large, high-energy event in which energetic particles up to several GeV were observed. As a relativistic particle event, the ground-level neutron monitor onset started about 20 minutes after the optical flare and peaked 20 minutes after onset as shown in figure 2. The intensities decayed 2 to 3 hours after the event. In contrast, the event of August 1972 was a relatively soft spectrum but of high intensity. Onset was 4 hours with peak intensities reaching a few hours after onset followed by slow decay over the next dozen hours. In terms of high-energy intensity and total proton fluence, these two events bracket most other large events.

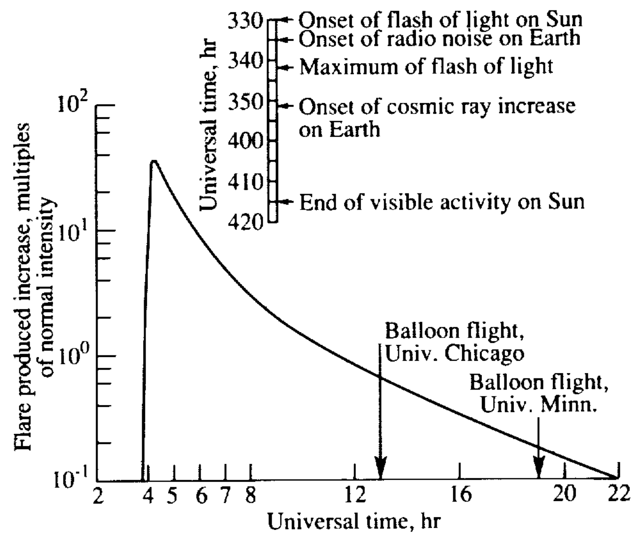

Figure 2. Cosmic ray neutron surge at sea level during large solar event of February 23, 1956.

A dose for a medium-size breast was calculated for these two events with two standard shield configurations. The first shield was an aluminum shield 0.5 g/cm^2 thick, which is representative of a hardened spacesuit, and the second was the least shielded region in the Space Shuttle Orbiter, which is representative of typical spacecraft shielding without the use of a storm shelter. The concern here is not so much the overall exposure, which varies greatly from event to event, but rather the dose distribution which may be important in assessing the exposure. Results are shown in figures 3 and 4. These results show that the large variations in exposure occur over a large volume of breast tissue for either event for the aluminum shield 0.5 g/cm^2 thick. Even for a typical spacecraft configuration, there exist large dose gradients within the breast tissues for the softer solar flare spectra. The exposure is expected to be fairly uniform within a spacecraft for high-energy spectra like the February 1956 event spectrum.

The average breast exposure is compared with exposure values for other critical organs in figures 5 and 6. The results show that the average breast exposure may be twice the exposure of the blood-forming organs (BFO), especially for low-energy, solar particle event (SPE) spectra. This is a potentially important factor in the overall exposure budget.

Qualitatively, there were no great differences observed in the dose gradient along the axis of symmetry so that average doses for the three breast sizes will be within 10 percent of the average among the sizes.

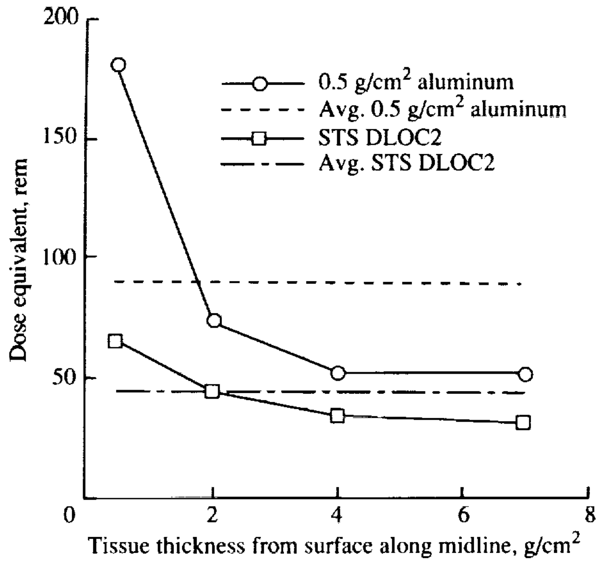

Figure 3. Dose equivalent exposure along breast centerline for February 23, 1956.

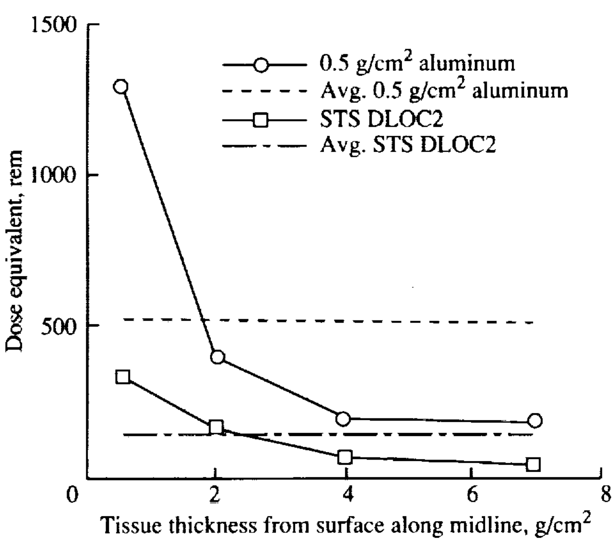

Figure 4. Dose equivalent exposure along the breast centerline for August 4, 1972.

This result occurs because dose distribution depends on the radius of curvature which varies slowly with breast size. This result greatly simplifies the monitoring of individual exposure, since the 10-cm radius model should provide adequate values for all. This is especially true if the astronauts are located inside the vehicle where breast-size effects are entirely negligible. However, even for extravehicular activity in heavy space suits (0.5 g/cm^2), this is a reasonably accurate approximation.

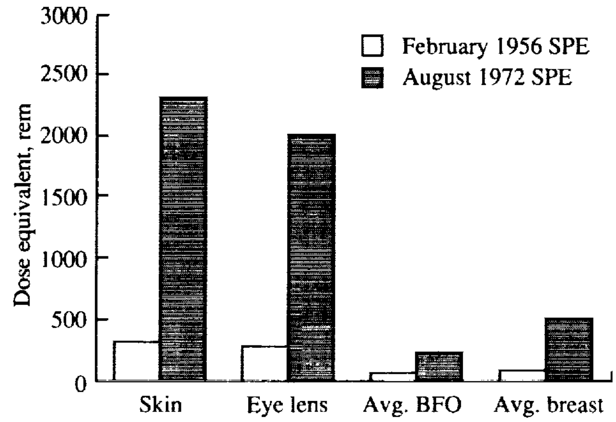

Figure 5. Organ dose equivalent for hardened space suit for two solar events.

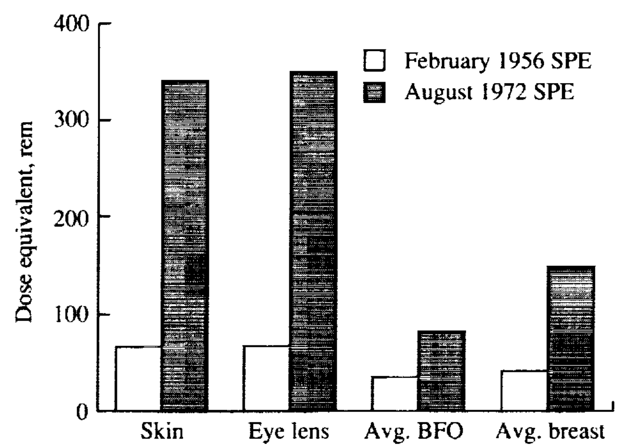

Figure 6. Organ dose equivalent for typical space vehicle for two solar events.

Concluding Remarks

Exposure estimates for the female breast in future space missions can be made on the basis of a fixed, typical breast size (Radius = 10 cm). One should bear in mind that dose variation within the sensitive volume is large (a factor of 2 to 3), although breast size appears not to be a sensitive factor. Further study in assessing the importance of this large dose variation should be made.

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15. Supplementary Notes

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