A CHORD Simulation for Insult Assessment to the Red Bone Marrow

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HEALTH PHYSICS DIVISION

A CHORD SIMULATION FOR INSULT ASSESSMENT TO THE RED BONE MARROW

T. D. Jones

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A CHORD SIMULATION FOR INSULT ASSESSMENT TO THE RED BONE MARROW*

T. D. Jones

Abstract

Critical Human Organ Radiation Dosimetry (CHORD) probability density functions for A-P, P-A, bilateral, rotational, and isotropic incidence, plus simple depth-dose data, permit the rapid estimation of the radiation insult to the active red bone marrow system of the ICRP Reference Man. The CHORD concept follows the variations in the microscopic processes of absorption, attenuation, and scattering on a macroscopic level so that it is not necessary to attempt detailed calculations for each and every case of interest. Similar techniques have been applied to reactor criticality calculations and the general logic of the CHORD process can be applied to any cause-response type situation which can be described in terms of variation with distance in the medium of interest. Doses to active bone marrow from exposures to photons and neutrons are presented and excellent agreement is shown with the few available experimental results.

Introduction to the CHORD Concept

When a bioorganism is subjected to a radiation environment, a critical organ or region of greatest risk usually is irradiated non-uniformly if the linear dimensions of the critical organ are not small

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or the depth of the critical organ within the bioorganism is not large[1] compared with the mean-free path of the irradiating particles. Radiation insult specific analyses are usually based on dose to cells, a small target site or cluster of cells within an organ such as the mandible, or a center such as the central nervous, or active bone marrow system. For some effects cells or sensitive sites within cells may not be irradiated uniformly,because of discrete energy loss events, and microdosimetric considerations (Rossi, 1968) may be desirable. On a more macroscopic scale, chronic effects such as bone sarcomas or even leukemia may, in some cases, be directly related to highly localized exposures such as usually encountered in radiotherapy of tumors where the maximum absorbed dose at a particular site (mass of a gram as opposed to an intercellular site) may be more meaningful than the mean absorbed dose to the complete active marrow system (Wilson and Carruthers, 1962; A. R. Jones, 1975). Detailed distributions of photon dose to specific active marrow regions for A-P, P-A, rotational, and side (lateral) incidence have been published and could be readily applied to many situations of interest (Jones, Auxier, Snyder, and Warner, 1973; Clifford and Facey, 1970; O'Brien and Sanna, 1976). For radiation protection and risk analyses from acute effects and those chronic effects where risk is thought to be proportional to the insult to the system such as usually assumed for leukemia, it is often not possible or desirable to establish insult-response type correlations on a microscopic level. Therefore, it

[1] The combination of insult specification, penetration depth, and the size of the critical organ influence the degree of nonuniform irradiation of an organ. Because the mutual ranges of these variables cannot be defined precisely, except for a specified irradiation it is difficult to quantify more precisely than "not small" and "not large".

becomes necessary to assign a "mean" insult or risk to a non-uniformly irradiated "critical organ".

A radiation insult to the human body is a phenomenon that cannot be calculated or measured directly. It is possible to simulate such a process directly in experimental analogues, but all calculational analogues are indirect simulations. The basic transport processes are often used in straightforward calculational simulations; however, adjoint methods are becoming more widely used because of the increased computational efficiency. Radiation protection has its own adjoint technique in the well known "theorem of reciprocity"; however, its validity is less obvious than the simple equality

$$(\text{statistical Wt} \times \text{Pr of occurrence})_{\text{unbiased}} = (\text{statistical Wt} \times \text{Pr of occurrence})_{\text{biased}}$$

which serves as the basis of many adjoint methods. All of this simply means that, all transport calculations are either "straightforward" or "backward" indirect simulations of actual events.

If it is possible to establish insult versus depth curves for a human analogue and a source field of interest, then it is possible to simulate the exposure to the active bone marrow by the use of a density function (CHORD) of penetration length (ℓ). If a point is chosen randomly and uniformly within a differential unit of mass of the active bone marrow, then the dose at this point may be estimated from the $D(\ell)$ curve. The method of CHORDS (a simple adjoint technique) depends completely upon establishing a response or insult versus distance correlation.

Usually, any specific CHORD or $p\{\ell\}\ d\ell$ distribution is obtained by assuming that the critical organ is simply a volume of constant density, and for each differential unit of mass dm, chosen by Monte Carlo techniques, the minimum distance ℓ to the closest irradiated air-tissue interface along a surface normal vector is uniquely determined. This process is continued until $p\{\ell\}\ d\ell$ is well known statistically. Since this technique is a "tool of simulation", its specific application must be adjusted to the type of insult versus distance relationship available.[2] Chord usually implies a straight line through two points on the surface, e.g., the skin; however, in this application CHORD is an acronym derived from Critical Human Organ Radiation Dosimetry and represents only a specific portion of a "true chord". The CHORD concept is illustrated in Figure 1 and the CHORD or $p\{\ell\}\ d\ell$ distribution provides "weighting" factors, in the detection site, for an integration over a specific insult such as a "multicollision" depth-dose curve for the source geometry of interest.

CHORD Applications to Red Bone Marrow

Figure 2 illustrates the distribution of the active red bone marrow in the normal adult and the corresponding analog for our Monte Carlo transport code. In the adult reference man (ICRP, 1975) there are 1500 grams of active red marrow and 1500 grams of yellow marrow which are predominately fat cells. Inactive yellow marrow may be transformed quickly into active marrow by a stimulus such as bleeding or infection; yellow marrow in bone shafts is known to contain some

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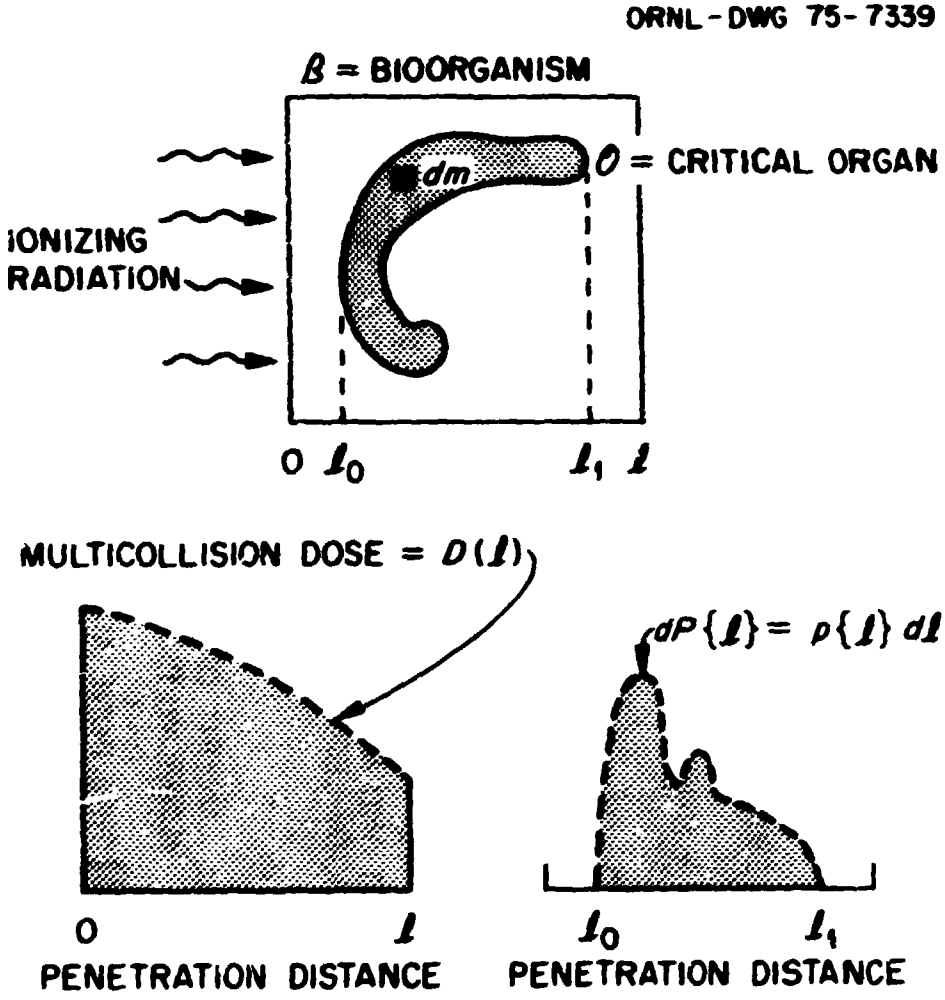
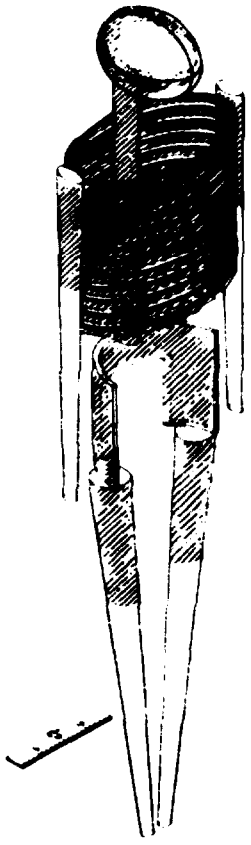
[2] $P\{\ell\}\ d\ell$ distributions in this paper have been computed for the depth-dose data to which they are applied, i.e. ℓ is not defined in the same manner for all exposure situations.



BUT $l = l(dm)$,

AND $\bar{D} = \int_0 D(l) \cdot p\{l\} \cdot dl \Big/ \int_{-\infty}^{\infty} p\{l\} \cdot dl$

Figure 1. Critical Human Organ Radiation Dosimetry - The CHORD Concept.



SKULL	13.1%
VERTEBRAE	28.4%
RIBS + STERNUM	10.2%
SCAPULAE	4.8%
HEAD AND NECK OF BOTH ARMS	1.9%
BOTH CLAVICLES	1.6%
HEAD AND NECK OF BOTH LEGS	3.8%
PELVIS	36.2%

TOTAL AMOUNT OF RED BONE MARROW: 1500 g

RED BONE MARROW

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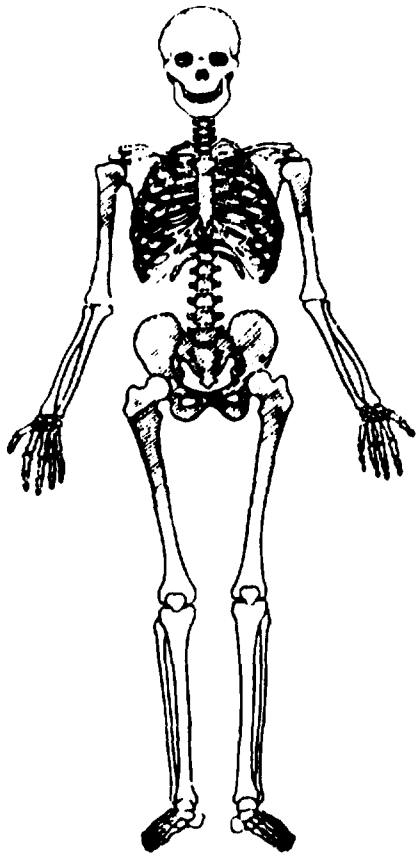

Figure 2. Distributions of the Active Bone Marrow.

active cells but, in general, the proportion of active cells in adult yellow marrow is usually considered to be small (Spiers, 1966). Thus, for most situations of interest, only the red marrow receives major consideration.

The importance of this estimate based on radiation damage to the active marrow system cannot be overstated as bone marrow damage usually will be the major mechanism in radiation death or acute radiation sickness sterilization whole body irradiation because it occurs at much lower levels (Hempelmann, 1968; Wald, 1975) than death or incapacitation due to radiation damage of the gut mucosa or the central nervous system. For sublethal criticality accident exposure levels, levels of interest in radiation protection, and population exposure levels, the most demanding recommendations of the ICRP (1964) relate to the maximum permissible doses to the gonads and the blood-forming organs. In radiation protection, the testes are usually considered to be the critical organ of primary interest because of their shallow location and because of the difficulty of estimating the bone marrow insult. However, if the exposure level subjects an individual to considerable risk or the individual is reproductively inactive, then an estimation of the insult to his active marrow system could be more meaningful (Wald, 1975).

The dose at a penetration depth of 4-5 cm (Spiers and Overton, 1962) is often chosen to describe the insult to the red bone marrow; however, for photon irradiation the "5 cm rule" can easily be in error by a factor of two or more and is expected to be even worse for neutron irradiation because irradiating particles may have much

shorter mean interaction distances. This approximation tends to retain popularity in spite of its inaccuracy, because the red marrow is distributed widely in the skeleton. The skeletal distribution shown in Figure 2 illustrates the fact that, in general, no specific depth can be applied for different exposure geometries and different irradiating particles or even different energies of the same type particles.

For internal dosimetry, especially for radionuclides deposited in or near the skeleton, a precise calculational analog of the active marrow system requires some postulations about cavity size variation and the distribution of these marrow cavities within the skeleton. However, for most situations of external exposure, the active marrow may be assumed to be uniformly deposited in certain regions of the skeleton. This simplification is possible because for external exposure, distance versus insult (dose) variation is much less than for internal radionuclide deposition where the insult (dose) usually varies even more rapidly than inversely with the square of the distance. There are two opposing effects that also influence the photon absorbed dose to marrow. These effects are the increased shielding by the bone structure and the enhancement of dose near the higher atomic number bone tissue (Spiers, 1966; Wilson and Carruthers, 1962). As demonstrated later, the net influence of these opposing effects is usually considered to be small (Facey and Clifford, 1973) for external exposure although such is not always the case for internal emitters.

CHORD Distribution and Marrow Doses

Figure 3 and Table 1 present CHORD density functions for active marrow in the Reference Man Phantom (ICRP, 1975) for A-P, P-A, bilateral, rotational, and isotropic exposure. Due to the nature of the CHORD concept and the general convexness of the Reference Man Phantom, there is no differentiation between 2π [3] and 4π CHORD distributions; however, depth-dose curves will reflect the different exposure geometries. The peak at 2 cm for rotational and isotropic exposure is due to the shorter penetration distances to the upper arm bones while the higher and broader peak at about 6 cm is predominantly from the vertebrae and pelvis. The CHORD distributions are influenced strongly by the pelvic region and the thoracic vertebrae which contain about 36% and 28%, respectively, of the total active marrow. For isotropic exposures (see Figure 3), ℓ varies to 10 cm because depth-dose data are expected to be related to the minimum distance to the closest irradiated surface, i.e. along the surface normal vector from the site of interest. Hence ℓ can never exceed the half-value thickness of the torso. For bilateral exposure, the A-P and P-A $P\{\ell\}\, d\ell$ values were averaged and are used with plane beam depth-dose data. Since no rotational depth-dose data were available in the literature, it was necessary to employ broad beam depth-dose data for this exposure situation. Therefore, for rotational exposures ℓ varies to 40 cm.

The CHORD distributions from Figure 3 were used in conjunction with depth-dose curves (Jones, 1976) according to (see Figure 1)

$$D_{\text{red marrow}} = \sum_{\ell} D(\ell) \cdot p\{\ell\} \cdot \Delta\ell$$

[3] 2π is used to describe a hemispherical cloud of radiation above an infinitely absorbing interface.

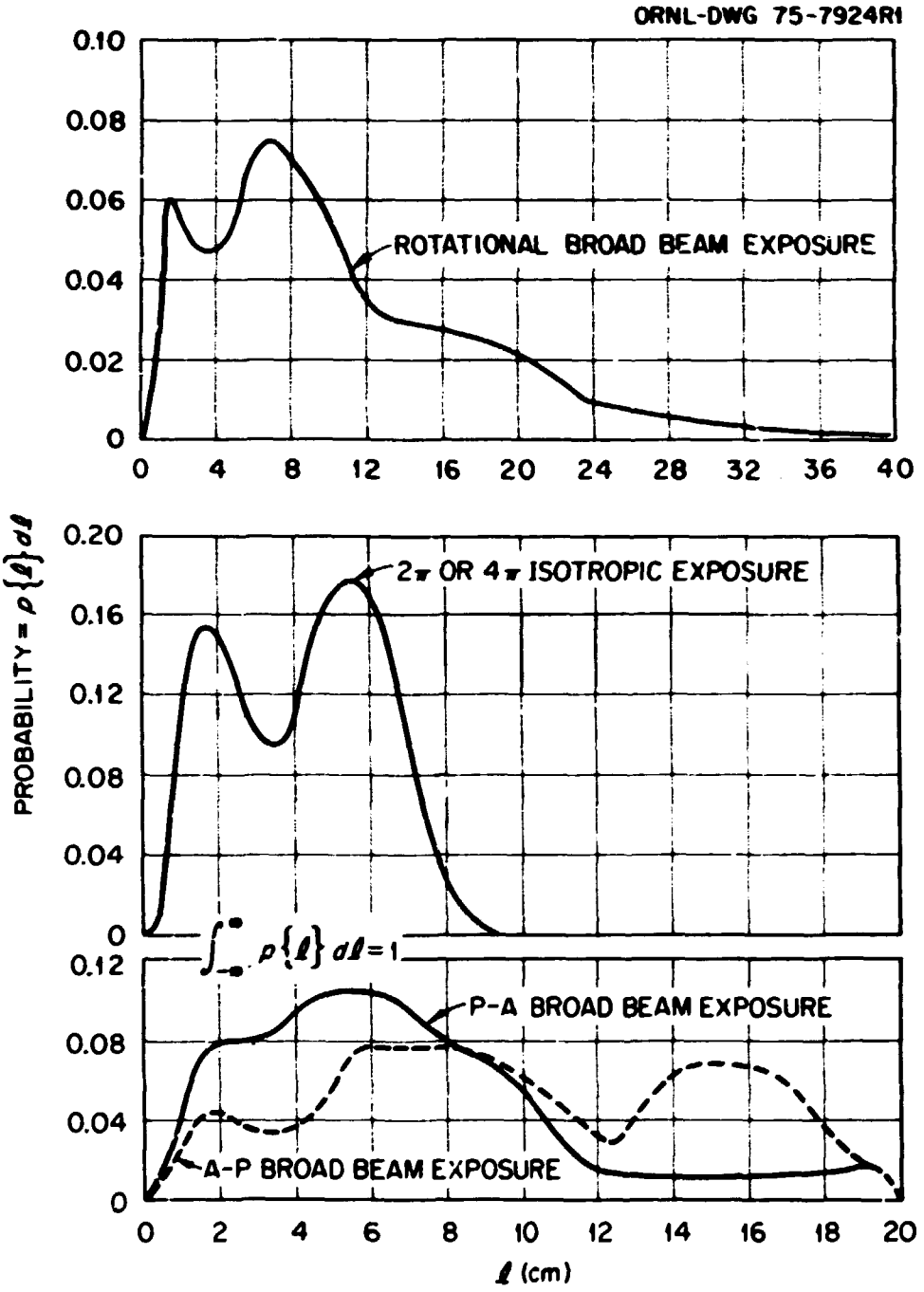

Figure 3. CHORD Density Functions for Active Marrow in Reference Man.

Table 1. CHORD $p\{\ell\}\Delta\ell$ Values for Active Marrow in Reference Man.

ℓ (cm)	Rotational	cv	A-P	cv*	P-A	cv	Bilateral	cv	Isotropic	cv
0–0.5	.00515	6	.00626	3	.00718	3	.00672	4	.0231	3
0.5–1	.0175	3	.0157	2	.0252	1	.0204	2	.0658	2
1–2	.0608	2	.0412	2	.0716	1	.0564	2	.154	2
2–3	.0508	3	.0361	2	.0791	1	.0576	2	.126	2
3–4	.0465	3	.0340	2	.0850	1	.0595	2	.0944	2
4–5	.0595	3	.0442	2	.107	1	.0756	2	.152	2
5–6	.0662	2	.0730	1	.126	1	.0995	2	.179	2
6–7	.0744	2	.0782	1	.109	1	.0936	2	.136	2
7–8	.0705	2	.0748	1	.0806	1	.0777	2	.0586	2
8–9	.0703	2	.0738	1	.0756	1	.0747	2	.0185	6
9–10	.0603	2	.0641	1	.0626	1	.0634	2		
10–11	.0482	3	.0522	1	.0440	2	.0481	2		
11–12	.0380	3	.0364	2	.0207	2	.0286	3		
12–13	.0311	3	.0292	2	.0127	3	.0210	4		
13–14	.0292	3	.0549	1	.0121	3	.0335	3		
14–15	.0282	3	.0658	1	.0119	3	.0389	3		
15–16	.0268	4	.0675	1	.0123	3	.0399	3		
16–17	.0285	3	.0643	1	.0129	3	.0386	3		
17–18	.0283	3	.0492	1	.0130	3	.0311	3		
18–19	.0237	4	.0231	2	.0154	3	.0192	4		
19–20	.0241	4	.0159	3	.0168	2	.0164	4		
20–21	.0218	4								
21–22	.0169	4								
22–23	.0135	5								
23–24	.00985	6								
24–25	.00866	6								
25–26	.00787	7								
26–27	.00672	7								
27–28	.00699	7								
28–29	.00545	8								
29–30	.00562	8								
30–31	.00385	9								
31–32	.00276	11								
32–33	.00194	13								
33–34	.00170	14								
34–35	.00147	15								
35–36	.00104	14								
36–37	.00126	16								
37–38	.00164	14								
38–39	.000908	19								
39–40	.000341	32								

*Coefficient of variation in percent.

because all CHORD distributions were normalized to unity. Photon dose to the active marrow as predicted by the CHORD concept is shown in Figure 4; however, bilateral and rotational results are not shown because of close agreement with the results for A-P exposure.

Figure 5 provides active marrow dose relative to exposure at the front of the chest for A-P incidence. Alun Jones' experimental results (1964) are included and the mean deviation between the two methods is only 6% to 1.25 MeV which is high into the Compton range shown in Figure 6. Figure 6 is intended to serve as a guideline for applications of the method of CHORDs to critical regions in or near bone tissue. Experimental results were not available for higher energies. Column 4 in Table 2 represents estimates from the CHORD method and column 5 is from a Monte Carlo transport code (Jones, Auxier, Snyder, and Warner, 1973). These values shown in column 5 were calculated at the time of the cited reference but have not been published previously in this form. The Monte Carlo results show excellent agreement in the photoelectric region (see Figure 6) but seem to become increasingly inaccurate in the Compton region. This unexpected characteristic of the Monte Carlo results defies explanation at this time but the effect will be investigated.

The important practical case of dose to the active marrow from broad beam incidence on a constantly rotating phantom is shown in Figure 7. Experimental results from Wilson and Carruthers (1962), Alun Jones (1964), and Facey (1968) may have suffered slight disfigurations due to replotting, but all appear to have been normalized to the same ordinate at 250 keV. Much concern has been

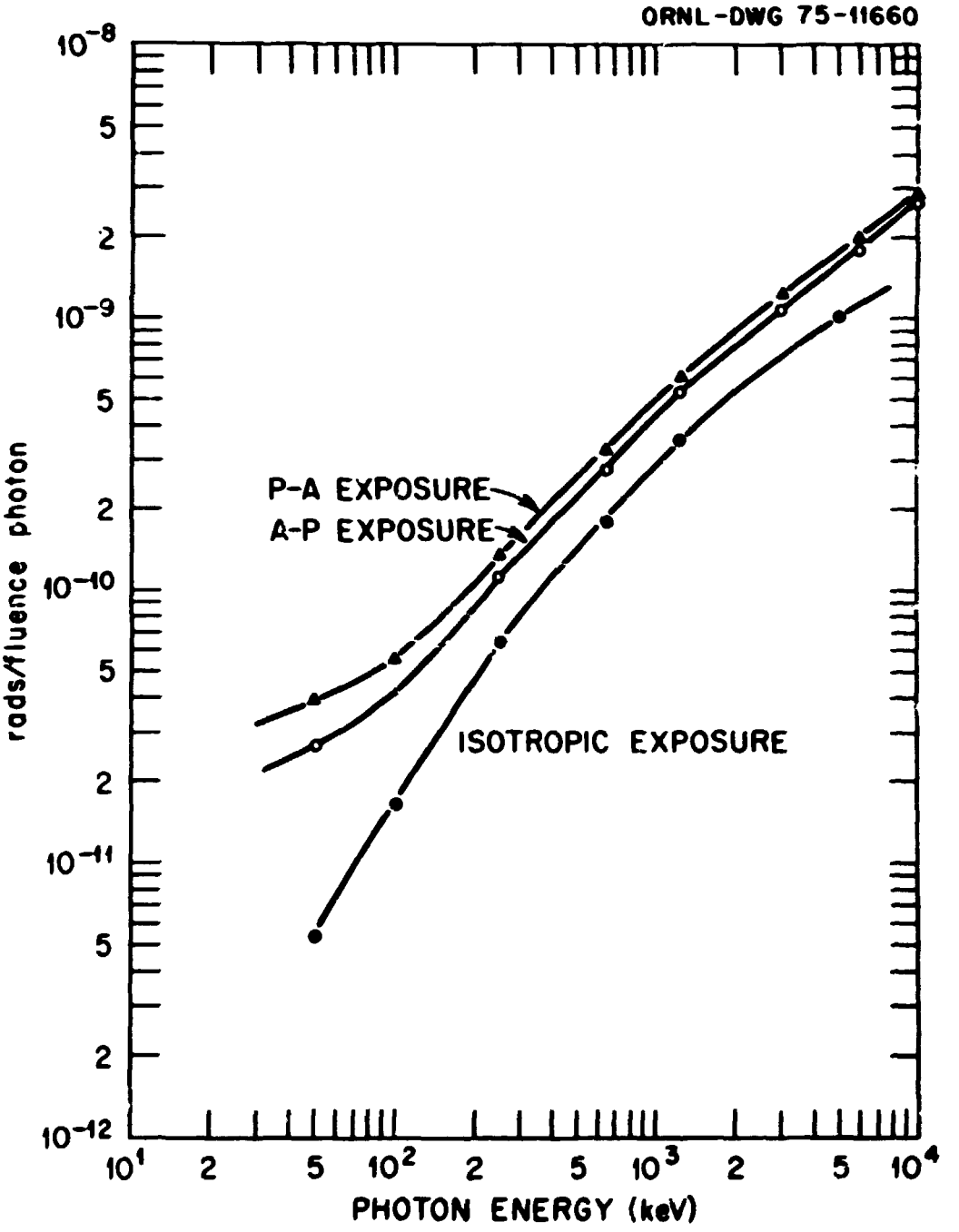

Figure 4. Dose to Active Marrow as Predicted by the CHORD Concept.

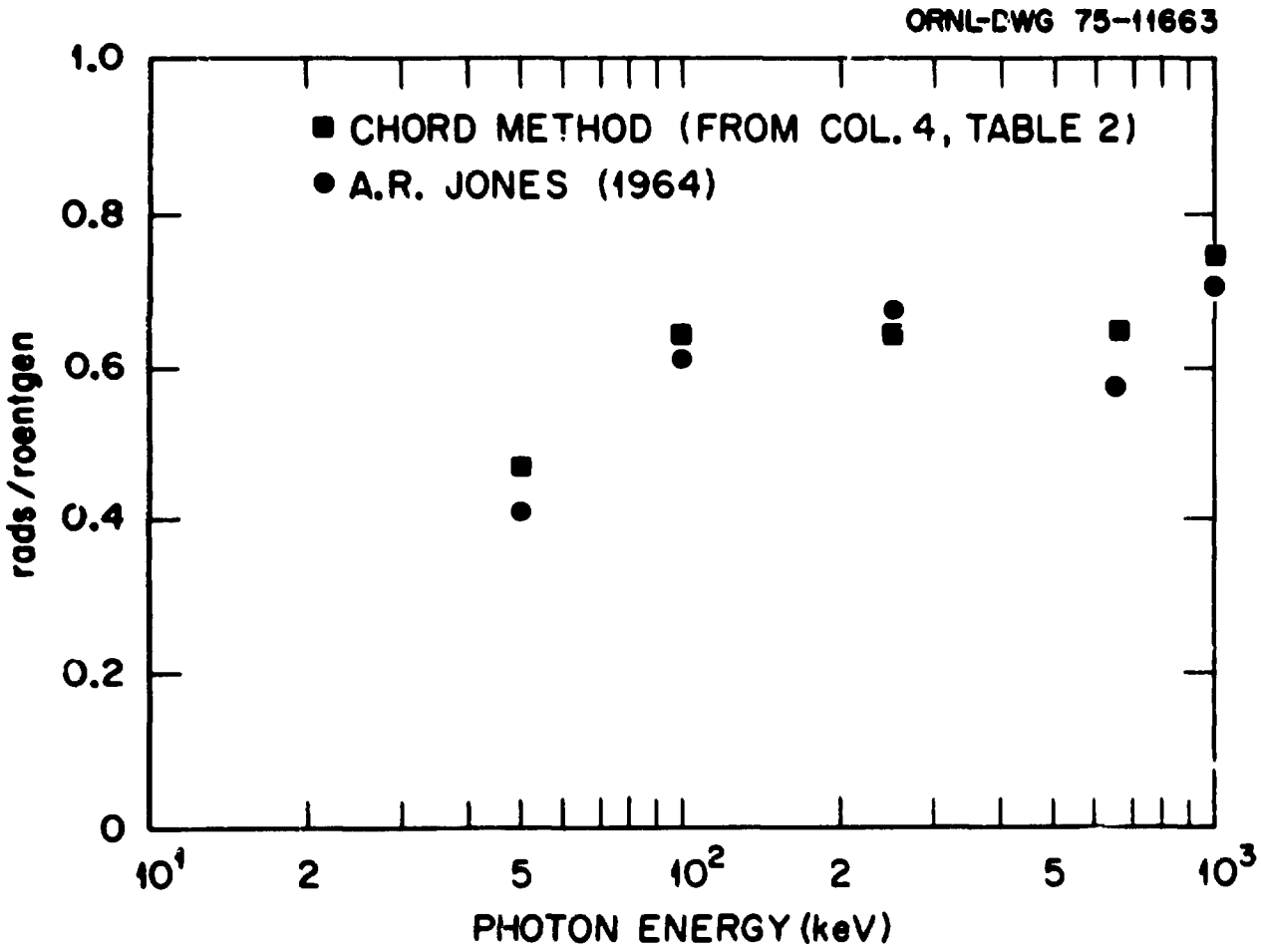

Figure 5. Active Marrow Dose Relative to Exposure at the Front of the Chest (A-P Exposure).

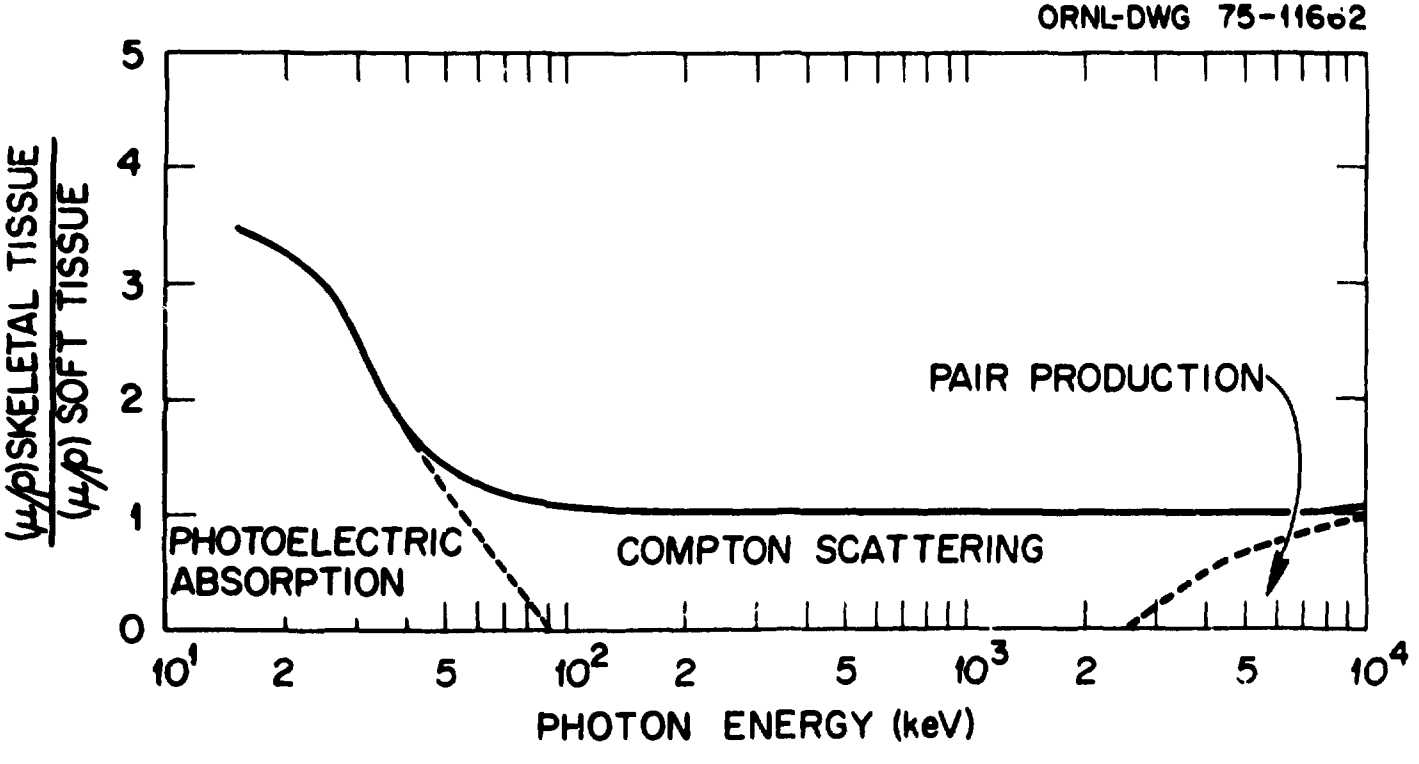

Figure 6. Photon Attenuation of Skeletal Tissue Compared to that of Soft Tissue.

Table 2. Active Marrow Dose Relative to Dose at the Front of the Chest.

γ-Energy	$\bar{D}$ (marrow)	D* (chest)	$\bar{D}/D$ CHORD	$\bar{D}/D$ Monte Carlo**
50 keV	.26†	.48	.54	.54
100	.42	.57	.74	.68
250	1.1	1.47	.75	.47
660	2.7	3.61	.75	.50
1.25 MeV	5.3	6.14	.86	.55

* 10^{-10} rads/fluence photon.

**T. D. Jones, Health Phys. 24, 248, 1973.

†Calculated at time of Health Phys. 24, 248, 1973, but unpublished.

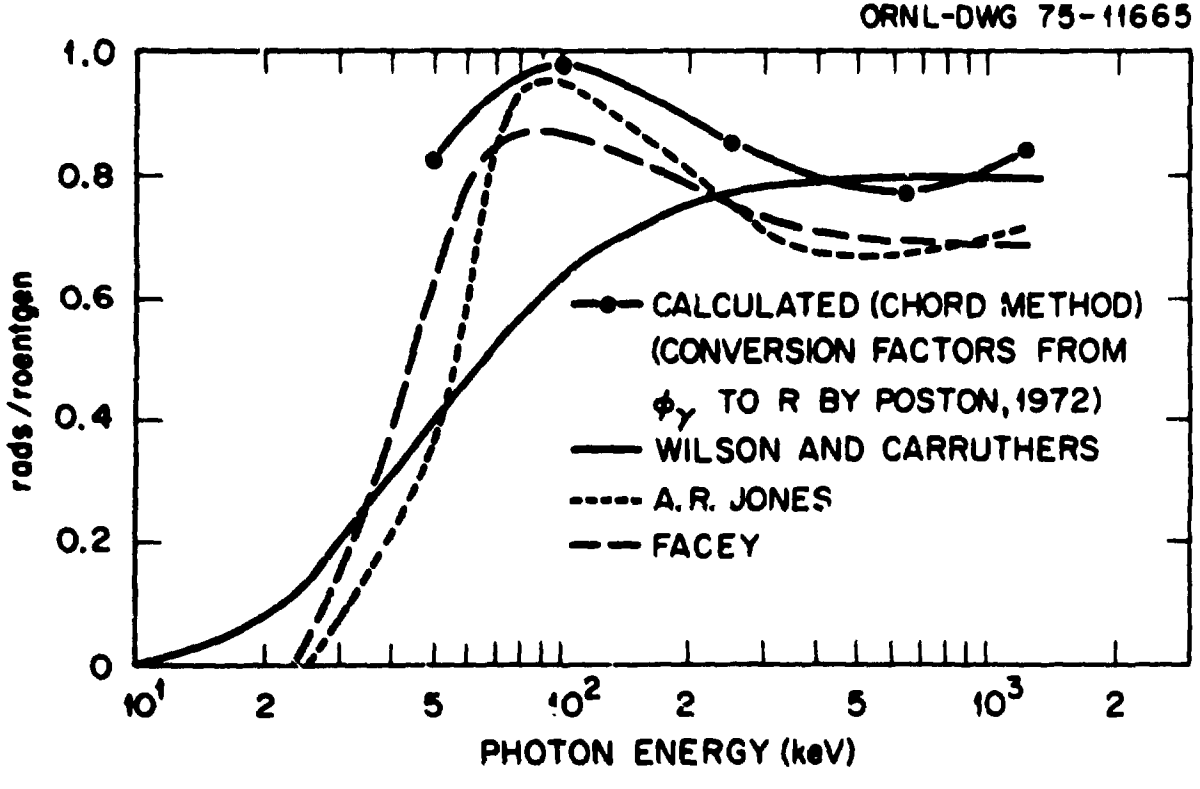

Figure 7. Dose to Bone Marrow from a Broad Beam Incident on a Rotating Phantom.

expressed (Facey 1968) about whether marrow dose per unit exposure should increase monotonically with energy as noted by Wilson and Carruthers (1962) or whether it should peak at about 100 keV as noted by Alun Jones (1964). The different shapes have been considered due to energy degradation within the phantom and the fact that the detector systems of Alun Jones (1964) and Wilson and Carruthers had energy dependences in opposite directions (Facey, 1968).

At this time, it seems more probable that the different shapes are due primarily to the fact that if one considers the shape of the curve describing the ratio of the photon fluence per unit exposure as a function of photon energy (Rad. Health Hbk, 1970; Fair, 1967) then the dose response curve must have a shape that peaks about 100 keV because the fluence per unit exposure varies more rapidly with energy than does the absorbed dose to the marrow, and secondarily to the fact that Wilson and Carruthers assumed that 60% of the active marrow received a dose similar to that measured in the thoracic vertebrae and 40% received a dose similar to that measured in the sternum.[4] The CHORD doses are in excellent agreement with Facey's results (1968), except for a consistent 12% overestimation. This deviation is attributed to the facts that (a) 13.1% of the active marrow is in the skull (see Figure 2) which Facey did not include, (b) experimental

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[4]This method of averaging would tend to underestimate dose at lower energies because as Facey (1968) points out, the "pelvis dominates dose at higher energies followed by the thoracic vertebrae and sacrum down to 30 keV. There the ribs enter second place and below 30 keV the ribs dominate." Facey (1968) attempted to resolve difficulties in the rotational case and his results are shown in Figure 7.

results from Facey appear to have been normalized to other experimental results at 250 keV, (c) experimentally obtained doses to the active marrow system necessitate the assumption of an "effective mass center" of each important marrow region (Clifford and Facey, 1970),[5] and (d) the CHORD estimate did not allow for increased attenuation by bone tissue shielding the marrow (Facey and Clifford, 1973). As seen in Figure 6, this effect is not large except for extremely low energies. At the low energies, dose to the shallow marrow becomes increasingly important, as is shown by the rapid attenuation of dose as a function of depth, and most experimental results are expected to be somewhat low because of the method of averaging. CHORD dose values were normalized per unit exposure according to the Rad. Health Hdbk. (1970).[6] In spite of factors a, b, c, and d, excellent agreement for A-P estimates (A. R. Jones, 1964; Facey, 1976) and rotational estimates (Facey, 1968) compared with the method of CHORDs is observed.

Spiers and Overton (1962) measured attenuation factors in an anthropomorphic phantom irradiated by twenty-five equal sources which "were distributed, five on each wall and on the ceiling of an empty room both in air and in the phantom. The sources were positioned, one in the centre and four towards the corners of each area, so that each

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[5]For precision, this "effective mass center" would have to be "weighed" proportionally to dose variations in the local volume of interest; however, most experimenters appear to have used the mass centroid.

[6]Poston's conversion values of fluence per unit exposure for the Reference Man tissue composition are, for all practical purposes, equal to those in the Rad. Health Handbook.

contributed nearly the same dose-rate to the centre of the room and, moreover, the radiation was incident nearly uniform over a solid angle somewhat greater than 3π." They plotted their attenuation factors as a function of depth from the nearest body surface and then computed a weighted mean transmission[7] to the bone marrow for 0.2, 0.5, 1.0, 1.5, and 2.0 MeV photons.

Transmission factors for isotropic exposure shown in Figure 4 were compared to this "nearly omni-directional gamma radiation." Spiers and Overton's results were consistently higher than those obtained from the method of CHORDS by about 20%. Although the source geometries were different, this was thought to be good agreement and especially encouraging was the fact that CHORD values were lower whereas for the rotational comparison, CHORD values were slightly higher.

Calculations of absorbed dose to the bone marrow for isotropic exposure to monoenergetic gamma rays have been published recently by O'Brien and Sanna (1976). They did not discuss their algorithms for the simulation of an isotropic field of photons; however, their results compared with Figure 4 according to: 5 MeV (8%), 2 MeV (4%), 1 MeV (4%), 500 keV (8%), and 200 keV (2%).

Figure 4, which shows the dose to the active marrow for exposure to monoenergetic photons, suggests that if one is concerned only about protection of his bone marrow, he should not do the instinctive thing and turn his back, but instead should face the hazard while backing away. The same effect was also observed by Piesch (1968) and holds for the neutron data in Table 3 which illustrates dose to the active

[7]Spiers and Overton used the term attenuation factors; however, their paper indicates that they actually worked with transmission factors.

Table 3. Dose to Active Marrow from Neutron Produced Recoil Ions as Predicted by CHORD Distributions.

Energy	Free-Space* Kerma	P-A**	A-P	Bilateral	Rotational	Isotropic
.025 eV	2.1	2.1	1.2	1.7	1.6	.70
1 keV	1.0	3.3	2.2	2.5	2.3	1.1
10 keV	10.	4.1	2.6	3.3	2.8	1.6
100 keV	70.	12.	7.4	9.9	9.2	5.4
1 MeV	230.	110.	67.	81.	75.	47.
2.5 MeV	340.	240.	180.	211.	190.	84.
14 MeV	690.	590.	520.	556.	540.	330.

*x 10^{-9} ergs/(gram-fluence neutron)

**x 10^{-11} rads/fluence neutron

marrow from exposure to monoenergetic neutrons (Facey and Clifford, 1973). Some of the data in Table 3 are plotted in Figure 8 for ease of application. Bilateral and rotational results are not shown in Figure 8 because of their close agreement with the results for A-P exposure. Absorbed dose from neutron produced recoil ions is usually characterized by the hydrogen atomic density, because about 70% of the absorbed dose is due to interactions with hydrogen atoms for neutron energies below 14 MeV (Auxier, Snyder, and Jones, 1968; Jones, 1974). Standard soft muscle tissue contains about 10% by weight hydrogen and has a specific gravity of unity, while bone tissue contains about one-half the weight percentage of hydrogen as does muscle tissue but has about twice the specific gravity of muscle tissue so that the hydrogen atomic density is not very different for the two types of biological tissue (Facey and Clifford, 1973). Lung tissue has a specific gravity of only about 0.3 and the hydrogen atomic density, therefore, is quite different; however, most critical organs of interest are either distant from the lung tissue or closer to an irradiated surface so that the penetration distance in grams/cm^2 is less than the other portion of the ray of travel that passes through a section of the lungs and is used as the index for dose assessment. Based on depth-dose curves from some previous calculations (Facey and Clifford, 1973; Jones, Auxier, Snyder, and Warner, 1973), it is believed that most regions of variable specific gravity do not significantly influence the application of the method of CHORDs, unless one is specifically interested in dose to the heart or to a volume of lung tissue.

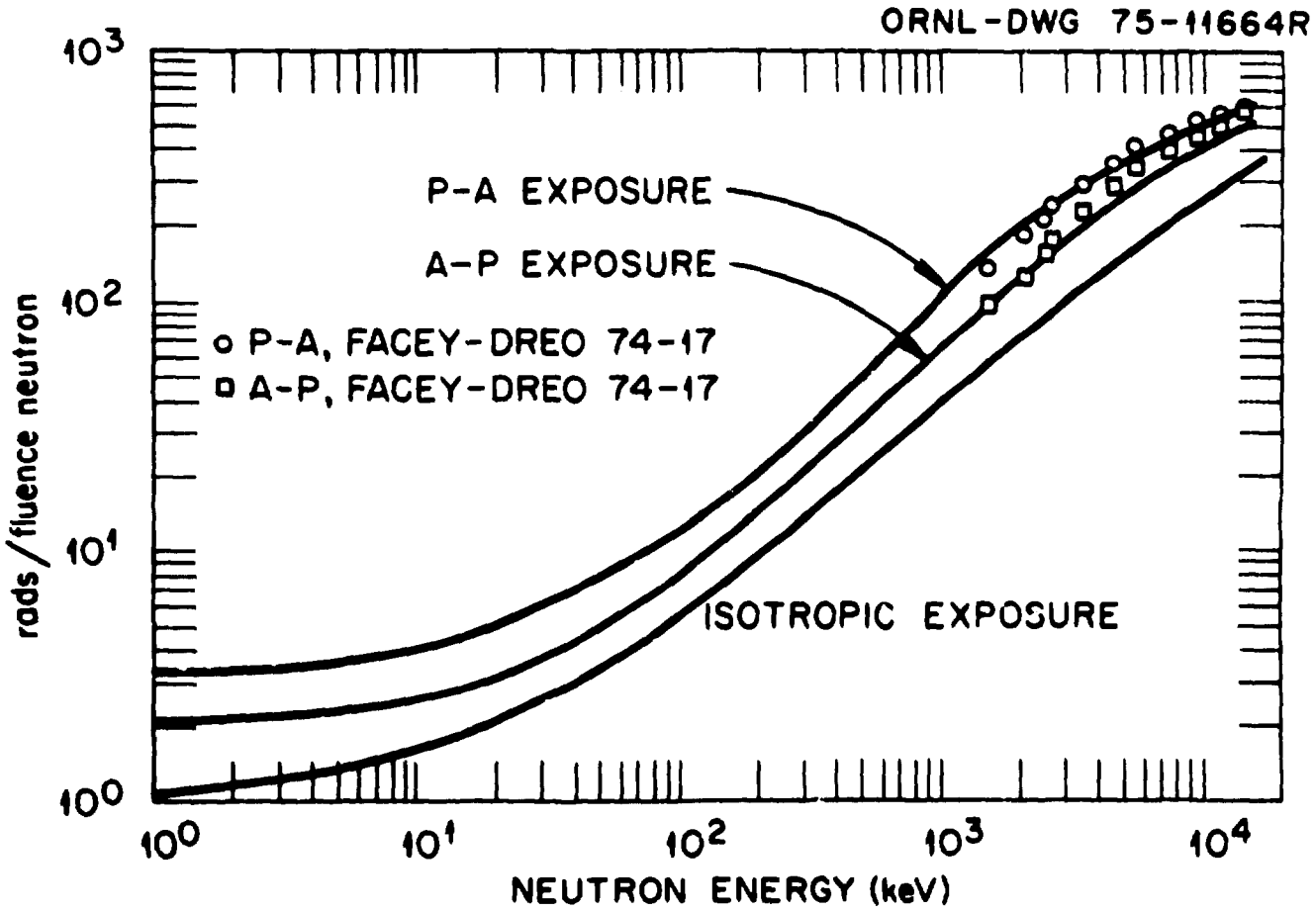

Figure 8. Dose from Recoil Ions to the Active Marrow as Predicted by the CHORD Concept.

Facey obtained P-A and A-P neutron dose predictions from "MOnoenergetic DOse Calculations (MODOC)" (Collins and Facey, 1976). MODOC dose values included the autointegral gamma contributions which based on ratios of total dose to recoil ion dose (Mechali, Dousset, Beau, and LeGrand, 1965; Mechali, 1967) were stripped from the dose estimates and the remainders were plotted on Figure 8 by Facey (1968). Facey (1976) commented, "As you can see, there are minor differences of slope, causing our P-A results to fall above yours at 5-10 MeV, and below yours at 1-3 MeV. Our A-P results are consistently higher than yours above 2.5 MeV. This makes the ratio of our P-A/A-P only 1.09 at 13.6 MeV compared with approximately 1.20 for your curves. Otherwise I think the agreement is remarkably good."

Dose to active marrow from neutron produced autogammas as predicted from CHORD distributions is shown in Table 4. For autogammas from 2.5 MeV neutrons having A-P incidence, Mechali (1965, 1967) estimated the marrow dose to be 3.1×10^{-10}; Facey and Clifford (1973) measured 3.4×10^{-10}; and Table 4 shows 3.31×10^{-10} rads cm^2 $neutron^{-1}$. For P-A incidence, Mechali estimated 3.1×10^{-10}; Facey and Clifford measured 3.7×10^{-10}, and Table 4 shows 3.17×10^{-10} rads cm^2 $neutron^{-1}$. In Table 4, dose from A-P exposure to autogammas from 2.5 MeV neutrons is higher than dose from P-A exposure because as illustrated in NCRP (1971), the integrated dose between 0-10 cm is less than the integrated dose between 10-20 cm.

Other CHORD Applications

Dose distributions (Jones, Auxier, Cheka, Kerr, 1975) inside cylindrical phantoms have been computed for the A-bomb produced

Table 4. Dose to Active Marrow from Neutron Produced Autogammas.

Energy	P-A*	A-P	Bilateral	Rotational	Isotropic
0.025 eV	25.8	15.8	21.5	18.3	8.2
1 keV	35.8	27.3	31.0	26.9	11.2
10 keV	34.3	26.6	29.9	26.2	9.8
100 keV	34.9	28.4	30.6	27.7	11.1
1 MeV	32.5	30.0	29.9	27.8	11.9
2.5 MeV	31.7	33.1	30.2	29.8	12.4
14 MeV	52.3	51.1	48.7	48.2	28.9

*x 10^{-11} rads/fluence neutron.

radiation environments of Hiroshima and Nagasaki. The dose distributions for the spatially dependent neutron environments, varied symmetrically with depth from the air-tissue interface and indicated that "multi-collision" processes overwhelmed the "first collision" processes. This fact plus the assumption of a 2π isotropic gamma environment permits the estimation of the mean absorbed dose to the active marrow of an A-bomb survivor inside a typical Japanese house according to

$$\bar{D} = \sum D(\ell) \cdot p(\ell)\ \Delta\ell$$

where $D(\ell)$ is dose versus penetration depth for an analogue having a radius of 12 cm, and $p(\ell)\ \Delta\ell$ is for isotropic exposure as listed in Table 1. This summation indicated that neutron dose to the active marrow, relative to "free-in-air kerma" from neutrons was 0.26; autogamma dose to the active marrow relative to "free-in-air kerma" from neutrons was 0.07; and gamma dose to the active marrow relative to "free-in-air dose" from gamma rays was 0.55.

Spiers and Overton did a spectral weighted average for their monoenergetic "nearly omni-directional gamma radiation" and estimated that the mean transmission[7] factor for fission product gamma rays was 0.67 which seems consistent with the difference in source geometries.

Dr. Mays and Dr. Rossi (1976) suggested that leukemia incidence appears to vary linearly with neutron dose; however, leukemia incidence seems to occur as the square of gamma dose. Therefore

[7]Spiers and Overton used the term attenuation factors; however, their paper indicates that they actually worked with transmission factors.

$$\bar{D} = \sum \left[D(\ell)\right]^2 p(\ell)\, \Delta\ell \Big/ \sum D(\ell)\, p(\ell)\, \Delta\ell$$

may be a more meaningful quantity. For this dose-square mean the marrow dose, relative to "free-in-air kerma" was found to be 0.59 while the dose-square-mean for autogammas remained at 0.07. The corresponding root-mean-square doses were found to be 0.56 and 0.07, respectively. Several independent analyses of the risk from neutrons relative to gamma rays are presently underway and should be available in the near future.

Figure 9 illustrates a proposed dosimeter or "riskmeter" in which the relative setting of the outer two dials selects the appropriate CHORD distribution and the relative setting of the inner two dials selects the insult (depth-dose) curve for the energy and type of incident radiation. Alun Jones (1966) suggested that dosimetry should be approached by matching variations in dose or risk with scattering, absorption, and attenuation; however, the CHORD method seems to permit this same precision of matching variability on a simplified macroscopic level.

Hopefully a schema such as incorporated into Figure 9 would render the absorbed dose index, D_I, and dose equivalent index, H_I, for the standard ICRU 30 cm sphere (ICRU, 1971) even less useful than it already is, because by using CHORD density functions plus standard insult (multicollision depth-dose) curves, a health physicist or dose meter having modest hardwired logic could easily and quickly estimate exposure values to any biological tissue at risk.

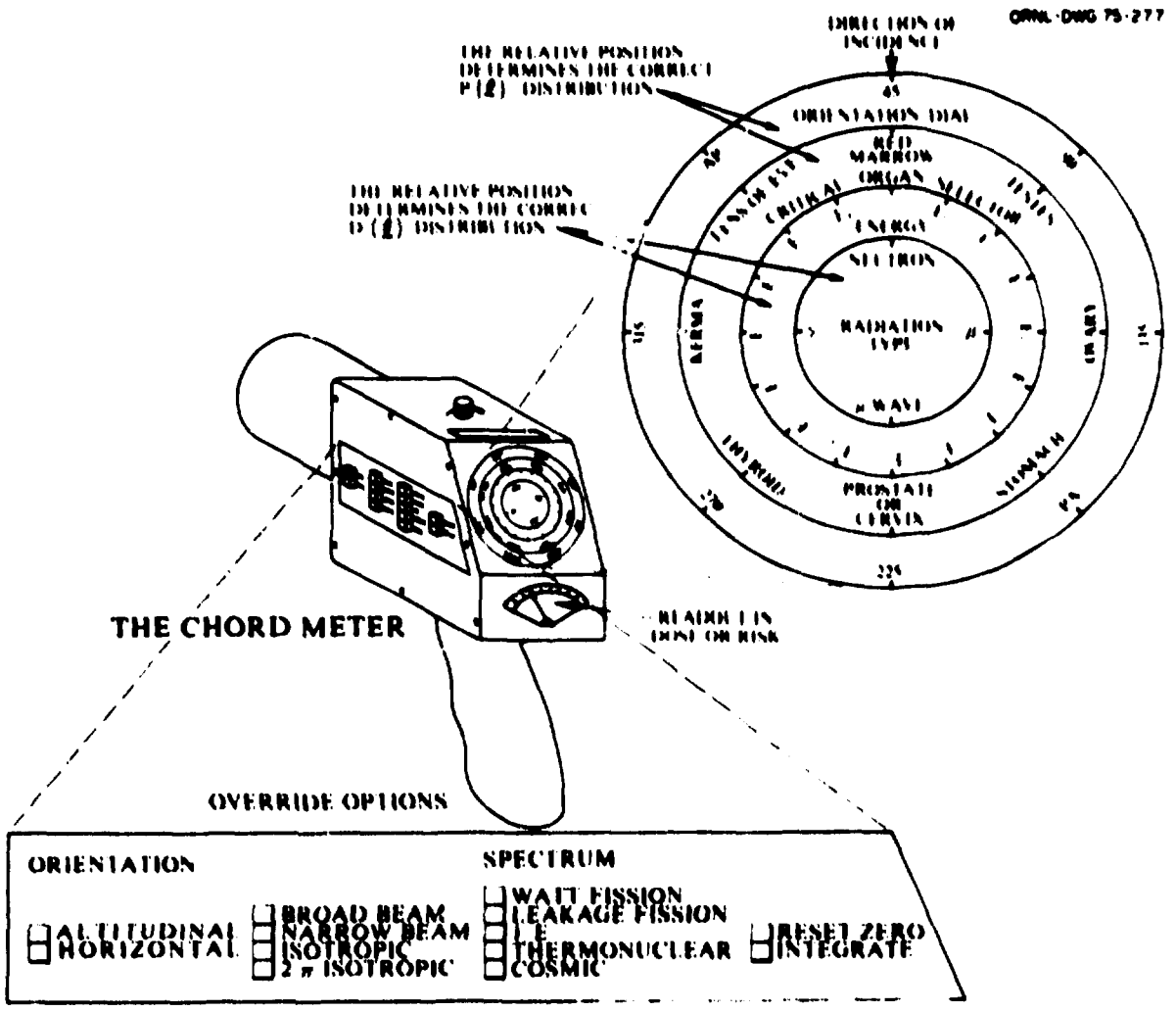

Figure 9. Critical Human Organ Radiation Dosimeter.

For RF and microwave radiation, Ho and Guy (1975) state:

"The specification of energy flux density alone may not be dosimetrically sufficient for relating results of biological effects experiments to radiation protection. It is suggested that the dosimetry in electromagnetic biological effects experiments could be more appropriately quantified in terms of absorbed dose. In addition, the dose-effect biological data, thus obtained, could be dosimetrically related to the radiation protection guide (in terms of energy flux density) by the additional determination of absorbed dose in human bodies due to a given exposure of electromagnetic waves." Ho and Guy (1975) present normalized absorbed dose rate distributions in units of W/kg as a function of distance along the axes of tissue equivalent spheres. Their spheres are irradiated from the -Z direction and dose profiles are presented along the X,Y, and Z axes for frequencies of 100 MHz, 1000 MHz, 2500 MHz, 5000 MHz, and 10,000 MHz. These insult versus depth distributions may be used in conjunction with Table 1 in order to estimate the mean insult to the active bone marrow. Their dose profiles along the three axes could even be averaged in order to approximate isotropic exposure. Of course, the precision of such an approximation will be unknown until more RF and microwave studies have been completed on systems involving bone-lung-tissue media in geometries more representative of man.

Conclusions

A personal dosimeter measures exposure at the surface of the chest; the measured exposure corresponds neither to the exposure in free space nor to the organ or whole body dose and area dosimeters

determine only free space exposure (Piesch, 1967). Alun Jones (1966, 1964) pointed out that a survey meter or personal dosimeter may overestimate the insult to the active marrow by a factor of 10 or underestimate by a factor of 6. In spatially dependent radiation fields, or for exposure to broad beam sources having an orientation other than A-P, it is usually very difficult to have an accurate risk estimate because of normalization to an inaccurate or shielded reading taken at the location of the chest (Facey and Clifford, 1973). In summary, the method of CHORDs permits rapid "critical organ" dose estimation and helps to circumvent some of the problems of relating organ dose or risk to readings from meters or film badges.

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This paper is heavily dependent upon experimental work for the discussion of the results and as a means of estimating the validity of the CHORD concept. It is also necessary to acknowledge the helpful suggestions and data supplied by R. A. Facey, Alun Jones, C. W. Mays, H. H. Rossi, M. F. Fair, and an NCRP Ad Hoc Task Group.

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