## Chapter 8 Appendix 1

# THE JAPANESE ADULT, CHILD, AND INFANT PHANTOMS

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The mathematical phantom for adult Japanese atomic-bomb survivors is a modification of the 57-kg Oak Ridge National Laboratory (ORNL) phantom for Western 15-year-old males and adult females.[1] For younger Japanese survivors mathematical phantoms were similarly modified from the 18 and 9 kg ORNL phantoms for Western 5- and 1-year-olds, respectively.[2] To make the phantom correspond more closely with dimensions and organ sizes recommended for Japanese adults by Maruyama and coworkers (cf El84), changes were made in the size of the lungs, the pancreas, the thyroid, and the testes and in the length of the legs. Also, the head-and-neck region was modified to improve the dose estimates for the thyroid from external radiation, after the ideas of Nagarajan et al.[3] The arms were separated from the trunk to represent more accurately the shielding by the phantom in external exposures. Furthermore, provisions were made to provide a phantom in a kneeling posture. The elemental composition of the tissues was changed to that given by Kerr.[4] The resulting phantom is slightly smaller in mass (55 kg). Details of these changes are given below.

### Description of the Japanese Phantoms

The description of the phantom will follow the format of Snyder et al,[5] Cristy,[2] and Cristy and Eckerman,[1] and even include language and diagrams used therein (without formal attribution in many cases) so that the reader will not have to refer to those publications constantly to fill in missing information.

Each phantom consists of four major sections: 1) an elliptical cylinder representing the trunk; 2) truncated circular cones representing the legs and feet; 3) a circular cylinder (neck) topped by an elliptical cylinder that in turn is topped by half an ellipsoid representing the head and neck; and 4) two truncated circular cones representing the arms, which may either

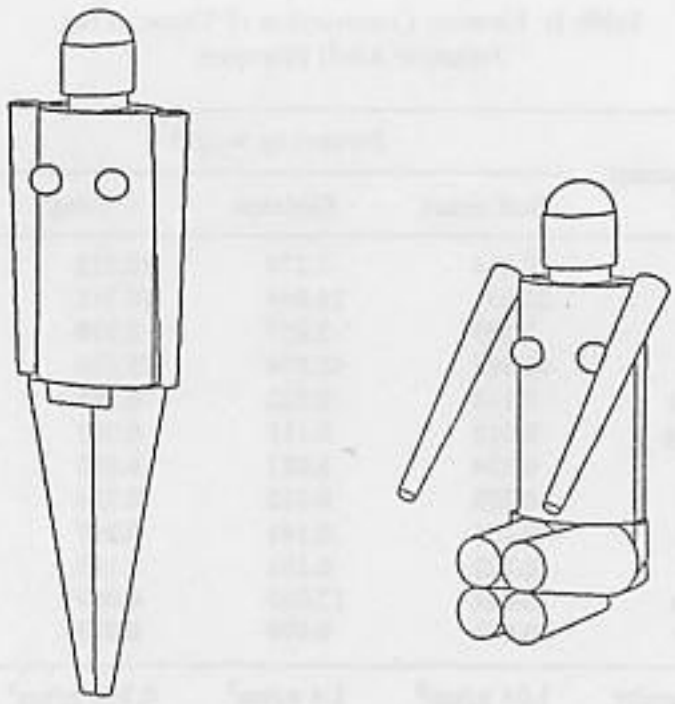

*Figure 1. The Japanese adult phantom*

hang down from the shoulders or be extended forward. Attached to the legs section is a small region with a planar front surface to contain the testes (this region is called the male genitalia). Attached to the trunk are portions of two ellipsoids representing the female breasts; these should be removed when dose to the lung in males from external radiation is required. The exterior of the phantom is depicted in Figure 1. Minor appendages such as hands, feet, ears, and nose are omitted. The neck region in this phantom is more realistic than in previous ORNL phantoms.

**Elemental Composition of the Tissues**

Three types of tissues - skeletal, lung, and all other tissues (called "soft tissue" here) - are recognized in the Monte Carlo radiation transport codes used at ORNL.[6,7] The elemental composition of each tissue type is from Kerr[4] and is given in Table 1. The compositions are similar to those given by Cristy and Eckerman[1] except that the calcium content of the skeleton is about 20% higher in Kerr's tabulations.

On the basis of data in Table 105 of ICRP Publication 23,[8] Cristy and Eckerman[1] changed the densities of skeletal and soft tissues slightly from those given by Snyder et al.[5] Compared with the densities assigned by Snyder et al, the new densities were changed from 1.4862 to 1.4 g $cm^{-3}$ for skeletal tissue and from 0.9869 to 1.04 g $cm^{-3}$ for soft tissue. The lung density is unchanged but was rounded to three significant digits (0.296 g $cm^{-3}$). These new densities are used here.

**Description of the Body Regions and Organs**

The exterior of the phantom has approximately the form of the human body; but, as in other ORNL phantoms, there has been no attempt to introduce small variations which are presumed to have only a small effect on the scattering of photons and neutrons. Similarly,

Table 1. Element Composition of Tissue in the Japanese Adult Phantom

| Element | Percent by weight | | |
|---|---|---|---|
| | Soft tissue | Skeleton | Lung |
| H | 10.514 | 7.279 | 10.212 |
| C | 22.631 | 24.644 | 10.241 |
| N | 2.339 | 3.057 | 2.910 |
| O | 63.686 | 46.884 | 75.630 |
| Na | 0.114 | 0.322 | 0.185 |
| Mg | 0.013 | 0.111 | 0.007 |
| P | 0.134 | 5.027 | 0.080 |
| S | 0.202 | 0.312 | 0.226 |
| Cl | 0.136 | 0.141 | 0.267 |
| K | 0.202 | 0.151 | 0.195 |
| Ca | 0.024 | 12.065 | 0.009 |
| Fe | 0.006 | 0.008 | 0.037 |
| Density | 1.04 g/cm$^3$ | 1.4 g/cm$^3$ | 0.296 g/cm$^3$ |

the description of the interior organs, while approximately correct as to size, shape, positions, composition, and density, are simplified to provide formulas which are readily calculated on a digital computer. The 15 internal organs specified for use in the dosimetry system are given below.

**Body Regions.** The body is represented as erect with the positive z-axis directed upward toward the head. The x-axis is directed to the phantom's left (the readers right in Figure 1), and the y-axis is directed toward the posterior side of the phantom.

In general, the dimensions (in centimeters) are given to two decimal places. The use of two decimal places does not imply that the average dimensions in some human population are known to such precision. This use is for convenience in designing the organs with correct volumes and spatial relationships. For each parameter three values will be given. They are for the adult, child, and infant Japanese phantoms.

**Trunk.** The trunk, exclusive of the female breasts, is represented by two sections of solid elliptical cylinders specified by:

$$\left[\frac{x}{a_{2S_c} + S}\right]^2 + \left[\frac{y}{b_{S_c} + S}\right]^2 \leq 1 \tag{1a}$$

when

$$0 \leq z \leq C_T$$
$$0 \leq y$$
$$-(a_R + S) \leq x \leq (a_R + S)$$

and by

$$[\frac{x}{a_R + S}]^2 + [\frac{y}{b_R + S}]^2 \leq 1 \tag{1b}$$

when

$$0 \leq z \leq C_T$$
$$y \leq 0$$

Here $a_{2S_e}$ = 16.36, 10.88, and 6.04 cm, $b_{S_e}$ = 9.60, 7.35, and 6.37 cm, $a_R$ = 14.66, 9.73, and 7.48 cm, $b_R$ = 9.60, 7.35, and 6.37 cm. $S$ is the skin thickness, and $C_T$ = 63.10, 40.80, and 30.70 $cm^3$. The parameters with the $S_e$ subscript are also found in the section on the scapulae. The parameters with the $R$ subscript are defined in the ribs description.

The volumes of the trunks are 29,745, 9716, and 4872 $cm^3$ excluding the volume of the breasts.

*Arms.* The individual arm regions are formed at the side of the trunk by two frustrums of two circular cones specified by:

$$[x \pm (a_R + S + RMT)]^2 + y^2 \leq [\frac{RMT + \frac{RMT}{C_T} z}{2}]^2 \tag{2}$$

when

$$0 \leq z \leq C_T$$

The $\pm$ sign is taken as minus for the left arm and plus for the right arm. $RMT$ is the arm radius at the shoulder and is calculated by:

$$\begin{aligned} RMT \;=\; & [\frac{12}{7}[\frac{A_T B_T}{2} - \frac{(a_R + S)(b_R + S)}{4} \\ & - \frac{(a_R + S)(b_{S_e} + S)\sqrt{(a_{2S_e} + S)^2 - (a_R + S)^2}}{2\pi(a_{2S_e} + S)} \\ & - \frac{(b_{S_e} + S)(a_{2S_e} + S)}{2\pi} sin^{-1}[\frac{a_R + S}{a_{2S_e} + S}]]]^{1/2} \end{aligned} \tag{3}$$

The parameters $a_R$, $b_R$, $a_{2S_e}$, $b_{S_e}$, and $C_T$ were defined in the preceding section. $S$ is skin thickness. The parameters $A_T$ = 17.25, 11.45, and 8.80 cm, $B_T$ = 9.80, 7.50, and 6.50 cm, and $RMT$ = 4.036, 2.938, and 2.394 cm.

The volumes of the arms are 3767, 1291, and 645 $cm^3$, about 7% of the total phantom volume.

*Head and Neck.* The head-and-neck section is a right circular cylinder (neck) topped by a right elliptical cylinder which in turn is topped by half an ellipsoid. The locus is specified by:

$$x^2 + y^2 \leq R_H^2 \text{ and } C_T \leq z \leq C_T + C_{H0} \tag{4}$$

or

$$[\frac{x}{A_H}]^2 + [\frac{y}{B_H}]^2 \leq 1 \text{ and } C_T + C_{H0} \leq z \leq C_T + C_{H0} + C_{H1}$$

or

$$[\frac{x}{A_H}]^2 + [\frac{y}{B_H}]^2 + [\frac{z - (C_T + C_{H0} + C_{H1})}{C_{H2}}]^2 \leq 1 \text{ and } z > C_T + C_{H0} + C_{H1}$$

where $A_H$ = 7.77, 7.13, and 6.13 cm, $B_H$ = 9.76, 9.05, 7.84 cm, $R_H$ = 6.80, 5.32, and 4.64 cm, $C_{H0}$ = 3.79, 3.30, 2.93 cm, $C_{H1}$ = 12.18, 10.01, and 9.42 cm, and $C_{H2}$ = 6.92, 6.31, and 5.41 cm. The volumes are 4570, 3670, and 2410 $cm^3$ and the masses are 5060, 3880, and 2470 g. The value of $C_T$ was given previously with the trunk values. A modification for use in calculating thyroid dose is described at the end of this appendix.

*Legs.* The legs region of each phantom consists of the frustrums of two circular cones specified by:

$$x^2 + y^2 \leq \pm x[A_T + \frac{A_T}{C_{L'}}z] \text{ and } -C_L \leq z \leq 0 \tag{5}$$

where the ± sign is taken as plus for the left leg and minus for the right leg, and where $C_L$ = 74.0, 48.0, and 26.5 cm, and $C_{L'}$ = 95.0, 65.0, and 37.1 cm. The value of $A_T$ is that given previously for the trunk. The volumes are 14,600, 4380, and 1470 $cm^3$ and the masses are 15,900, 4630, and 1550 g.

*Male Genitalia.* The male genitalia are in the region specified by:

$$\begin{gathered} z_1 \leq z \leq 0 \\ -r \leq x \leq r \\ -r \leq y \leq 0 \text{ and } (x \pm r)^2 + y^2 \geq r^2 \end{gathered} \tag{6}$$

The last inequality must hold for either choice of sign (i.e., the genital region lies outside both legs). The value of $r$ is given by the expression 0.5 $A_T$ $(1 + z/C_{L'})$, where $A_T$ is the trunk dimension and $C_{L'}$ is the leg dimension defined previously. The value of $z_1$ is given by the expression $-(2c + S)$, where $c$ is the parameter defined below for the testes and $S$ is the skin thickness. Thus, all of the parametric values are defined elsewhere. The volumes are 154, 23.2, and 12.1 $cm^3$ , and the masses are 161, 24.1, and 12.6 g.

*Mass of Total Body.* The total body masses of the phantoms are 55.0, 19.1, and 9.4 kg. The male genitalia and the female breasts are included, and the different densities of lung, skeleton, and soft tissues were taken into account.

**Organs.** In the text below, each organ is explicitly defined and the volume given. The mass determined by this volume and the appropriate density is given in Chapter 8 Appendix 1a.

In the equations of the organs, which follow, the body section parameters $A_T, B_T, C_T$, $A_H, B_H$, $C_{H0}, C_{H1}, C_{H2}, C_L, C_{L'}$, and the skin thickness $S$ will be used without further explanation or denotation. Symbols for other parameters, usually lower case letters, will have meaning only for the organ being defined. The symbols "a," for example, is used in defining many different organs.

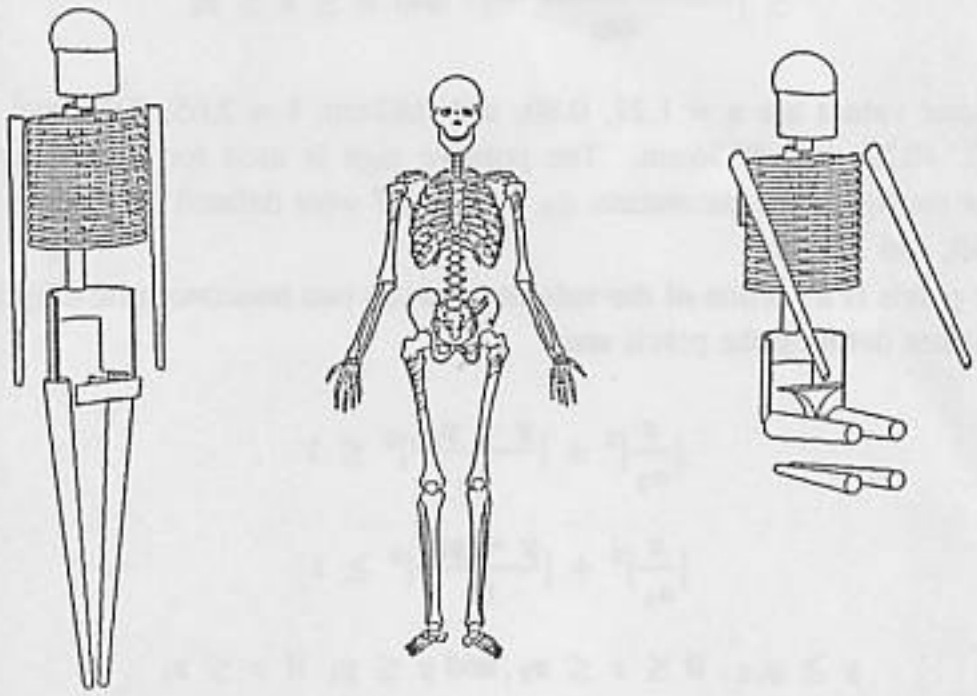

*Figure 2. Skeleton of Japanese adult. Standing phantom (left), kneeling phantom (right), and anatomically correct skeleton (center).*

*Skeletal System.* The skeletal system consists of 13 parts described below. A view of the whole skeleton is shown in Figure 2.

Leg Bones. Each leg bone is the frustrum of a circular cone. In the defining inequalities below, the sign $\pm$ is taken as minus for the left leg bone and plus for the right:

$$[x \pm [\frac{A_T}{2} + \frac{kz}{C_L - S}]]^2 + y^2 \leq [R_1 + [\frac{R_1 - R_2}{C_L - S}]z]^2$$

and

$$-(C_L - S) \leq z \leq 0 \tag{7}$$

where

$$k = \frac{A_T}{2}[1 - \frac{C_{L'} - C_L}{C_{L'}}]$$

$$R_1 = 0.175\, A_T$$

and

$$R_2 = \frac{A_T}{4}[\frac{C_{L'} - C_L}{C_{L'}}]$$

The volumes are 1990, 610, and 207 $cm^3$.

Arm Bones. Each arm bone is the frustrum of an elliptical cone. It is placed off-center in the arm region, such that the outside edge of the bone is in the center of the arm region. It is defined by:

$$\left[\frac{\frac{a}{2z_2}(z - z_2) + (x \pm (a_R + S + RMT - \frac{a}{2}))}{a}\right]^2 + \left[\frac{y}{b}\right]^2$$

$$\leq \left[\frac{2z_2 + (z - z_2)}{2z_2}\right]^2 \text{ and } 0 \leq z \leq z_2 \tag{8}$$

The parameter values are $a$ = 1.21, 0.80, and 0.62 cm, $b$ = 2.65, 2.03, and 1.76 cm, and $z_2$ = 62.20, 40.22, and 30.26 cm. The positive sign is used for the left arm bone, and negative for the right. The parameters $a_R$ and $RMT$ were defined previously. The volumes are 731, 239, and 121 $cm^3$.

Pelvis. The pelvis is a portion of the volume between two nonconcentric elliptical cylinders. The inequalities defining the pelvis are:

$$\left[\frac{x}{a_2}\right]^2 + \left[\frac{y - y_{o2}}{b_2}\right]^2 \leq 1$$

$$\left[\frac{x}{a_1}\right]^2 + \left[\frac{y - y_{o1}}{b_1}\right]^2 \geq 1$$

$$y \geq y_{o2},\ 0 \leq z \leq z_2, \text{and } y \leq y_1 \text{ if } z \leq z_1 \tag{9}$$

The parameter values are $a_1$ = 9.75, 6.47, and 4.97 cm, $b_1$ = 11.07, 8.48. and 7.35 cm, $a_2$ = 10.35, 6.87, and 5.28 cm, $b_2$ = 11.76, 9.00, and 7.80 cm, $y_{o1}$ = -3.72, -2.85, and -2.47 cm, $y_{o2}$ = -2.94, -2.25, and -1.95 cm, $y_1$ = 4.90, 3.75, and 3.25 cm, $z_1$ = 12.62, 8.16, and 6.14 cm, and $z_2$ = 19.83, 12.82, and 9.65 cm. The volumes are 460, 151, and 76 $cm^3$.

Spine. The position of the spine within the head-and-neck region was changed from that given in Cristy and Eckerman[1] for the phantom because of the changes made in the head-and-neck region itself. The spine in the head-and-neck region is offset from the spine in the trunk to give it a more realistic position within the neck of the phantom. The length of the spine within this region was shortened slightly so that it would not overlap the top of the trunk. The spine consists of elliptical cylinders given by:

$$\left[\frac{x}{a}\right]^2 + \left[\frac{y - y_o}{b}\right]^2 \leq 1 \text{ and } z_1 \leq z \leq z_3 - S$$

or

$$\left[\frac{x}{a}\right]^2 + \left[\frac{y}{b}\right]^2 \leq 1 \text{ and } z_3 \leq z \leq z_4 \tag{10}$$

It is divided into three portions - an upper, middle, and lower - such that dose can be estimated separately for each portion. The upper portion is that in the head-and-neck region

($z \geq z_3$), the lower portion is that below the plane $z = a_2$, and the middle portion is that between the planes $z = z_2$ and $z = z_3 - S$. The values of the parameters are $a$ = 1.73, 1.15, and 0.88 cm, $b$ = 2.45, 1.88, and 1.63 cm, $y_o$ = 5.39, 4.13, and 3.58 cm, $z_1$ = 19.83, 12.82, and 9.65 cm, $z_2$ = 31.64, 20.46, and 15.39 cm, $z_3$ = 63.10, 40.80, and 30.70 cm, and $z_4$ = 72.58, 48.83, and 38.01 cm. $S$ is the skin thickness (0.17, 0.09, and 0.08 cm). The volumes of the spines are 702, 245, and 128 $cm^3$.

Skull. The skull comprises the cranium and the facial skeleton. The cranium is represented by the volume between two concentric ellipsoids defined by:

$$[\frac{x}{a}]^2 + [\frac{y}{b}]^2 + [\frac{z - [C_T + C_{H0} + C_{H1}]}{c}]^2 \geq 1$$

and

$$[\frac{x}{a+d}]^2 + [\frac{y}{b+d}]^2 + [\frac{z - [C_T\ ,+\ , C_{H0} + C_{H1}]}{c+d}]^2 \leq 1 \qquad (11)$$

The values of $a$, $b$, and $c$ are the same as those given for the brain. The values of $d$ are 0.76, 0.56, and 0.30 cm. The volumes of the crania are 508, 339, and 139 $cm^3$.

The facial skeleton is represented by a portion of the volume between two concentric elliptical cylinders. The portion of the volume that intersects the cranium and brain is excluded. The inequalities are:

$$[\frac{x}{a_1}]^2 + [\frac{y}{b_1}]^2 \leq 1$$

$$[\frac{x}{a_1 - d}]^2 + [\frac{y}{b_1 - d}]^2 \geq 1$$

$$y \leq 0$$

$$C_T + z_1 \leq z \leq C_T + z_5$$

and

$$[\frac{x}{a_2}]^2 + [\frac{y}{b_2}]^2 + [\frac{z - [C_T + C_{H0} + C_{H1}]}{c_2}]^2 > 1 \qquad (12)$$

The variables $a_2$, $b_2$, and $c_2$ equal the terms (a+d), (b+d), and (c+d), respectively, in the statements defining the cranium. The other parameter values are $a_1$ = 6.92, 6.68, and 5.73 cm, $b_1$ = 8.91, 8.60, and 7.44 cm, $d$ = 1.10, 0.58, and 0.14 cm, $z_1$ = 3.79, 3.30,, and 2.93 cm, and $z_5$ = 14.05, 12.57, and 11.18 cm. The volumes of the facial skeletons are 234, 114, and 22.8 $cm^3$.

Rib Cage. The rib volume is a series of bands between two concentric, right vertical elliptical cylinders. This region is sliced by a series of equispaced horizontal planes into slabs, every other slice being a rib. The statements that must be satisfied are:

$$[\frac{x}{a}]^2 + [\frac{y}{b}]^2 \leq 1 \qquad (13)$$

$$[\frac{x}{a-d}]^2 + [\frac{y}{b-d}]^2 \geq 1$$

$$z_1 \leq z \leq z_2$$

and

$$INT\,[\frac{z-z_1}{c}] \text{ must be even.} \tag{13a}$$

The function $INT$(u) is the integral part of u [e.g., $INT(3.67) = 3$]. Thus the statement, $INT[(z-z_1)/c]$ is even, amounts to requiring:

$$0 \leq \frac{z-z_1}{c} < 1 \text{ or } 2 \leq \frac{z-z_1}{c} < 3 \text{ or } 4 \leq \frac{z-z_1}{c} < 5, \text{ etc.} \tag{13b}$$

The parameter values are $a$ = 14.66, 9.73, and 7.48 cm, $b$ = 9.60, 7.35, and 6.37 cm, $d$ = 0.47, 0.34, and 0.28 cm, $z_1$ = 31.67, 20.53, and 15.44 cm, $z_2$ = 60.65, 39.16, and 29.47 cm, and $c$ =1.26, 0.81, and 0.61 cm. The volumes of the ribs are 531, 174, and 87.4 $cm^3$.

Clavicles. The clavicles are represented as two portions of a torus that lies along the circular arc $x^2 + (y - y_o) = R^2$ at $z = z_1$ and has a smaller radius of $r$. The clavicles include only the portion of the torus between planes $(y_o - y) = |x| \cot \beta_1$ and $(y_o - y) = |x| \cot \beta_2$. (The absolute value sign on $x$ allows for both a right and a left clavicle.) These equations can be reduced to the form:

$$(z - z_1)^2 + [R - \sqrt{x^2 + (y - y_o)^2}]^2 \leq r^2$$

$$\cot\beta_2 \leq \frac{y_o - y}{|x|} \leq \cot\beta_1 \text{ and } y < 0 \tag{14}$$

The parameter values are $y_o$ = 7.22, 3.14, and 1.38 m, $z_1$ = 61.52, 39.78, and 29.93 cm, $R$ = 15.93, 9.80, and 7.14 cm, $r$ = 0.7274, 0.4991, and 0.3930 cm, cot $\beta_1$ = 6.45852, 5.9977, and 5.6814, and cot $\beta_2$ = 0.73137, 0.56391, and 0.43161. The volumes of the two clavicles together are 41.6, 13.7, and 6.85 $cm^3$.

The clavicles are slightly inside the cylinder defining the rib cage and just above the top rib.

Scapulae. The scapulae are defined as part of the volume between two concentric elliptical cyclinders. For each scapula, the volume is bounded by the planes $z = z_1, z = z_2, y = m_1|x|$, and $y = m_2|x|$. (The absolute value sign on $x$ allows for both a right and left scapula.) The defining inequalities are:

$$[\frac{x}{a_2}]^2 + [\frac{y}{b}]^2 \leq 1$$

$$[\frac{x}{a_1}]^2 + [\frac{y}{b}]^2 > 1$$

$$z_1 \leq z \leq z_2$$

$$y > 0$$

and

$$m_1 < \frac{y}{|x|} < m_2 \tag{15}$$

The parameter values are $a_1$ = 14.66, 9.73, and 7.48 cm, $a_2$ = 16.36, 10.88, and 8.36 cm, $b$ = 9.60, 7.35, and 6.37 cm, $z_1$ = 45.88, 29.67, and 22.32 cm, and $z_2$ = 60.67, 39.23, and 29.52 cm, $m_1$ = 0.28, 0.33, and 0.37, and $m_2$ = 0.91, 1.05, and 1.18. The volumes of the two scapulae together are 154, 50.4, and 25.3 $cm^3$ .

Bone Marrow. On the left in Figure 2 is shown a standing adult skeleton. On the right is shown a kneeling adult skeleton. In the center is shown an adult skeleton with the areas containing active marrow cross-hatched.

The approximate weights of the total (active plus inactive) marrow are 2600, 460, and 170 g; the active (hematopoietic) marrow are 1050, 320, and 150 g; and the inactive (fatty) marrow are 1550, 140, and 20 g. The percentages of active and inactive marrow and of bone mass for individual bones, parts of bones, and bone groups of the phantoms are given in Tables 2 to 4. The weights of active and inactive marrow in individual bones are given in Chapter 8 Appendix 1a. The marrow from the lumbar vertebra $L_5$ and 50% of the upper half of the femora were assigned to the pelvis of each phantom (Tables 2 to 4). This assignment occurs because of the simplicity of the skeleton in the phantoms. For example, approximately the upper quarter of the femora is adjacent to the os coxae of the pelvis in humans, but in the phantoms the leg bones begin below the pelvis.

The total masses of the skeletons (bone marrow plus other tissues within the skeleton) are 7500, 2800, and 1210 g.

**Other Organs.**

Brain. The brain is an ellipsoid given by:

$$[\frac{x}{a}]^2 + [\frac{y}{b}]^2 + [\frac{z - [C_T + C_{H0} + C_{H1}]}{c}]^2 \leq 1 \tag{16}$$

The parameter values are $a$ = 6.58, 6.34, and 5.63 cm, $b$ = 8.57, 8.26, and 7.34 cm, $c$ = 5.73, 5.52, and 4.91 cm. The volumes are 1350, 1210, and 850 $cm^3$ .

Breasts. The female breasts are represented by a portion of two ellipsoids attached to the trunk and given by:

$$[\frac{x - x_o}{a}]^2 + [\frac{y - y_o}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1 \tag{17}$$

and

$$[\frac{x}{a_R + S}]^2 + [\frac{y}{b_R + S}]^2 > 1 \tag{17a}$$

where

$$y_o = -b_R + S\sqrt{1 - [\frac{x_o}{a_R + S}]^2}$$

Table 2. Active Marrow in Individual Bones, Parts of Bones, or Bone Groups Expressed as Percent of Active Marrow In the Body

| Phantom skeletal region | Corresponding skeletal region(s) | Percentage | | |
|---|---|---|---|---|
| | | Japanese Adult | Japanese Child | Japanese Infant |
| Skull (cranium + facial skeleton)[a] | Skull (cranium + mandible)[a] | 10.12 | 17.44 | 27.47 |
| Scapulae | Scapulae | 3.26 | 2.72 | 2.73 |
| Clavicles | Clavicles | 0.98 | .85 | .83 |
| Ribs | Ribs + sternum | 16.27 | 10.58 | 9.61 |
| Spine (upper portion[b]) | Cervical vertebrae $C_1$-$C_5$ | 2.25 | 1.46 | 1.88 |
| Spine (middle portion[b]) | Cervical vertebrae $C_6$-$C_7$ + all thoracic vertebrae | 14.75 | 9.58 | 9.27 |
| Spine (lower portion[b]) | Lumbar vertebrae $L_1$-$L_4$ | 8.29 | 5.39 | 3.37 |
| Pelvis | Sacrum + os coxea + lumbar vertebra $L_5$ + 50% of upper 1/2 femora | 33.60 | 23.33 | 16.47 |
| Leg bones (upper portion[c]) | 50% of upper 1/2 femora | 4.60 | 3.41 | 2.07 |
| Leg bones (middle portion[c]) | Lower 1/2 femora | 2.04 | 6.28 | 3.88 |
| Leg bones (lower portion[c]) | Tibiae, fibulae, patellae + ankle and foot bones | 0 | 11.55 | 13.40 |
| Arm bones (upper portion[d]) | Upper 1/2 humeri | 3.14 | 2.36 | 2.41 |
| Arm bones (middle portion[d]) | Lower 1/2 humeri | 0.70 | 2.18 | 2.25 |
| Arm bones (lower portion[d]) | Radii and ulnae + wrist and hand bones | 0 | 2.88 | 4.36 |

[a] In column 1, cranium does not include the facial skeleton, but in column 2, cranium includes all the facial skeleton except the mandible.

[b] The upper, middle, and lower portions of the spine are defined in the section on the spine.

[c] The upper portion of the leg bones is defined as the upper 14% of the length of the bones; the lower portion is defined as the lower 57%; and the middle portion is the rest. The unevenness of these numbers results from the assignment of part of the marrow in the upper femora to the pelvis.

[d] The upper portion of the arm bones is defined as the upper 25% of the length of the bones; the lower portion is defined as the lower 50%; and the middle portion is the rest.

Since the outer thickness $S$ is counted as skin, the breast tissue is represented by:

$$[\frac{x-x_o}{a-S}]^2 + [\frac{y-y_o}{b-S}]^2 + [\frac{z-z_o}{c-S}]^2 \leq 1$$

and

$$[\frac{x}{a_R+S}]^2 + [\frac{y}{b_R+S}]^2 > 1 \qquad (17b)$$

The parameter values are $a$ = 4.50, 0.79, and 0.63 cm, $b$ = 4.00, 0.79, and 0.63 cm, $c$ = 3.80, 0.79, 0.63 cm, $x_o = \pm$ 8.63, $\pm$ 5.73, and $\pm$ 4.40 cm, and $z_o$ = 46.87, 30.31, and

Table 3. Inactive Marrow in Individual Bones, Parts of Bone, or Bone Groups Expressed as Percent of Inactive Marrow in the Body

| Phantom skeletal region | Corresponding skeletal region(s) | Percentage | | |
|---|---|---|---|---|
| | | Japanese Adult | Japanese Child | Japanese Infant |
| Skull (cranium + facial skeleton)[a] | Skull (cranium + mandible)[a] | 5.63 | 10.17 | 11.33 |
| Scapulae | Scapulae | 1.82 | 1.60 | 1.06 |
| Clavicles | Clavicles | 0.61 | .53 | .35 |
| Ribs | Ribs + sternum | 3.70 | 4.32 | 3.90 |
| Spine (upper portion[b]) | Cervical vertebrae $C_1$-$C_5$ | 0.51 | .61 | .78 |
| Spine (middle portion[b]) | Cervical vertebrae $C_6$-$C_7$ + all thoracic vertebrae | 3.34 | 3.95 | 3.82 |
| Spine (lower portion[b]) | Lumbar vertebrae $L_1$-$L_4$ | 1.90 | 2.21 | 1.46 |
| Pelvis | Sacrum + os coxea + lumbar vertebra $L_5$ + 50% of upper 1/2 femora | 13.28 | 13.28 | 6.79 |
| Leg bones (upper portion[c]) | 50% of upper 1/2 femora | 3.83 | 2.36 | .84 |
| Leg bones (middle portion[c]) | Lower 1/2 femora | 12.53 | 5.95 | 3.72 |
| Leg bones (lower portion[c]) | Tibiae, fibulae, patellae + ankle and foot bones | 36.66 | 39.29 | 43.35 |
| Arm bones (upper portion[d]) | Upper 1/2 humeri | 2.62 | 1.63 | .97 |
| Arm bones (middle portion[d]) | Lower 1/2 humeri | 4.29 | 2.06 | 2.21 |
| Arm bones (lower portion[d]) | Radii and ulnae + wrist and hand bones | 9.28 | 12.04 | 17.45 |

a In column 1, cranium does not include the facial skeleton, but in column 2, cranium includes all the facial skeleton except the mandible.

b The upper, middle, and lower portions of the spine are defined in the section on the spine.

c The upper portion of the leg bones is defined as the upper 14% of the length of the bones; the lower portion is defined as the lower 57%; and the middle portion is the rest. The unevenness of these numbers results from the assignment of part of the marrow in the upper femora to the pelvis.

d The upper portion of the arm bones is defined as the upper 25% of the length of the bones; the lower portion is defined as the lower 50%; and the middle portion is the rest.

22.81 cm. The positive values of $x_o$ are for the left breast and the negative values for the right. The parameters $a_R$, $b_R$, and $S$ were defined previously. The volumes of the two breasts together are 302, 2.09, and 1.06 $cm^3$ including the skin and 265, 1.45, and 0.704 $cm^3$ excluding the skin.

There is some diasagreement between Kramer and coworkers[9,10] and Cristy[2,11] on the appropriate size of the breast for a reference adult female (Western populations). Cristy[11] recommends a volume of 190 to 200 ml for the size of a single breast, in accord with the 180 g mass recommended by the ICRP.[8] Kramer and coworkers first recommended a volume of about 365 ml,[9] but later changed their recommendation to 260 to 270 ml.[10] The present difference in recommended representative breast sizes (195 ml versus 265 ml) is similar to the

Table 4. Bone Mass in Individual Bones, Parts of Bones, or Bone Groups Expressed as Percent of Bone Mass in the Body

| Phantom skeletal region | Corresponding skeletal region(s) | Percentage | | |
|---|---|---|---|---|
| | | Japanese Adult | Japanese Child | Japanese Infant |
| Skull (cranium + facial skeleton)[a] | Skull (cranium + mandible)[a] | 13.9 | 17.9 | 23.9 |
| Scapulae | Scapulae | 2.9 | 2.6 | 2.6 |
| Clavicles | Clavicles | .8 | .7 | .7 |
| Ribs | Ribs + sternum | 9.9 | 8.9 | 9.0 |
| Spine (upper portion[b]) | Cervical vertebrae $C_1$-$C_5$ | 2.4 | 2.5 | 2.8 |
| Spine (middle portion[b]) | Cervical vertebrae $C_6$-$C_7$ + all thoracic vertebrae | 7.8 | 7.0 | 7.1 |
| Spine (lower portion[b]) | Lumbar vertebrae $L_1$-$L_4$ | 2.9 | 2.6 | 2.7 |
| Pelvis | Sacrum + os coxea + lumbar vertebra $L_5$ + 50% of upper 1/2 femora | 8.6 | 7.8 | 7.8 |
| Leg bones (upper portion[c]) | 50% of upper 1/2 femora | 10.0 | 9.5 | 8.0 |
| Leg bones (middle portion[c]) | Lower 1/2 femora | 14.9 | 14.6 | 12.2 |
| Leg bones (lower portion[c]) | Tibiae, fibulae, patellae + ankle and foot bones | 12.3 | 13.5 | 11.2 |
| Arm bones (upper portion[d]) | Upper 1/2 humeri | 5.1 | 4.6 | 4.7 |
| Arm bones (middle portion[d]) | Lower 1/2 humeri | 3.9 | 3.5 | 3.5 |
| Arm bones (lower portion[d]) | Radii and ulnae + wrist and hand bones | 4.6 | 4.1 | 4.2 |

[a] In column 1, cranium does not include the facial skeleton, but in column 2, cranium includes all the facial skeleton except the mandible.

[b] The upper, middle, and lower portions of the spine are defined in the section on the spine.

[c] The upper portion of the leg bones is defined as the upper 14% of the length of the bones; the lower portion is defined as the lower 57%; and the middle portion is the rest. The unevenness of these numbers results from the assignment of part of the marrow in the upper femora to the pelvis.

[d] The upper portion of the arm bones is defined as the upper 25% of the length of the bones; the lower portion is defined as the lower 50%; and the middle portion is the rest.

difference between the median (193 ml) and the mean (238 ml) in one study (see Reference 11),[12] and the standard deviation of the mean is large (50%). This difference in breast size does not yield important differences in estimates of dose to the breast from either internal or external sources of photons, except at energies well below 0.025 MeV and possibly for external sources of neutrons.[13]

For the Japanese adult phantom the breast dimenisions in the ORNL age-15-male and adult-female phantom[1] were reduced by approximately 10%, yielding a volume reduction of approximately 25%. This reduction was based on anecdotal evidence (no reliable data for breast size in adult female A-bomb survivors was found). The largest error from using an inappropriate breast size in the A-bomb dosimetry would probably be in dose to the lungs in

adult females from radiation entering the body through the breasts rather than in the breast dose itself. However, any reliable data on breast size in Japanese adult women would be welcome.

Eye Lens. The left eye lens is represented by a line segment defined by:

$$x = -\frac{A_H}{2}$$

$$-\sqrt{\frac{3}{4}}B_H + 0.4 \leq y \leq -\sqrt{\frac{3}{4}}B_H + 0.6$$

and

$$z = C_T + \frac{2}{3}(C_{H0} + C_{H1}) \tag{18}$$

For the right lens, $x$ is replaced by $x = A_H/2$. The values of the parameters are listed in previous sections. Each lens was modeled as a millimeter line segment located one-third of the distance from the top of the right elliptical cylinder that forms the facial region, 5 mm below the facial skin, and half of the semiminor axis distance of the facial elliptical cylinder from the phantom center line.

It was assumed that the lens does not change in size with age.

Gastrointestinal Tract and Contents. Stomach. The stomach wall is represented by the volume between two concentric ellipsoids. The contents are represented by the volume within the inner ellipsoid. The wall is defined by:

$$[\frac{x - x_o}{a}]^2 + [\frac{y - y_o}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1$$

and

$$[\frac{x - x_o}{a - d}]^2 + [\frac{y - y_o}{b - d}]^2 + [\ fracz - z_o c - d]^2 \geq 1 \tag{19}$$

The contents are defined by:

$$[\frac{x - x_o}{a - d}]^2 + [\frac{y - y_o}{b - d}]^2 + [\frac{z - z_o}{c - d}]^2 > 1 \tag{20}$$

The parameter values are $a$ = 3.43, 2.55, and 1.85 cm, $b$ = 2.92, 2.40, and 2.05 cm, $c$ = 7.16, 4.66, and 3.51 cm, $d$ = 0.56, 0.45, and 0.33 cm, $x_o$ = 6.90, 4.59, and 3.52 cm, $y_o$ = -3.92, -3.15, and -2.70 cm, and $z_o$ = 31.55, 20.40, and 15.35 cm. The volumes of the walls are 113, 47.2, and 20.9 $cm^3$ , and the volumes of the contents are 187, 72.2, and 34.8 $cm^3$. Upper large intestine. The upper large intestine consists of an ascending colon and a transverse colon. The ascending colon wall is defined to be the space between two coaxial elliptical cylinders:

$$[\frac{x - x_o}{a}]^2 + [\frac{y - y_o}{b}]^2 \leq 1$$

$$[\frac{x-x_o}{a-d}]^2 + [\frac{y-y_o}{b-d}]^2 \geq 1$$

and

$$z_1 \leq z \leq z_2 \tag{21}$$

The contents are defined by the space within the inner cylinder:

$$[\frac{x-x_o}{a-d}]^2 + [\frac{y-y_o}{b-d}]^2 < 1$$

and

$$z_1 \leq z \leq z_2 \tag{22}$$

The parameter values are $a$ = 2.16, 1.43, and 1.10 cm, $b$ = 2.45, 1.88, and 1.63 cm, $d$ = 0.65, 0.46, and 0.37 cm, $x_o$ = -7.33, -4.87, and -3.74 cm, $y_o$ = -2.31, -1.77, and -1.53 cm, $z_1$ = 13.03, 8.42, and 6.34 cm, and $z_2$ = 21.63, 13.99, and 10.53 cm. The volumes of the ascending colon walls are 69.5, 22.9, and 11.5 $cm^3$, and the volumes of the contents are 73.4, 24.1, and 12.1 $cm^3$.

The transverse colon wall is also defined by the space between two coaxial elliptical cylinders:

$$[\frac{y-y_o}{b}]^2 + [\frac{z-z_o}{c}]^2 \leq 1$$

$$[\frac{y-y_o}{b-d}]^2 + [\frac{z-z_o}{c-d}]^2 \geq 1$$

and

$$-x_1 \leq x \leq x_1 \tag{23}$$

The contents are defined by the space within the inner cylinder:

$$[\frac{y-y_o}{b-d}]^2 + [\frac{z-z_o}{c-d}]^2 < 1$$

and

$$-x_1 \leq x \leq x_1 \tag{24}$$

The parameter values are $b$ = 2.45, 1.88, and 1.63 cm, $c$ = 1.35, 0.87, and 0.65 cm, $d$ = 0.49, 0.33, and 0.26 cm, $y_o$ = -2.31, -1.77, and -1.53 cm, $z_o$ = 22.99, 14.86, and 11.18 cm, and $x_1$ = 9.06, 6.01, and 4.62 cm. The volumes of the transverse colon walls are 92.3, 30.2, and 15.2 $cm^3$, and the volumes of the contents are 96.0, 31.6, and 15.5 $cm^3$.

Lower large intestine. The lower large intestine consists of a descending colon and a sigmoid colon. The descending colon wall is defined by the space between two coaxial elliptical cylinders. The axis of the cylinders is at a slight angle with the z-axis of the phantom. The ends of the descending colon are defined by the horizontal planes $z = z_1$ and $z = z_2$. The wall is specified by:

$$[\frac{x-x_o}{a}]^2 + [\frac{y-y_o}{b}]^2 \leq 1$$

$$[\frac{x-x_o}{a-d}]^2 + [\frac{y-y_o}{b-d}]^2 \geq 1$$

and

$$z_1 \leq z \leq z_2 \tag{25}$$

where

$$x_o = x_1 + \frac{m_x(z-z_2)}{z_2-z_1}$$

and

$$y_o = \frac{m_y(z_1-z)}{z_2-z_1}$$

The contents of the descending colon are defined by the space within the inner cylinder, i.e.,

$$[\frac{x-x_o}{a-d}]^2 + [\frac{y-y_o}{b-d}]^2 < 1$$

and

$$z_1 \leq z \leq z_2 \tag{26}$$

The parameter values are $a$ = 1.62, 1.08, and 0.83 cm, $b$ = 2.09, 1.60, and 1.38 cm, $d$ = 0.49, 0.34, and 0.27 cm, $x_1$ = 7.98, 5.30, and 4.07 cm, $m_x$ = 0.6728, 0.4466, and 0.3432 cm, $m_y$ = 2.450, 1.875, and 1.625 cm, $z_1$ = 7.86, 5.08, and 3.82 cm, and $z_2$ = 21.63, 13.99, and 10.53 cm. The volumes of the descending colon walls are 68.3, 22.3, and 11.0 $cm^3$, and the volumes of the contents are 78.2, 26.1, and 13.1 $cm^3$.

The sigmoid colon plus contents is represented by portions of two flattened tori; that is, the axis of each torus is circular but the crosssection is elliptical. The wall is defined as follows:

(portion of upper torus)

$$[\frac{\sqrt{(x-x_o)^2+(z-z_o)^2}-R_1}{a}]^2 + [\frac{y}{b}]^2 \leq 1$$

$$[\frac{\sqrt{(x-x_o)^2+(z-z_o)^2}-R_1}{a-d}]^2 + [\frac{y}{b-d}]^2 \geq 1$$

$$x \geq x_o$$

and

$$z \leq z_o \tag{27}$$

and (portion of lower torus)

$$[\frac{\sqrt{(x-x_o)^2+z^2}-R_2}{a}]^2+[\frac{y}{b}]^2 \leq 1$$

$$[\frac{\sqrt{(x-x_o)^2+z^2}-R_2}{a-d}]^2+[\frac{y}{b-d}]^2 \geq 1$$

$$x \leq x_o$$

and

$$z \geq 0 \tag{28}$$

The contents of the sigmoid colon are defined as follows:
(portion of upper torus)

$$[\frac{\sqrt{(x-x_o)^2+(z-z_o)^2}-R_1}{a-d}]^2+[\frac{y}{b-d}]^2 < 1$$

$$x \geq x_o$$

and

$$z \leq z_o \tag{29}$$

and (portion of lower torus)

$$[\frac{\sqrt{(x-x_o)^2+z^2}-R_2}{a}]^2+[\frac{y}{b}]^2 \leq 1$$

$$[\frac{\sqrt{(x-x_o)^2+z^2}-R_2}{a-d}]^2+[\frac{y}{b-d}]^2 \geq 1$$

$$x \leq x_o$$

and

$$z \geq 0 \tag{30}$$

The parameter values are $a$ = 1.18, 0.88, and 0.69 cm, $b$ = 1.76, 1.21, and 1.02 cm, $d$ = 0.59, 0.42, and 0.34 cm, $x_o$ = 2.59, 1.72, and 1.32 cm, $z_o$ = 7.86, 5.08, and 3.82 cm, $R_1$ = 5.16, 3.33, and 2.51 cm, and $R_2$ = 2.70, 1.75, and 1.31 cm. The volumes of the sigmoid colon walls are 53.8, 17.6, and 8.78 $cm^3$, and the volumes of the contents are 26.8, 9.11, and 4.49 $cm^3$.

Liver. The liver is defined by an elliptical cylinder cut by a plane as follows:

$$[\frac{x}{a}]^2+[\frac{y}{b}]^2 \leq 1$$

$$\frac{x}{x_m}+\frac{y}{y_m}-\frac{z}{z_m} \leq -1$$

and

$$z_1 \leq z \leq z_2 \tag{31}$$

The parameter values are $a$ = 14.23, 9.39, and 7.20 cm, $b$ = 7.84, 6.30, and 5.47 cm, $x_m$ = 31.51, 16.27, and 12.83 cm, $y_m$ = 44.75, 20.34, and 16.55 cm, $z_m$ = 38.76, 25.06, and 18.86 cm, $z_1$ = 24.34, 15.74, and 11.84 cm, and $z_2$ = 38.76, 25.06, and 18.86 cm. The volumes of the livers are 1360, 562, and 281 $cm^3$.

The liver in the ORNL age-15-male and adult-female phantom[1] was changed slightly from that given for the age-15 phantom in Reference 2 to match the data for a (Western) reference adult female.[8] The size is also close to that for Japanese adults.

Lungs. Each lung is represented by half an ellipsoid with a section removed. Note that the section removed from the left lung is larger than that removed from the right lung because of the position of the heart. The right lung is defined as follows:

$$[\frac{x + x_o}{a}]^2 + [\frac{y}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1 \tag{32}$$

and

$$z \geq z_o$$

and, if $z_{1R} \leq z \leq z_{2R}$ and $y < y_{2R}$, then $x \leq x_{1R}$ must also hold.

The statements for the left lung are similar, but replace $(x + x_o)$ with $(x - x_o)$; and $z_{1R}$, $z_{2R}$, and $y_{2R}$ with $z_0$, $z_{2L}$, and $y_{2L}$, respectively; and replace the inequality $(x \leq x_{1R})$ with $(x \geq x_{1L})$. The letters $R$ and $L$ refer to right and left.

The values of the parameters are $a$ = 4.70, 3.47, and 2.68 cm, $b$ =7.50, 5.63, and 4.88 cm, $c$ = 23.00, 13.99, and 10.53 cm, $x_o$ = 7.33, 4.87, and 3.74 cm, and $z_o$ = 39.21, 25.35, and 19.08 cm. The values of the other parameters for the right lung are $x_{1R}$ = -5.00, -3.50, and -2.90 cm, $y_{2R}$ = 1.20, 1.00, and 0.70 cm, $z_{1R}$ = 41.60, 26.90, and 20.10 cm, and $z_{2R}$ = 48.50, 32.30, and 24.60 cm. The values of the other parameters for the left lung are $x_{1L}$ = 7.10, 5.00, and 3.90 cm, $y_{2L}$ = 1.00, 0.50, and 0.40 cm, and $z_{2L}$ = 50.00, 32.60, and 24.80 cm.

The volumes of the left lungs are 1393, 454, and 225 $cm^3$, the volumes of the right lungs are 1614, 526, and 259 $cm^3$, and the volumes of the two lungs together are 3007, 980, and 484 $cm^3$.

The size of the lungs in the Japanese phantoms was made larger than that in the ORNL age-15-male and adult-female phantom to correspond more closely with the measured lung size in Japanese adults. This size was determined by assuming that lung size relative to trunk size in Japanese adults is the same as the lung size relative to trunk size in Western adults, and that the Western adult lungs weigh an average 1170 g and have a density of 0.296 g $cm^{-3}$.[8]

Ovaries. Each ovary is an ellipsoid and is given by:

$$[\frac{x - x_o}{a}]^2 + [\frac{y}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1 \tag{33}$$

The parameter values are $a$ = 0.92, 0.53, and 0.38 cm, $b$ = 0.60, 0.35, and 0.28 cm, $c$ =

1.80, 1.07, and 0.77 cm, $x_o = \pm$ 5.18, $\pm$ 3.44, and $\pm$ 2.64 cm, and $z_o$ = 13.52, 8.74, and 6.58 cm. The values of $x_o$ are taken as positive for the left ovary and negative for the right ovary. The volumes of the two ovaries together are 8.32, 1.66, and 0.686 $cm^3$.

The ovaries in the ORNL age-15-male and adult-female phantom[1] were changed from those in the age-15 phantom in Reference 2 to represent an adult female rather than an adolescent female. These new values were retained for the Japanese adult phantom.

Pancreas. The pancreas is half an ellipsoid with a section removed. It is defined by:

$$[\frac{x - x_o}{a}]^2 + [\frac{y}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1 \qquad (34)$$

$$x \geq x_o$$

and

$$z \geq z_o, \quad \text{if} \quad x > x_1$$

The parameter values are $a$ = 14.91, 9.16, and 6.85 cm, $b$ = 1.25, 0.90, and 0.71 cm, $c$ = 3.21, 1.92, and 1.41 cm, $x_o$ = -0.72, -0.57, and -0.43 cm, $z_o$ = 33.35, 21.57, and 16.23 cm, and $x_1$ = 3.01, 1.72, and 1.32 cm. The volumes of the pancreases are 85.7, 22.7, and 9.87 $cm^3$.

The pancreas was enlarged somewhat from that given in Cristy and Eckerman[1] for the ORNL age-15-male and adult-female phantom to correspond more closely with Japanese autopsy data. Space-fitting problems precluded an even closer correspondence.

Skin. The skin is represented as a layer of thickness S extending over the exterior of the phantom, including the exposed top of the trunk and bottom of the legs but excluding the exposed bottom of the trunk and top of the legs. The part of the legs covered by the male genitalia region has skin, but the part of the trunk covered by the female breasts does not.

The value of S used in the ORNL age-15-male and adult-female phantom[1] was retained for the Japanese adult phantom. Doses to radiosensitive cells in the skin from the external radiation may not correspond well with doses to the skin of the phantom, and we recommend that other methods be used to estimate this dose.

The values of S are 0.17, 0.09, and 0.08 cm.

Testes. The testes are represented by the ellipsoids:

$$[\frac{x \pm a}{a}]^2 + [\frac{y - y_o}{b}]^2 + [\frac{z + c}{c}]^2 \leq 1 \qquad (35)$$

where the $\pm$ sign is taken as positive for the right testis and negative for the left testis.

The parameter values are $a$ = 1.25, 0.45, and 0.41 cm, $b$ = 1.45, 0.52, and 0.47 cm, $c$ = 2.22, 0.80, and 0.72 cm, and $y_o$ = -6.75, -4.98, and -3.73 cm. The volumes of the two testes together are 33.7, 1.57, and 1.16 $cm^3$.

The testes were enlarged from those given in the ORNL age-15-male and adult-female phantom[1] to match more closely the Japanese autopsy data.

Thyroid. The lobes of the thyroid lie between two concentric cylinders and are formed by a cutting surface. The statements defining this organ are:

$$x^2 + (y - y_o)^2 \leq R^2$$

$$x^2 + (y - y_o)^2 \geq r^2$$

$$y \leq y_o$$

$$C_T \leq z \leq C_T + c$$

and

$$[(y - y_o) - |x|]^2 \geq 2[x^2 + (y - y_o)^2]\tau^2 \tag{36}$$

in which

$$\tau = [\frac{\sqrt{2} - 2}{2}][\frac{z - C_T}{0.25\,c}] + 1 \text{ for } 0 \leq z - C_T \leq 0.25c$$

and

$$\tau = [\frac{2 - \sqrt{2}}{2}][\frac{z - C_T}{0.75c}] + \frac{2\sqrt{2} - 1}{3} \text{ for } 0.25\,c \leq z - C_T \leq c$$

The parameter values are $R$ = 2.10, 1.21, and 0.97 cm, $r$ = 0.95, 0.55, and 0.44 cm, $c$ = 4.77, 2.76, and 2.21 cm, and $y_o$ = -3.91, -3.31, and -2.87 cm. The volumes of the thyroids are 17.3, 3.32, and 1.71 $cm^3$.

The size of the thyroid was increased over that used by Cristy and Eckerman[1] for the ORNL age-15-male and adult-female phantom to match more closely the Japanese autopsy data (Table 6 of Chapter 8). It is also associated with a modified neck, as described at the end of this appendix.

Urinary Bladder and Contents. The bladder wall is represented by the volume between two concentric ellipsoids. The contents are represented by the volume within the inner ellipsoid. The wall is defined by:

$$[\frac{x}{a}]^2 + [\frac{y - y_o}{b}]^2 + [\frac{z - z_o}{c}]^2 \,, \leq 1$$

and

$$[\frac{x}{a - d}]^2 + [\frac{y - y_o}{b - d}]^2 + [\frac{z - z_o}{c - d}]^2 \geq 1 \tag{37}$$

The contents are defined by:

$$[\frac{x}{a - d}]^2 + [\frac{y - y_o}{b - d}]^2 + [\frac{z - z_o}{c - d}]^2 < 1 \tag{38}$$

The parameter values are $a$ = 4.27, 3.04, and 2.35 cm, $b$ = 3.38, 2.77, and 2.42 cm, $c$ = 3.11, 2.16, and 1.64 cm, $d$ = 0.23, 0.17, and 0.14 cm, $y_o$ = -4.41, -3.38, and -2.93 cm, and $z_o$ = 7.21, 4.66, and 3.51 cm. The volumes of the urinary bladder walls are 34.5, 14.0, and 7.41 $cm^3$, and the volumes of the contents are 154, 62.2, and 31.7 $cm^3$.

Uterus. The uterus is an ellipsoid cut by a plane and given by:

$$[\frac{x}{a}]^2 + [\frac{y - y_o}{b}]^2 + [\frac{z - z_o}{c}]^2 \leq 1$$

and

$$y \geq y_1 \tag{39}$$

The uterus in the ORNL age-15-male and adult-female phantom[1] was changed from that in the age-15 phantom of Reference 2, to represent an adult female rather than an adolescent. This change was retained in the Japanese adult phantom.

The parameter values are $a$ =2.47, 0.78, and 0.61 cm, $b$ = 5.61, 2.00, and 1.80 cm, $c$ = 1.55, 0.47, and 0.36 cm, $y_o$ = -1.96, -1.50, and -1.30 cm, $z_o$ = 12.62, 8.16, and 6.14 cm, and $y_1$ = -4.77, -2.51, and -2.20 cm. The volumes of the uteruses are 76.0, 2.60, and 1.40 $cm^3$.

**Kneeling Posture Modifications**

Many of the Japanese A-bomb survivors were in a kneeling posture at the time of their exposure to radiation. While there are a number of different kneeling, squating, and sitting styles in Japan, the predominate nonstanding posture, especially for the man or woman at home, is the traditional kneeling position. The person kneels with toes pointed backward, ankles and knees flat against the floor, the buttocks are resting against the heels or ankles, the trunk is straight, and the arms are extended down and out toward the knees. This is a common position for preparing food, eating, or working in the home. The phantom description is generally very similar to the standing phantom. The differences are found in the folded legs, the forming of a buttocks, shortening the trunk, and extending the arms down and out at a 45° angle from the shoulders. The only organs that are affected are the leg bones, arm bones, and the male genitalia and testes.

**Trunk.** The trunk remains the same shape except the limits on its length are changed to:

$$\frac{A_T}{2} < z < C_T \tag{40}$$

The volumes of the trunks are now 25679, 8353, and 4173 $cm^3$.

**Arms.** The arms are rotated at the shoulders by 45° to the front so that:

$$[x' \pm (a_R + S + RMT)]^2 + y'^2 \leq [\frac{RMT + \frac{RMT}{C_T} z'}{2}]^2 \tag{41}$$

$$o \leq z' \leq C_T$$

$$x = x'$$

$$y = 0.707\,(y' + z' - C_T)$$

$$z = 0.707\,(-y' + z' - C_T) + C_T$$

The parameters $a_R, S, RMT,$ and$C_T$ were defined in the section on the arm while standing. The volume of the arm remains unchanged.

**Legs for Kneeling Posture.** The legs are separated into the tibiae and femora regions. The lower 57% of leg forms the tibiae region, the upper 43% forms the femora region. The femora region begins at the bottom of the pelvis bone and extends forward from the trunk. The tibiae region is placed underneath the femora region so that the knee surfaces are in a common plane and the lower part of the tibiae is under and behind the buttocks.

The femora region is defined by:

$$x'^2 + y'^2 \leq \pm x' \left[A_T + \frac{A_T}{2C'_L} z'\right] \tag{42}$$

where

$$x = x'$$
$$y = z' + y_K$$
$$z = -y' - \frac{A_T z'}{2\,C'_L}$$
$$Y_K \geq y \geq Y_K - 0.43\,C_L$$

The tibiae region is defined by the same equation, where

$$x = x' \tag{43}$$
$$y = -z' + Y_K - 0.86\,C_L$$
$$z = +y' + \frac{A_T z'}{2\,C'_L} + A_T - 2\,A_T\left[\frac{C'_L - 0.43\,C_L}{C'_L}\right]$$
$$Y_K + 0.14\,C_L \geq y \geq Y_K - 0.43\,C_L$$

The parameter $Y_K$ is the starting location for the legs and is set equal to the value of $y_{o2}$ in the pelvis. $Y_K$ = -0.294, -2.25, and -1.95 cm. Other parameters are defined in the section on the leg while standing.

**Genitalia for Kneeling Posture.** The genitalia are moved and rotated about 90° with the legs. They are specified by:

$$-r \leq x' \leq r \tag{44}$$
$$-r \leq y' \leq 0$$

and

$$(x' \pm r)^2 + y'^2 \geq r^2$$

where

$$x = x'$$
$$y = +z' + Y_K$$

$$z = -y' - \frac{A_T z'}{2\,C'_L}$$

$$Y_K \leq y \leq Y_K + z_1$$

The value of $z_1$ is given by -(2c + S).

The same discussion concerning the parameters of the genitalia while standing hold for the genitalia while kneeling. The volumes are the same.

**Buttocks for Kneeling Posture.** The buttocks are formed so that there is a smooth surface of tissue from the vertical back of the trunk to the undersides of the horizontal thighs. They are specified by:

$$[\frac{x}{A_T}]^2 + [\frac{y}{B_T}]^2 \leq 1 \tag{45}$$

and

$$y > Y_K$$

$$\frac{-A_T}{2} < z < \frac{A_T}{2},$$

$$[\frac{y - Y_K}{B_T - Y_K}]^2 + [\frac{z - A_T/2}{A_T}]^2 \leq 1$$

Also, if $z < 0$ and $|x| > A_T/2$, then

$$[\frac{x - \frac{A_T}{2}}{\frac{A_T}{2}}]^2 + [\frac{z}{\frac{A_T}{2}}]^2 < 1$$

The volumes of the buttocks are approximately equal to the volumes removed from the trunk, i.e., 4066, 1363, and 699 $cm^3$.

**Arm Bones for Kneeling Posture.** The arm bones are rotated at the shoulder by 45° to the front so that:

$$[\frac{\frac{a}{2z_2}(z' - z_2) + (x' \pm \{a_R + S + RMT - \frac{a}{2}\})}{a}]^2 + [\frac{y}{b}]^2 \leq$$

$$[\frac{2z_2 + (z' - z_2)}{2\,z_2}]^2 \tag{46}$$

$$0 \leq z' \leq z_2$$

and

$$x = x'$$

$$y = 0.707\,(y' + z' - C_T)$$

$$z = 0.707\,(-y' + z' - C_T) + C_T$$

The parameters are given in the section on the arm bone. The volumes are unchanged.

**Leg Bones for Kneeling Posture.** The leg bones are divided into the femora and tibiea. The femora is defined by:

$$[x' \pm [\frac{A_T}{2} + \frac{kz'}{C_L - S}]]^2 + y'^2 \leq [R_1 + [\frac{R_1 - R_2}{C_L - S}]\,z']^2 \tag{47}$$

where

$$x = x'$$
$$y = +z' + Y_K$$
$$z = -y' - \frac{A_T z'}{2\,C_{L'}}$$
$$Y_K \geq y \geq Y_K - 0.43\,C_L$$

The tibiae is defined by the same equation, where:

$$x = x' \tag{48}$$

$$y = -z' + Y_K - 0.86\,C_L$$

$$z = +y' + \frac{A_T z'}{2\,C_{L'}} + A_T - 2\,A_T\,[\frac{C_{L'} - 0.43\,C_L}{C_L}]$$

$$Y_K + 0.14\,C_L \geq y \geq Y_K - 0.43\,C_L$$

The parameters are the same as those given for the leg in the standing position. The volume is unchanged.

**Tests for Kneeling Posture.** The testes are moved and rotated about 90° with the legs and genitalia. They are defined by:

$$[\frac{x' \pm a}{a}]^2 + [\frac{y' - y_o}{b}]^2 + [\frac{z' + c}{c}]^2 \leq 1 \tag{49}$$

where

$$x = x'$$
$$y = +z' + Y_K$$
$$z = -y' - \frac{A_T z'}{2\,C_{L'}}$$

The parameters $a$, $b$, $c$, and $y_o$ are the same as for the testes while standing. $Y_K$ =

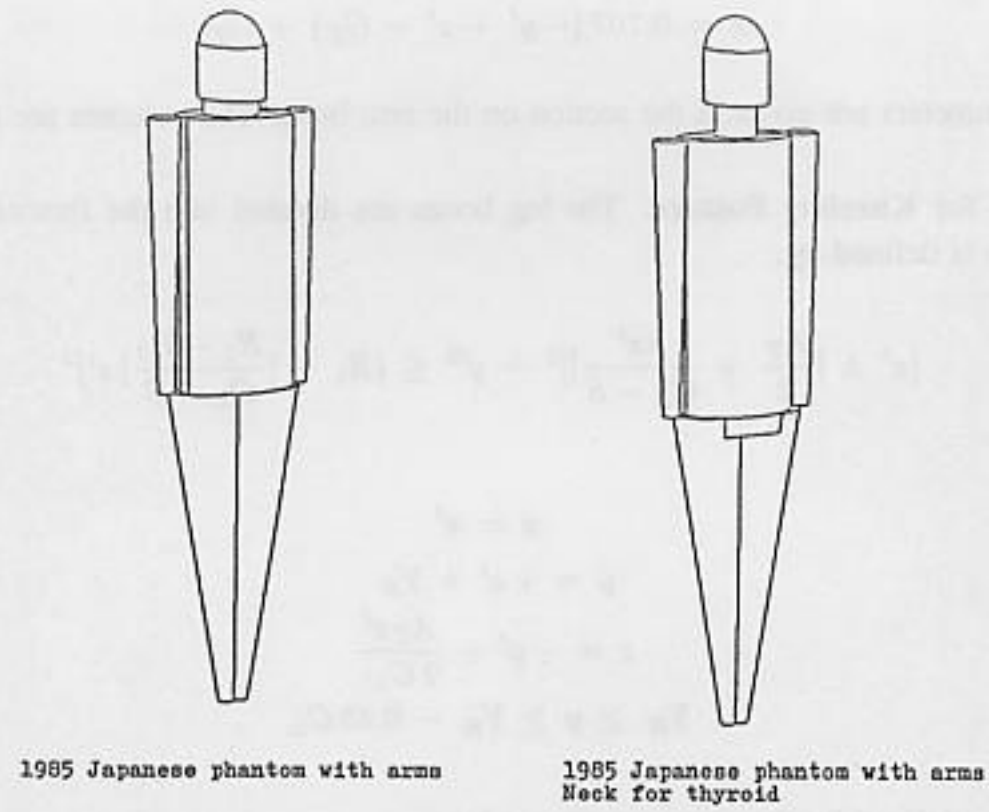


*Figure 3. Adult Japanese phantom (left) and modified phantom for thyroid dose calculation (right)*

-2.94, -2.25, and -1.95 cm. The volumes are unchanged.

**Modified Neck for Thyroid Dose Calculations**

Calculations of dose to the thyroid for standing and kneeling postures were performed with phantoms modified in the neck region. As shown in Figure 3, the neck was made longer, slimmer, and, it is thought, more realistic than that in the phantom used in the balance of the organ dose calculations. The need for this modification was recognized late in the phantom design-calculation process. Therefore, rather than increase the phantom height beyond that deemed reasonable or modify the trunk to accomodate the longer neck, within height constraints, it was decided to use the modified neck for thyroid dose calculations only.

The modified neck specifications are $R_H$ =5.20, 3.80, and 3.60 cm, $C_{H0}$ = 7.70, 3.30, and 2.30 cm, and $C_{H1}$ = 12.18, 10.01, and 9.42 cm. The location of the thyroid was also modified to bring it closer to the surface of the neck, such that $y_o$ = -2.30, -1.99, and -1.53 cm. See sections Head and Neck and Thyroid for the meaning of these parameters in conjunction with neck size and thyroid location, respectively.

**References**

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2. Cristy, M., 1980. *Mathematical Phantoms Representing Children of Various Ages for Use in Esti-*