An Estimate of the Average Absorbed Dose to the Bone Marrow of Patients Subjected to Complete Skeletal X-ray Diagnostic Procedures at Argonne National Laboratory.

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by L. D. Marinelli

The estimate described above and the estimate of absorbed dose to the progenitor cells on bone surfaces are essential to an estimate of most of the cancerogenic risk undergone by radium patients being followed at the Center for Human Radiobiology at ANL. The restriction of our attention to overall risk to these two tissues is based mainly on the observations of Court Brown and Doll on mortality of cancer following radiotherapy for ankylosing spondylitis (1). The latter show that the overall increase in the combined number of leukemias and cancer of the irradiated skeleton is nearly 3/5 of total increase in all cancer cases occurring within the same period.

Dose to the Active Bone Marrow

Basically, the estimates herein presented are based on the average absorbed dose to the marrow for chest, spinal and pelvic diagnostic exposures investigated experimentally by the S. K. I. group (2) (3) who judiciously placed ionization chambers at representative sites within most bones containing marrow, under various Kvp's and filters. Portions of active marrow present in the irradiated field are stated in reference 2, where reference is made to the pertinent anatomical literature. Calculation of the doses accruing in ANL procedures were mostly impossible to calculate by direct interpolations from the published data on mrads per Milliampere-second (MAS) at a given Kvp (Kilovolt peak) because the number of MAS used at ANL is unknown, since the timings are based on an empirically calibrated phototimer.[4] Except for this parameter, other exposure factors such as target-film distance, filter and use of intensifying screen and grid,* filtration and rectification of the H. V. applied to the x-ray tube are

*The single exception is the presence of the grid in the ANL technique for the lateral view of the cervical spine contrasted to the lack of it at Sloan-Kettering Institute (SKI).

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identical at both institutions. In Table I, exposure parameters at ANL and SKI are compared for chest, spinal and pelvic exposures. The estimates of MAS effective at ANL for the usually slightly different Kvp values at SKI are calculated by the empirical formula derived from Reference (8) for 2 mm Al filtration, namely

$$(MAS)_A = (MAS)_S \times \frac{(Kvp)_S^2}{(Kvp)_A^2}$$

where the subscripts A and S refer to ANL and SKI respectively; these and other assumed MAS values in Table I are enclosed in parentheses.

In particular, the estimated ANL values of average marrow dose in mrads have been estimated for the various exposures as follows:

Chest: Identical MAS value to SKI's because of the very slight difference in values of Kvp's.

Cervical Spine, A.P.: Although the dose at ANL should be lower than SKI's because of higher Kvp's[5], this is compensated by both field overlap and slightly larger film size at ANL. So no change from the SKI estimate was made.

Cervical Spine, Lateral: The main correction on the SKI value is made for the presence of grid at ANL. A factor of 4 x the SKI dose is assumed to compensate for this. (See ref. 1, p.99).

Thoracic Spine, A.P. and Lateral: Correction for influence of different Kvp on MAS has been made in opposite directions for each of the two views and the corrections almost compensate each other, dosewise.

Lumbar Spine, A.P. and Lateral: The doses assumed are identical to the ones at SKI, although downward corrections in MAS are probably in order. The omission is made to compensate for field overlap.

Pelvis, A.P.: The MAS for this technique was not derived from SKI exposure data but from MIT techniques, because the Kvp used there were identical to ANL. Average marrow dose per MAS are

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taken from the appropriate SKI graph. The deliberate choice in A. ' 's higher MAS value is to compensate for probably field overlap.

Published measurements and estimates of marrow doses at SKI are limited to the fields mentioned above which comprise the bulk of the exposure to the active marrow. Comprised in ANL skeletal survey, however, are included other diagnostic fields including marrow. Thus:

Femora, Right and Left: The MAS are assumed to be 1/2 the number used for the pelvis. This ratio is derived from the relative values of the MAS used for both exposures at MIT (0.4) correcting for difference in Kvp $(65/60)^2$ + a 7% correction for field overlap. The amount of marrow exposed is assumed to be 8% of the total, namely 4% in the head of the femur[6] and 4% in the overlap of the sockets; this is 0.2 of the amount of active marrow irradiated in the pelvic exposure [1] (including the femoral heads and necks). Hence, to a first approximation,

Average Dose from 2 femoral films = 2 x 1/2 x .2 x 44 ≃ 9 mrads.

Humeri, Right and Left, A.P.: The assumption is made that the MAS (30) are identical to MIT's, using identical Kvp. The average marrow mrad/MAS (.15 at 60 Kvp[2]) is taken to be identical to the exposure of the cervical spine A.P. (3.4% of total marrow) corrected for fraction of marrow[6] in the head of two humeri (4%).

The result is:

Average marrow dose = 30 x .15 x 4/3.4 ≃ 5.3 mrads.

Skull (A.P., Lateral and Waters' view) ± 2 Lateral Mastoids ± 2 Posterior Mastoids

The estimate of the average dose to the marrow, resulting from the diagnostic procedures, of the skull and mastoids, is a very difficult problem, enhanced by the shape of the skull bones and the distribution of the marrow within

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them. To avoid dosimetric errors easily made by simplifying assumptions on the role of these two factors, it was thought best to depend mainly on the experimental data and on calculations provided by the extensive dosimetric studies at N. Y. U. pertinent to the x-ray epilation treatment of lineas capitis in children (7); this study explored the marrow dose resulting from the Adamson-Kienbock technique. The latter consists of 5 exposures: 2 laterals, 2 A.P.'s and one vertical to the top of the skull; except for the latter, these exposure fields approximate well the 7 fields used in the diagnostic procedures at ANL. A voltage of 100 Kvp and no added filter were used in the treatment and the T. S. D. was 20 - 25 cm and LiF dosimeters were placed at several positions above and below scalp to record the dose as accruing from the 5 exposures used in the treatment; interpolation was used between these readings to calculate the dose to the marrow assuming that the full thickness of skull bones averaged the equivalent of 2 mm of Al and that it was uniform throughout. The N. Y. U. doses at mid level of the cranium from the combination of all 5 fields averaged 250 rad (no correction for secondary electrons from bone) whereas the average dose to the scalp was 600 rads: this leads to a preliminary "depth dose ratio" of 250/600 = .385.

Some corrections to this figure ought to be contemplated. Because of the very different target-skin distances between ANL procedures and N.Y.U. treatment (~ 85 or 25 cm respectively) the "depth dose ratio" correction of 1.06 should apply to the ANL figures. A more drastic correction is due to the "depth dose ratio" because the Kvp's and filtration in the two instances are considerably different. Assuming the thickness of the tissue of the scalp as equivalent to .2 mm Al and the mid skull thickness of 1.0 mm Al, we must correct for the transmission of 100 Kvp no filter (H.V. < 0.7 mm Al) through tissue equivalent to 1.2 mm Al and the transmission of 70 Kvp at 3.2 mm Al as compared to that of 2 mm of Al. The ratio of these transmissions[8] comes approximately to .70/.50 = 1.4 which is the factor by which the NYU "depth dose ratio" ought to be corrected: these revisions increase the depth dose ratio for ANL techniques to 1.4 x .385 x 1.06 = .57. This is a rather generous correction because the

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effective thickness of the skull, which the x-rays must cross in lateral and frontal projections to reach the marrow, is higher than 1.0 mm of Al equivalent and the rates above will decrease and eventually become less than unity as the filtration increases at oblique angles. As a rough approximation, we shall also assume that the target-skin distance to the head and pelvis are approximately the same. It follows that the skin dose, as measured at SKIat 70 Kvp + 2 mm Al, 14 x 17 field size and same distance as ANL (Ref. 2, Table I) is 96 mr for the 10 MAS used at ANL. Corrections of fraction of marrow in skull (.12), the number of exposures at ANL 7 vs 5 at NYU (1.4) and the "depth dose" mentioned above lead the overall estimate to:

$$96 \times .12 \times 1.4 \times .57 = 9 \text{ mrads}$$

as the average to the marrow, with no secondary electron correction.

This is a high figure also because the vertical field, used in the therapy set up, but not in the diagnostic one, contributes the highest dose to the scalp and the effect of overlapping fields has been taken into account in the therapeutic dose measurements and calculations.

The total dose to the marrow for complete skeletal x-ray will be the total of the underlined values in Table I (420 mrads) times the correction necessary to the estimate of the contribution of the photoelectrons generated in bone and ending in the marrow. A perusal of the values shown by Spiers[9] suggests a correction of 1.1 which brings the average dose to the marrow to 460 mrads. It is obvious from Table I that the average marrow dose can be reduced to nearly 1/2 by simply omitting the lateral exposure to the lumbar spine and to about 1/3 by foregoing also the lateral view of the thoracic spine. A preliminary estimate of the average marrow dose accruing in MIT diagnostic procedures (where all MAS are explicitly stated) yields a value of about 550 mrads. (See Table II).

An approximation to the dose to the progenitor endosteal cells can be made by assuming that, on the average, these cells--being close to the bone--will receive a dose approximately 1.5 times the average marrow dose (7), namely, roughly 700 mrads on the average.

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TABLE I

Estimate of Average Absorbed Dose to Marrow From Complete Skeletal X-Rays As Given At ANL

Part	Position	Institution	Intensifying Screen *	Grid	KVP(peak)	MAS	A.V. Marrow dose mrads
Chest	A.P.	ANL	+14x17	-	85	(10)	3
Chest	A.P.	SKI	+14x17	-	86	10	3
Cerv. sp.	A.P.	ANL	+10x12	+	70	(32)	6.4
Cerv. sp.	A.P.	SKI	+8 x10	+	56	50	6.4
Cerv. sp.	Later.	ANL	+10x12	+	76	(32)	9.6
Cerv. sp.	Later.	SKI	+8 x10	-	68	40	2.4
Thorac. sp.	A.P.	ANL	+14x17	+	65	(87)	32
Thorac. sp.	A.P.	SKI	+14x17	+	70	75	30
Thorac. sp.	Later.	ANL	+14x17	+	76	(180)	68
Thorac. sp.	Later.	SKI	+14x17	+	72	200	72
Lumbar sp.	A.P.	ANL	+14x17	+	70	(72)	23
Lumbar sp.	A.P.	SKI	+14x17	+	68	75	23
Lumbar sp.	Later.	ANL	+14x17	+	85	(375)	210
Lumbar sp.	Later.	SKI	+14x17	+	82	400	210
Pelvis	A.P.	ANL	+14x17	+	65	(100)	44
Pelvis	A.P.	SKI	+14x17	+	68	75	38
2xfemora	A.P.	ANL	+14x17	+	65	(50)	9
2xhumeri	A.P.	ANL	+11x14	+	60	(30)	5.3
Skull	A.P.	ANL	-10x12	+	75	10	
Skull	Later.	ANL	-10x12	+	70	10	
Skull	Waters	ANL	-10x12	+	70	10	9.0
2xmastoids	Later.	ANL	-10x12	+	70	10	
2xmastoids	Poster.	ANL	-10x12	+	70	10	

TFD = 72" (chest); 40" for all others. Filtration = 2 mm Al

(+) or (-) = presence or absence of either grid of int. screen.* Numbers indicate the dimensions of film.

A.P. = anterior, posterior. Later. = lateral

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Table II. Data for skeletal X-rays as given at MIT.

RADIATION BONE SURVEY

HT 5' 1/2"
WT 153 lbs.

Name (FEMALE) Case No. _____ Age 70

Part	Kv	MA	Time	Cassette	Body
Skull - AP	76	100	1/2	yes	yes
Skull - Lateral	65	100	1/2	yes	yes
Skull - Submentovertical	90	100	1/2	yes	yes
Sinuses - Waters	85	100	1/2	yes	yes
Left Mandible - Lateral	40	100	1/4	yes	no
Right Mandible - Lateral	40	100	1/4	yes	no
~~Teeth~~ STAINERS	60	100	1/2	no	no
Cervical spine - AP	60	100	1/2	yes	yes
Cervical spine - Lateral	63	300	1/10	yes	no
Left shoulder - AP 16 X 12	60	100	3/10	no	yes
Right shoulder - AP 10 X 12	60	100	3/10	no	yes
Left Humerus - AP - include elbow 11 X 14	60	100	3/10	no	yes
Right humerus - AP	60	100	3/10	no	yes
Left forearm - AP 10 X 12	60	100	1/2	no	no
Right forearm - AP 10 X 12	60	100	1/2	no	no
Both hands and wrists - PA 10 X 12	45	100	1/2	no	no
Dorsal spine - AP	68	100	1	yes	yes
Dorsal spine - Lateral	65	50	3.5	yes	yes
Lumbar spine - AP - 14 X 17 KUB	75	100	1	yes	yes
Lumbar spine - Lateral 11 X 14	75	300	1	yes	yes
Pelvis - AP - 14 X 17 to include hips	65	200	1/2	yes	yes
Left hip - Lateral	65	200	1/2	yes	yes
Right hip - Lateral	65	200	1/2	yes	yes
Left femur - AP 14 X 17	60	100	2/5		
Right femur - AP 14 X 17 to include knee	60	100	2/5		
Left knee - AP	60	100	3/10	no	yes
Left knee - Lateral	55	100	3/10	no	yes
Right knee - AP	60	100	3/10	no	yes
Right knee - Lateral	55	100	3/10	no	yes
Left leg - AP to include ankle	60	100	1/10	no	yes
Right leg - AP to include ankle	60	100	3/10	no	no
Left ankle - Lateral	60	100	1/2	no	no
Right ankle - Lateral	60	100	1/2	no	no
Left foot - PA	50	100	1/2	no	no
Right foot - PA	50	100	1/2	no	no
Chest	95	300	1/60	yes	no

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