I. DOSIMETRY

B. Physical Dose Estimates for A-bomb Survivors

— Studies at Chiba, Japan

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In-air tissue absorbed doses** from the primary and scattered radiations of the Hiroshima and Nagasaki atomic bombs, without shielding, were estimated as function of distance from the hypocenters. Gamma-ray dose was determined from the thermoluminescence in bricks and tiles; neutron dose, from ^{60}Co activity induced in concrete-imbedded iron of buildings. The ratio of the absorbed dose in critical organs to the in-air tissue absorbed dose was determined by phantom measurements using simulated radiation sources for the atomic bombs. The absorbed doses in the thyroid gland, the gonads, and the fetus *in utero* were thus estimated as a function of distance from the hypocenters.

INTRODUCTION

Dose estimation from atomic bomb radiations has been made by many Japanese and American scientists, including the Oak Ridge National laboratory Group.¹⁻¹¹⁾ (see also the review by Auxier in the issue). Hashizume *et al* have estimated the in-air tissue absorbed dose from gamma-rays and neutrons in Hiroshima and Nagasaki from the radioactivity and the thermoluminescence induced in building materials at various distances from the hypocenters.¹²⁾ In assessing the dose response relationship with respect to radiation injury of interest, the biologically significant doses are those absorbed in critical organs. The following organs can be considered critical for corresponding potential late effects: (1) thyroid and other organs for carcinogenesis; (2) gonads for impairment of fertility and genetic effects; (3) fetus or embryo *in utero* for malformations, carcinogenesis and genetic effects and (4) hemopoietic system for leukemogenesis.

The present review summarizes the studies of the dose estimation of thyroid, testis, ovary and fetus or embryo carried out at the National Institute of Radiological Sciences (NIRS), Chiba, Japan. Further details in making the dose estimation should be referred to earlier reports.¹³⁻¹⁴⁾

I. ESTIMATIONS OF IN-AIR TISSUE ABSORBED DOSE

The survivors were exposed to radiation in air from the bomb with or without attenuation by shielding materials and to scattered radiation from the earth and buildings. The angular distribution of radiations on the ground was very complicated.¹⁵⁾ The in-air tissue absorbed dose was corrected for the angular distribution of atomic bomb

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** The term in-air tissue absorbed dose in this review is the same as 'air dose' of Auxier's review.

radiations, using data¹⁶⁾ proposed for the Atomic Bomb Casualty Commission by the Oak Ridge National Laboratory.

a. *Gamma-ray dose*

Bricks and ornamental tiles of buildings were used to estimate gamma-ray dose because: (1) ionic crystals in these materials are sensitive to gamma-rays, but respond negligibly to neutrons; and (2) these materials were free from radiation effects prior to the bombs, having been heated when they were baked. Bricks and polished wall tiles were collected from six Hiroshima and five Nagasaki sites.

Since thermoluminescent dosimeters were not commercially available at the time of those estimates, a special apparatus was constructed by us to determine the amount of thermoluminescence from the samples. The glow curves from the samples were recorded on an X-Y recorder by plotting the photoelectric current on the Y-axis and the heating time on the X-axis. The amount of thermoluminescence was measured from a part of the area under the glow curve.

The in-air tissue absorbed dose of gamma-rays, D_{rg} , for the incident angle (θ) of atomic bomb radiations was calculated according to the following equation, using the amount of thermoluminescence measured:

$$D_{rg} = L \cdot G \cdot C_\theta \cdot R \quad \dots\dots\dots (1)$$

where L is the amount of thermoluminescence per unit weight of the sample, G is the gamma-ray dose per unit amount of thermoluminescence, C_θ is the correction factor for the angular distribution of incident gamma-rays, R is the fading factor, and θ is the incident angle, which is given by the angle between the normal line to the wall of the building and the direction of the epicenter.

The values of C_θ , R and G were experimentally determined using a gamma-ray

Table 1. In-air tissue dose in both cities as a function of distance from hypocenter

		Distance from hypocenter (m)	Radiation Dose (rad)	
			mean	standard deviation
Gamma-rays	Hiroshima	140	10118	1130
		155	9990	869
		170	8578	892
		415	4065	390
		605	1582	158
		710	1043	127
		965	338	34
	Nagasaki	95	24311	1945
		520	6435	595
		635	4240	377
		860	1639	226
		875	1471	150
		970	937	111
		1020	824	83
Neutrons	Hiroshima	260	7864	1250
		640	1188	144
		779	541	85
		1180	51	13
	Nagasaki	590	514	49
		1030	52	8

source spectrally equivalent to the atomic bombs. The source was prepared from X-rays of a 6 MeV linear accelerator representing a high energy component, and gamma-rays from ^{60}Co and ^{137}Cs as an intermediate energy component. An incident angle, θ , was calculated in relation to a distance from the hypocenter, assuming the heights of the epicenters to be 590 and 500 m, Hiroshima and Nagasaki, respectively. The gamma-ray doses are given in Table 1 and Fig. 1.

Fig. 1. A. The in-air tissue absorbed dose due to gamma-rays in Hiroshima and Nagasaki as a function of distance from hypocenters. Full line with open circles shows gamma-ray dose estimated by NIRS (see Table 1.). The dotted line shows gamma-ray dose by York.¹⁾ The broken line shows gamma-ray dose by ORNL.⁹⁾

B. The in-air tissue absorbed dose due to neutrons in Hiroshima and Nagasaki as a function of distance from hypocenters. Full line with open circles shows neutron dose estimated by NIRS (see Table 1.). The dotted line shows neutron dose by York.¹⁾ The broken line shows neutron dose by ORNL.⁹⁾

The gamma-ray doses are given in Table 1 and Fig. 1.

b. Neutrons

^{60}Co activity induced by the atomic bombs was used to estimate neutron dose because: (1) ^{59}Co is an impurity in iron and becomes ^{60}Co through (n, γ) reaction by thermal neutrons; (2) ^{60}Co was one of the most intense radionuclides detectable even 20 years after the atomic bombs; and (3) iron samples were readily obtainable at various sites in both cities.

It is noted that the $^{59}\text{Co}(n, \gamma)^{60}\text{Co}$ reaction is induced predominantly by thermal neutrons, while thermal neutrons contributed little to the total neutron dose from atomic bombs.¹⁵⁾ The application of the reaction to neutron dosimetry, then, requires a specified condition where fast neutrons are slowed down to thermal neutrons by a moderator of some sort, frequently found in the bombed areas. In the present study, the moderator chosen was concrete from ferroconcrete buildings. The preliminary experiments showed that a maximal ^{60}Co activity was detected in iron, found at a depth of 8 cm from the surface of the buildings.

For the neutron dose estimation, the materials from ferroconcrete buildings were selected by the following criteria: (1) building walls were directly exposed to atomic bomb radiations without intervening objects which might scatter radiations; (2) the angle between the wall surface and the direction of the hypocenter was from 70° to 90° ; (3) the samples were located at

least 1 m above the ground or the surface of a rooftop; (4) wall thickness of sampled concrete buildings was greater than 25 cm; and (5) portions of iron rods embedded in concrete found either on its surface or beneath a 8 cm thickness of concrete were used. At Hiroshima, four 'surface' samples and five embedded samples were collected. At Nagasaki, two of each sample were collected.

Approximately 5 g of iron samples were dissolved in concentrated hydrochloric acid, followed by iron extraction and separation of cobalt from iron. Finally, cobalt was electroplated onto a platinum planchet.¹⁷⁾ The radioactivity of ^{60}Co was determined by a coincidence type low background beta-ray spectrometer.¹⁸⁻²⁰⁾

The in-air tissue absorbed dose from neutrons, $D_{n\theta}$, for the incident angle θ was calculated by the following equation:

$$D_{n\theta} = A_{\theta} \cdot Q_{\theta} \cdot N_{\theta} \cdot T \quad \dots\dots\dots (2)$$

where A_{θ} is the specific activity of ^{60}Co at a depth of 8 cm, Q_{θ} is the ratio of contribution of fast neutrons to the overall activity of ^{60}Co at a depth of 8 cm in walls of concrete buildings, N_{θ} is the neutron dose per unit specific activity of ^{60}Co (cpm/mg Co) and T is the correction factor for the decay of ^{60}Co . The N_{θ} values were determined from the ^{60}Co activity in iron irradiated in a concrete block having the same density as concrete used in Hiroshima buildings, with a known neutron dose from the Health Physics Research Reactor (HPRR) at Oak Ridge National Laboratory and from the $^9\text{Be}(d,n)^{10}\text{B}$ reaction using a Van de Graaff generator at NIRS. The value of Q_{θ} was determined using the ^{60}Co activities in iron on the surface and at a depth of 8 cm in the concrete block irradiated with fast neutrons from the $^9\text{Be}(d,n)^{10}\text{B}$ reaction, and with thermal neutrons. The values of A_{θ} , N_{θ} and Q_{θ} were corrected for the angular distribution of neutrons from the A-bombs. The half life (T) of ^{60}Co was estimated to be 5.26 years.

The resultant neutron doses are given in Table 1. and Fig. 1B. In Fig. 1., the gamma-ray and neutron doses by NIRS were plotted together with those of York¹⁾ and of Oak Ridge National Laboratory group (ORNL).⁹⁾ (See the Auxiev's review in this issue). In Hiroshima, the present gamma-ray doses superimposed well with ORNL's estimate, but deviated significantly from York's early estimate. Similarly, neutron doses of NIRS matched far better with ORNL values than those of York (Fig. 1 a). At Nagasaki, the present gamma-ray doses were not much different from those of York and ORNL. However, the neutron dose of NIRS seemed to fit better with York's curve than the ORNL's curve. These disagreements may be due to difference of methods used for dose estimations.

II. ESTIMATION OF ABSORBED DOSES IN CRITICAL ORGANS

To estimate absorbed doses in critical organs, the ratio (RATA) of the absorbed dose in critical organs to the in-air tissue absorbed dose was determined using tissue-equivalent phantoms exposed to radiations from simulated gamma-ray and neutron sources.

Simulated radiation sources of the A-bomb radiations of two cities were setup by 12 MV X-rays from a betatron and neutrons from the $^9\text{Be}(d,n)^{10}\text{B}$ reaction with 2.5 MeV deuteron bombardment. The resultant gamma-ray spectrum was lower in the less-than-0.8 MeV component and higher in the 0.8-to-2 MeV region than those of the A-bombs.¹⁴⁾ However, the average gamma-ray energy of the simulated source was 1.46 MeV, close

to 1.54 MeV of Glasstone's spectrum²¹⁾ and to 1.42 MeV of recent data of Straker and Grintzner.²²⁾ In the simulated neutron source, the spectrum¹⁴⁾ was lower in the region less than 0.7 MeV and higher in the 0.7–1.6 MeV region than those of the A-bombs.²¹⁾ The average neutron energy of the simulated source was 1.9 MeV¹⁴⁾, while that of A-bombs was 1.1 MeV.²¹⁾ However, the depth dose curves of the simulated neutron source in tissue-equivalent phantoms were superimposed on those of the A-bombs.¹⁴⁾

The absorbed doses from neutrons were categorized according to types of neutron-tissue interaction: (1) recoil proton dose from elastic collision of neutrons with hydrogen nuclei; (2) gamma-ray dose from $^1\text{H}(n, \gamma)^2\text{D}$ reaction; (3) proton dose from $^{14}\text{N}(n, p)^{14}\text{C}$ reaction.

The ratio of absorbed dose in critical organs to the in-air tissue absorbed doses for a monodirectional radiation beam, RATA_m , was estimated either by experiments or by calculation based on experiments. RATA_m was determined as a function of the incident angle in terms of a latitudinal angle θ and a longitudinal angle ϕ , which were taken to be $\theta=0^\circ$ and $\phi=0^\circ$ in a direction toward the normal line to the front surface of the phantoms. Correction of RATA_m for the angular distribution of radiations from the A-bombs was described in detail previously.¹⁴⁾

RATA for Thyroids and Gonads

The locations of critical organs are assumed as follows: (1) thyroid is situated at 0.9 cm beneath the anterior surface of neck; (2) ovary is at 5 cm laterally from the minor axis of the torso and at 10 cm depth, assuming the phantom's anteroposterior measurement to be 20 cm; (3) testis is at 0.7 cm depth along the minor axis of the torso.

The 12 MV X-ray dose was measured using a thermoluminescent dosimeter made of thin glass tubing, 1 mm in diameter and 6 mm in length filled with $\text{Mg}_2\text{SiO}_4(\text{Tb})$ powder (Dai Nippon Toryo Co. Ltd. Tokyo, Japan.). For neutron doses, the paired chambers, consisting of polyethylene-ethylene and carbon- CO_2 , measured absorbed doses principally due to recoil protons from elastic collisions with fast neutron. These dosimeters were placed at the locations of the critical organs in the phantoms. RANDO and REMAB phantom (Alderson Research Laboratories, Stamford, Conn., U. S. A.) were used for X-rays and neutrons, respectively. The REMAB phantom was filled with a soft tissue-equivalent liquid,²³⁾ and a lung tissue-equivalent plastic powder of 0.3 g/cm^3 for the lungs.

The absorbed doses from the $^1\text{H}(n, \gamma)^2\text{D}$ and $^{14}\text{N}(n, p)^{14}\text{C}$ reactions at the locations of the critical organs were calculated from the thermal neutron distributions measured with a BF_3 -proportional counter in an elliptically cylindrical polyethylene container $32.5 \times 20 \times 60 \text{ cm}$ in width, depth and height, filled with a soft tissue-equivalent liquid, using the method reported by Smith and Boot.²⁴⁾

The in-air tissue absorbed dose for X-rays and neutrons was determined with a Farmer sub-standard chamber (Nuclear Enterprise Co. Ltd. London, England). and the paired chambers (handmade).

RATA for Fetus or Embryo in utero

The RATA_m of a fetal head was calculated using a depth-dose curve and a dose build-up factor experimentally determined using the simulated radiation sources for the A-bomb radiations. Assuming that the monodirectional radiation beams are incident on the center of the fetal head through a point on the maternal surface at a latitudinal

angle θ and a longitudinal angle ϕ , the $RATA_m(\theta, \phi)$ for the monodirectional beams can be estimated as

$$RATA_m(\theta, \phi) = r(l) \cdot B(\theta, \phi) \quad \dots\dots\dots (3)$$

where $r(l)$ is the tissue-air ratio determined from the depth dose curve, dependent on the depth l , $B(\theta, \phi)$ is the dose build-up factor.

Miniature paper phantoms simulating the maternal body shape at the 1st, 4th, 7th and 9th month of pregnancy were made from torso contours of pregnant Japanese women, data on fetal dimensions, and the length of the fundus uteri. In determining the depth l , except for lung, the entire maternal body was assumed to consist of soft tissue.

The central axis depth-dose curve for the 12 MV X-rays and for neutrons was determined with a Farmer sub-standard chamber and the paired chambers, respectively. For the gamma-rays and protons from the $^1\text{H}(n, \gamma)^2\text{D}$ and $^{14}\text{N}(n, p)^{14}\text{C}$ reactions, respectively, the absorbed dose was determined using the method described in the section for RATA for the thyroids and the gonads. The tissue-air ratio was determined by dividing the absorbed dose to the fetal head by the in-air tissue absorbed dose measured with the ionization chambers.

The dose build-up factor was evaluated by the phantom measurements. The $RATA_m$ was determined by equation (3), using these data. The $RATA_m$ for gamma-ray spectrum of Straker and Grintzner²²⁾ was calculated by using the depth-dose curves for conventional X-rays, ^{137}Cs and ^{60}Co gamma-rays, and 4 to 10 MV X-rays.²⁵⁾ In this case, the dose build-up factor was assumed to be the same as that of 12 MV X-rays. The resultant tissue-air ratios for 12 MV X-rays, Straker and Grintzner's gamma-ray spectrum and neutrons from the $^9\text{Be}(d, n)^{10}\text{B}$ reaction are shown in Fig. 2 and 3 respectively, as a function of the depth.

Fig. 2. Ratio (RATA) of absorbed dose in tissue-equivalent phantom to in-air tissue absorbed dose in relation to depth of phantom (distance from front surface of phantom) at $\theta=0^\circ$ and $\phi=0^\circ$. Gamma-ray doses. Open circles show the values estimated by a thermoluminescent dosimeter. Full line is the curve calculated by using Glasstone's gamma-ray spectrum of A-bomb.²¹⁾

Fig. 3. Ratio (RATA) of absorbed dose in tissue-equivalent phantom to in-air tissue absorbed dose in relation to depth of phantom (distance from front surface of phantom) at $\theta=0^\circ$ and $\phi=0^\circ$. Neutron doses. The curve for recoil protons was measured with paired chambers. The curves for $^1\text{H}(n, \gamma)^2\text{D}$ reaction and for $^{14}\text{N}(n, p)^{14}\text{C}$ reaction were calculated from thermal neutron distributions determined with a BF_3 proportional counter. The curve for total gives the sum of ratios for recoil protons, gamma-rays from the $^1\text{H}(n, \gamma)^2\text{D}$ reaction and protons from the $^{14}\text{N}(n, p)^{14}\text{C}$ reaction. These curves were determined as a function of depth in the phantom for incident radiation beams at $\theta=0^\circ$ and $\phi=0^\circ$.

and Nagasaki. Those are due to difference in height of epicenters (Hiroshima; 590 m vs Nagasaki; 500 m) and to difference in types of radiations.

The RATA values in relation to angle ϕ_0 remained below 10 percent variations in the deep-seated organs (ovary, fetus or embryo), while the values exceeded 10 percent or more of variations in near-surface organs (testis and thyroid). This means that the correction by the angle ϕ_0 may be necessary for the estimation of the absorbed doses of near-surface organs. In practice, however, it is impossible to identify precisely the posture of survivors at the time of the A-bomb detonations. To simplify the dose estimations of critical organs, practical RATA values were calculated by numerically integrating the RATA (θ_0, ϕ_0) with the angle ϕ_0 for a given angle of θ_0 . The resultant values are given in Table 7. The RATA for mammae, lungs and stomach will be described elsewhere.²⁶⁾ The practical RATA values were given at the angles $\phi_0=0^\circ, 90^\circ$ and 180° for near-surfaced organs, and single values for deep-seated organs. Uncertainties of RATA values derived from the use of the practical RATA values can be less

Derivation of Absorbed Dose in Critical Organs from In-Air Tissue Absorbed Dose

The absorbed dose in the critical organs, $D(\theta_0, \phi_0)$, can be obtained by the following equation:

$$D(\theta_0, \phi_0) = D_{\text{air}}(\theta_0) R(\theta_0, \phi_0) \quad (4)$$

where $D_{\text{air}}(\theta_0)$ is the in-air tissue absorbed dose (Table 1 and Fig. 1). $R(\theta_0, \phi_0)$ is RATA corrected for the angular distribution of A-bomb radiations¹⁴⁾ (Tables 2 to 5), in which angle θ_0 represents that between the normal line to the front surface of survivors and the direction toward the the epicenter, and the angle ϕ_0 is the angle between the normal line to the survivors and the direction toward the hypocenter. It is noted that a correction for shielding is not included, here.

For example, the absorbed doses in the critical organs of survivors who were standing straight ($\phi_0=0^\circ$) at 1000 m from the hypocenter in both cities are given in Table 6. In these dose estimations, the RATA value at $\phi_0=0^\circ$ was used, so that these absorbed doses were at their maximums.

Total errors in determining the RATA are estimated to be less than 11% for gamma-rays, 34% for recoil protons and less than 13% for gamma-rays and protons from the neutron reactions in the human body.¹³⁻¹⁴⁾ As given in Tables 2 to 4, there are slight differences of RATA values between Hiroshima

than uncertainties of exposure factors such as the posture of survivors, so that the practical RATA values are conventionally used for the dose estimation of critical organs.

Table 2. The ratio (RATA) of the absorbed dose in a critical organ to the in-air tissue absorbed dose for ovary, testis and thyroid at $\phi_0=0^\circ$.

Critical organs	ϕ_0^{***}	RATA*						
		Gamma-rays				Neutrons		
		Hiroshima		Nagasaki		Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
		G-spec.**	S-spec.**	G-spec.	S-spec.			
Ovary	45°	0.62	0.45	0.62	0.45	0.097	0.095	0.0061
	30°	0.64	0.47	0.64	0.48	0.10	0.10	0.0062
	15°	0.65	0.49	0.66	0.50	0.11	0.10	0.0062
Testis	45°	0.86	0.74	0.87	0.75	0.59	0.095	0.013
	30°	0.87	0.78	0.88	0.80	0.60	0.095	0.013
	15°	0.87	0.79	0.88	0.81	0.62	0.095	0.013
Thyroid	45°	0.80	0.71	0.81	0.71	0.41	0.10	0.011
	30°	0.81	0.77	0.82	0.78	0.43	0.10	0.011
	15°	0.82	0.79	0.83	0.80	0.46	0.10	0.011

* The RATA was estimated for survivors, who are facing toward the point of detonation and are standing straight ($\phi_0=0^\circ$) in open field (no shielding).

** The RATA values under columns of G-spec. and S-spec. are RATA values calculated by using either gamma-ray spectrum of A-bombs of Glasstone²¹⁾ or of Straker and Grintzner²²⁾, respectively.

*** The angle θ_0 : The epicenters at Hiroshima and Nagasaki are assumed to be 590 m and 500 m. At $\theta_0=45^\circ$ distances from the hypocenter are 590 m at Hiroshima and 500 m at Nagasaki: At $\theta_0=30^\circ$, distances are 1022 m at Hiroshima and 866 m at Nagasaki: At $\phi_0=15^\circ$, distances are 2201 m at Hiroshima and 1887 m at Nagasaki.

Table 3. The RATA for ovary, testis and thyroid, $R(\theta_0, \phi_0)$, at the incident angle of 30° (distance from hypocenter; Hiroshima 1022 m, Nagasaki 866 m).

Critical organs	ϕ_0^*	Gamma-rays				Neutrons		
		Hiroshima		Nagasaki		Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
		G-spec.**	S-spec.**	G-spec.	S-spec.			
Ovary	0°	0.64	0.45	0.64	0.45	0.10	0.10	0.0062
	45°	0.62	0.45	0.63	0.44	0.092	0.095	0.0054
	90°	0.62	0.43	0.62	0.42	0.081	0.090	0.0050
	135°	0.64	0.48	0.65	0.48	0.10	0.095	0.0056
	180°	0.65	0.50	0.66	0.50	0.11	0.10	0.0061
Testis	0°	0.87	0.78	0.88	0.80	0.60	0.095	0.013
	45°	0.84	0.75	0.85	0.76	0.55	0.095	0.013
	90°	0.71	0.54	0.70	0.52	0.40	0.095	0.013
	135°	0.68	0.49	0.67	0.47	0.30	0.095	0.019
	180°	0.72	0.56	0.72	0.56	0.30	0.095	0.025
Thyroid	0°	0.81	0.77	0.82	0.78	0.43	0.10	0.011
	45°	0.81	0.77	0.81	0.78	0.39	0.10	0.011
	90°	0.80	0.76	0.80	0.77	0.32	0.11	0.011
	135°	0.76	0.71	0.76	0.72	0.24	0.11	0.010
	180°	0.75	0.71	0.75	0.72	0.22	0.11	0.0099

* ϕ_0 represents the angle between the normal line to the front surface of the survivors and the direction toward the hypocenter.

** see foot note of Table 2.

Table 4. The RATA* for fetus or embryo exposed *in utero* at the end of 1st, 4th, 7th and 9th gestation month, $R(\phi_0, \phi_0)$, at $\phi_0=0^\circ$.

Developmental age of fetus or embryo	θ_0	Gamma-rays				Neutrons		
		Hiroshima		Nagasaki		Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
		G-spec.**	S-spec.**	G-spec.	S-spec.			
1st month	45°	0.67	0.51	0.67	0.51	0.14	0.10	0.0079
	30°	0.68	0.53	0.69	0.54	0.15	0.10	0.0081
	15°	0.69	0.55	0.70	0.56	0.16	0.11	0.0082
4th month	45°	0.65	0.43	0.65	0.43	0.13	0.10	0.0068
	30°	0.67	0.44	0.67	0.44	0.14	0.10	0.0070
	15°	0.68	0.45	0.69	0.45	0.15	0.10	0.0072
7th month	45°	0.60	0.37	0.60	0.37	0.094	0.095	0.0062
	30°	0.62	0.38	0.62	0.38	0.10	0.10	0.0064
	15°	0.64	0.39	0.64	0.39	0.11	0.10	0.0065
9th month	45°	0.56	0.32	0.56	0.32	0.076	0.090	0.0044
	30°	0.57	0.34	0.57	0.34	0.081	0.090	0.0046
	15°	0.59	0.37	0.60	0.38	0.086	0.090	0.0046

* The RATA were calculated for the pregnant women exposed to radiations, facing to the point of detonation. These RATAs were corrected for the angular distribution of radiations from the atomic bombs by a method described elsewhere.⁽¹⁾

** see foot note of Table 2.

Table 5. The RATA for fetus or embryo exposed *in utero* at the end of 1st, 4th, 7th and 9th gestation month, $R(\theta_0, \phi_0)$, for the incident angle of 30° (distance from the hypocenter; Hiroshima 1022 m, Nagasaki 866 m).

Developmental age of embryo or fetus	ϕ_0^*	Gamma-rays				Neutrons		
		Hiroshima		Nagasaki		Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
		G-spec.**	S-spec.**	G-spec.	S-spec.			
1st month	0°	0.68	0.53	0.69	0.54	0.15	0.10	0.0081
	45°	0.66	0.49	0.67	0.50	0.13	0.10	0.0072
	90°	0.62	0.42	0.62	0.41	0.11	0.095	0.0058
	135°	0.64	0.46	0.65	0.46	0.11	0.095	0.0058
	180°	0.66	0.49	0.67	0.50	0.12	0.10	0.0060
4th	0°	0.67	0.44	0.67	0.44	0.14	0.10	0.0070
	45°	0.64	0.42	0.64	0.42	0.12	0.095	0.0061
	90°	0.59	0.39	0.58	0.39	0.093	0.085	0.0045
	135°	0.58	0.38	0.58	0.38	0.085	0.080	0.0037
	180°	0.58	0.38	0.58	0.38	0.083	0.080	0.0036
7th	0°	0.62	0.38	0.62	0.38	0.10	0.10	0.0064
	45°	0.60	0.37	0.60	0.37	0.094	0.094	0.0056
	90°	0.57	0.35	0.57	0.35	0.081	0.085	0.0043
	135°	0.57	0.35	0.57	0.35	0.077	0.080	0.0036
	180°	0.57	0.35	0.57	0.35	0.077	0.080	0.0035
9th	0°	0.57	0.34	0.57	0.32	0.081	0.090	0.0046
	45°	0.56	0.33	0.56	0.32	0.077	0.085	0.0040
	90°	0.56	0.32	0.56	0.31	0.073	0.080	0.0034
	135°	0.56	0.32	0.56	0.32	0.072	0.075	0.0030
	180°	0.56	0.32	0.57	0.33	0.072	0.075	0.0030

* ϕ_0 represents the angle between the horizontal line on the anterior abdomen of mother and the direction toward the hypocenter.

** see foot note of Table 2.

Table 6. The absorbed dose in the critical organs for gamma-rays and neutrons in Hiroshima and Nagasaki at 1000 m from the hypocenters.

Critical organs or Developmental age	Gamma-rays (rad)				Neutrons (rad)					
	Hiroshima		Nagasaki		Hiroshima					
	G-spec.*	S-spec.*	G-spec.	S-spec.	Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$	Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
Ovary	182	134	539	450	15.5	15.0	0.930	6.51	6.40	0.384
Testis	247	222	808	736	89.3	14.3	1.95	37.4	5.89	0.806
Thyroid	231	219	754	726	64.5	15.0	1.65	27.0	6.20	0.682
1st month	194	145	635	506	22.2	15.8	1.22	9.30	6.50	0.502
4th	190	125	616	405	20.2	15.0	1.04	8.68	6.20	0.434
7th	176	108	570	350	15.0	15.0	0.954	6.20	6.20	0.397
9th	162	97	529	330	12.1	13.5	0.690	5.05	5.60	0.285

1. The in-air tissue absorbed doses at 1000 m (table 1 and Fig. 1) were 285 rads of gamma-rays and 150 rads of neutrons at Hiroshima, and 920 rads of gamma-rays and 62 rads of neutrons at Nagasaki.
2. * see foot note of Table 2.
3. These doses were calculated by assuming the survivors to be standing straight ($\phi_0=0^\circ$) in open field (no shielding) at 1000 m from the hypocenters.

Table 7. Practical RATA values for critical organs

Critical organs	Exposure factor	Gamma-rays		Neutrons		
		G-spec.*	S-spec.*	Recoil protons	$^1\text{H}(n, \gamma)^2\text{D}$	$^{14}\text{N}(n, p)^{14}\text{C}$
Mamma	Front	0.91	0.85	0.65	0.08	0.008
	Side	0.85	0.75	0.55	0.07	0.007
	Back	0.72	0.60	0.30	0.06	0.005
	in-doors	0.83	0.73	0.52	0.07	0.007
Thyroid	Front	0.81	0.76	0.40	0.10	0.01
	Back	0.75	0.72	0.24	0.10	0.01
	in-doors	0.78	0.75	0.32	0.10	0.01
Testis	Front	0.85	0.77	0.57	0.10	0.01
	Back	0.70	0.53	0.30	0.10	0.01
	in-doors	0.76	0.62	0.43	0.10	0.01
Ovary**		0.63	0.47	0.10	0.10	0.006
Stomach**		0.68	0.53	0.12	0.10	0.007
Fetus or Embryo**						
1st (developmental age)		0.66	0.50	0.12	0.10	0.007
4th		0.61	0.42	0.09	0.10	0.006
7th		0.59	0.38	0.08	0.09	0.005
9th		0.56	0.32	0.07	0.08	0.004

* see foot note of Table 2.

Front; The survivors were exposed to the A-bombs facing front in open field.

Side; The survivors were exposed to the A-bombs facing sideways in open field.

Back; The survivors were exposed to the A-bombs with their back toward in open field.

In-door; The survivors were exposed to the A-bombs inside a Japanese style slated wooden house.

** For deep-seated organs, the present practical RATA values can be used both in case of indoor and open field exposure.

Assuming that the angular distributions of radiations for in-door exposure are approximately isotropic, the practical RATA values should be used for the dose estimation of in-door exposures.

In the estimation of RATA, the different RATA values were obtained when using gamma-ray spectrum of Glasstone²¹⁾ and that of Straker and Grintzner²²⁾ (see Table 2 to 5). The differences can be attributed to the differences in the tissue-air ratios in relation to depth which depend on the gamma-ray spectrum. This suggests that precise information on gamma-ray spectrum becomes important especially in the deep-seated organs.

For ovary, fetus or embryo, about 50% of the contribution to neutron dose is by protons due to elastic collision and the $^{14}\text{N}(n, p)^{14}\text{C}$ reaction, and about 50% from the gamma-rays due to the $^1\text{H}(n, \gamma)^2\text{D}$ reaction. In contrast, for the thyroid and testis, about 80% of the contribution to neutron dose is by protons, and 20% or less from the gamma-rays due to the $^1\text{H}(n, \gamma)^2\text{D}$ reaction. If protons are the major cause for high RBE values of neutron irradiations, biological effects on near-surface organs (e. g. thyroid and testis) might be greater than those of deep-seated organs (e. g. ovary, fetus or embryo). Moreover, neutron-rich radiations of Hiroshima would accentuate further biological effects of near-surface organs, while neutron-poor radiations of Nagasaki would enable us to deemphasize contribution of high RBE effects of neutrons in the deep-seated organs (see Table 6).

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