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CLEANUP AND REHABILITATION OF ENEWETAK ATOLL

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APPENDIX V

Annual Bone and Whole-Body Doses

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1. Introduction

The purpose of this appendix is to evaluate the potential annual bone doses for adults and children for the six living patterns considered in the Enewetak Radiological Survey Report (NVO-140). The bone doses presented in NVO-140 were calculated for mineral bone for adults as integrated doses for 5-, LO-, 30-, and 70-yr periods. Bone and whole-body doses to children were not considered separately because in most cases the doses predicted for adults are usually a good estimate of the dose to children. For example, the external gamma contributes similarly to both adults and children. Strontium-90 and ^{137}Cs contribute over 95% of the food-chain dose and there is evidence to show that doses to children from ingestion of ^{137}Cs are usually less than those to adults. Strontium-90 differs from ^{137}Cs. Doses to children can exceed adult doses; however, the additional dose increment to children over the first 1 to 5 yr is not large and increases the integral 30- and 70-yr doses by only a few percent. With the uncertainties involved in other parts of the dose assessment, for example the actual diet at time of return, the differentiation between child and adult integrated doses was not included in the tables.

Because of the magnitude of some of the 30-yr integral bone doses, it was decided that annual bone doses should be evaluated to indicate the living patterns and agricultural situations which are within FRC guides for annual bone doses. The more detailed assessment of bone doses is directed at estimating the dose to the critical cell population at risk

in bone - the bone marrow - rather than to the entire bone mass, as was calculated in the original report (NVO-140). In adopting this approach, we are following the recommendations of the ICRP (ICRP-11) and the approach of Spiers used by UNSCEAR (22).

The following text considers the information available for estimating the doses to the fetus, the newborn, and children relative to adults, and also the dietary changes which are assumed for children.

2. Dose to Fetus and Newborn Relative to Adults

The Sr/Ca ratio in the fetus and in mothers' milk is determined by the Sr/Ca ratio in the maternal blood. Sr/Ca discrimination across the placental barrier and across the mammary gland is nearly the same.[1,2] In fact, the observed ratio OR $\frac{\text{fetus or mothers' milk}}{\text{maternal blood}}$

$$\left(\text{OR} = \frac{(\text{pCi } ^{90}\text{Sr/g Ca}) \text{ milk or fetus}}{(\text{pCi } ^{90}\text{Sr/g Ca}) \text{ maternal blood}}\right) \text{is} \sim 0.5.$$ [1-3] Therefore, the Sr/Ca ratio of the fetus or newborn is very similar to that of the mothers' milk.

There is considerable evidence to show that the OR milk/diet for human breast milk is in the range of 0.1 to 0.16.[3,5] The same observed ratio exists for the fetus and newborn relative to the adult diet.[1,2] This ratio has been observed directly and can also be calculated from data which indicate that the average OR body/diet for adults is 0.25;[1,6] when this is combined with a further discrimination of approximately a factor of 2 across the placental or mammary membrane, the range of values of 0.1 to 0.16 for milk or fetus is obtained.

As a result, the Sr/Ca ratio in the fetus and newborn is approximately 1/8 to 1/10 that of the adult, and the resulting dose to the fetus is less than that to adults.

The dose to a young infant being breast fed will of course also be less than that calculated for adults. The OR body/diet for young infants is 0.9;[1,4] that is, the young infant nearly equilibrates with his diet. However, the mothers' milk, as discussed previously, has a Sr/Ca ratio ~ 0.1 that of the adult diet. The OR body/diet then decreases to 0.5 for a l-year-old and by approximately 3 or 4 years of age has reached the adult value of 0.25.[2,4,6]

Similar data are available for ^{137}Cs. Cesium-137 is metabolized and turned over more rapidly in pregnant women than in nonpregnant women.[7,8] As a result, ^{137}Cs incorporation in the fetus and the resulting exposure are less than would be expected from normal retention times observed for adults. Experimental data further indicate that for the fetus and for breast-fed infants the concentration of ^{137}Cs and the resulting dose never exceeds that of the mother or of other adults.[9,10] Therefore, as indicated in reports by Rundo,[9] Iinuma et al.,[10] and Cook and Snyder,[11] the dose calculated for an adult for ^{137}Cs is a conservative estimate for the fetus and the newborn.

3. Dose to Children Relative to Adults

^{137}Cs -A considerable body of evidence is available which indicates that the half-time for ^{137}Cs in the body is a function of age, with a more rapid turnover for younger ages.[11-14] The biological half-time appears to

be the order of 10-15 days for 1- to 2-year-old children and increases to ~ 100 days by age 20. It then remains reasonably constant throughout adult life. The body mass is less for the younger age groups, and these two factors tend to offset each other in dose calculations. Doses to children are generally less than for adults as a result of the combination of these two offsetting factors. When the relative dietary intake is included, children receive a lesser dose than adults. Therefore, dose estimates for adults are usually a conservative estimate for children.

^{90}Sr — Reports by Loutit,[15] Bennett,[16] and Rivera[17] indicate that the pCi ^{90}Sr/g Ca in human bone is greater for ages 1-5 than for ages greater than 6 yr, including-adults. However, the turnover rate is much more rapid and the retention time much shorter for ^{90}Sr in ages 1-5. The combination of these two factors determines the bone burden, the annual dose, and the dose commitment resulting from a specified ingestion of ^{90}Sr. For children, these two factors tend to offset each other; the resulting dose to children, therefore, is not straightforward and is dependent upon the relative interaction of these two factors.[1] Any comparison with adults must therefore take into account the age dependence of these factors, as well as the difference in dietary intake. The model reported by Bennett[16] is therefore used for estimating the doses to children.

4. Dose Models and Diet

^{90}Sr — Models developed by ICRP for estimating the bone dose from ingested ^{90}Sr are considered to be age invariant.[18-20] A recent model from Bennett" does model the child separately from the adult, and this model is applied for estimatingthe bone doses to children.

The bone-marrow dose-rates to children are calculated by combining Bennett's model for children with the approach developed by Spiers[21] and used in the UNSCEAR report[22] for estimating bone-marrow dose from the mineral or matrix bone dose. The values used for converting D_o doses, to bone-marrow and endosteal cell doses, are 0.314 and 0.434 respectively. Bennett's model also extrapolates to the adult case and is combined with the Spiers approach for predicting the bone-marrow doses to adults.

The bone mass is assumed to correlate directly with body mass, and these data as a function of age are taken from Spiers.[21] These body masses are based upon average data from the U.S. population and a factor of 0.85 was incorporated to account for the smaller size of the Enewetakese. The calcium concentration in bone (gCa/g bone) as a function of age is taken from Bennett.[16]

In calculating the mineral bone dose (D_o dose) in NVO-140, the approach of ICRP[18] was followed, using a QF = 1 and n = 5. The doses calculated from this model are compared to the 3-rem/yr guide (ICRP 9)[23] for bone for general public. However, in assessing the <u>annual</u> dose to both children and adults, the bone marrow is taken as the critical organ, and the recommendations in ICRP 11[24] are used.

In this model the quality factor is still one (Q,F = 1), and the "n" factor is no longer applicable. The bone marrow is considered in the category of sensitive blood-forming organs, and the corresponding dose guide for such organs is 0.5 rem/yr rather than the 3 rem/yr for mineral bone.

^{137}Cs — In the dose model for ^{137}Cs, it is assumed that the loss of ^{137}Cs from the body can be described as an exponential loss with a turnover time that varies as a function of age.[10-14] The annual dose is calculated, always taking into account the residual body burden from the previous year. Body mass as a function of age is taken from Spiers.[21] Initial dietary intakes are calculated and doses are predicted, based upon the initial intake and the exponential loss of ^{137}Cs in the diet at a rate equal to the physical half-time of ^{137}Cs.

Diet — The diet for adults is that listed in the original report NVO-140. For children from ages 1 through 10, the intake of coconut milk and coconut meat is doubled to 600 and 200 g/day, respectively. These two products are the most likely to be consumed in greater quantity by children than by adults. The rest of the diet for children is assumed to be one-half of the adult diet.

At age 10, it is assumed that the child is on the full adult diet. From information available, this is a conservative assumption in that children are not usually considered to reach the average adult intake until age 14 or 15. However, because of the diet changes which occur at 10 yr (i.e., pandanus, breadfruit, coconut, etc., which become available) it is convenient to use this point for adjusting the child to the adult diet, and if anything, this adjustment produces a slightly conservative dose estimate for the children due to the high ^{90}Sr content in the adult diet.

5. Results

The results of the calculations based upon the models described above and upon the diets listed in NVO-140 and altered for children as previously discussed, are listed in Tables 1-8. The data are presented as maximum annual bone-marrow and whole-body doses. The living patterns are listed after Tables 1 and 6 for convenience of reference; they are the same as those listed in NVO-140.

The annual doses for external exposure and for food chain exposure from ^{137}Cs and ^{90}Sr are calculated for 70 yr, beginning at either age 1 or age 20. The three different components contributing to the dose produce a maximum dose at different times. The external component, for instance, is maximum at 1 yr and decreases thereafter with the physical half-life of ^{137}Cs and ^{60}Co; the effective decay depends on the particular percentage of each isotope in the soil. Strontium-90 delivers its maximum dose several years after intake of the nuclide begins. The year of maximum dosage depends upon whether an adult or child is considered and upon whether or not a diet change is involved at some point in time. The dosage from ^{137}Cs incorporated in man via food chains tends to peak early and decreases exponentially thereafter. The annual dose is then selected for the years at which the sum of these three components was maximum.

The maximum annual bone-marrow doses are listed in Table 1 for the case where no restrictions are placed upon the location of agriculture and source of the diet and no modifications are made for external gamma on the village island. Table 2 lists the results for the case where no restrictions

are placed upon the diet but where the village island has been modified by plowing and graveling. Living Pattern 1, where the home island and agriculture are on southern islands, is the only living pattern for these two situations where the total bone-marrow doses do not exceed 50% of the FRC guide; in this instance, it is less by a factor of 5. All other living patterns lead to an annual dose which for at least 1 yr, and in most cases several years, exceeds the FRC guide.

The results also indicate that there is not a great deal of difference between the predicted child and adult maximum annual doses. This is due in part to the assumed diets of adults and children and the large ^{90}Sr and ^{137}Cs intake via the food chains for such products as pandanus, breadfruit, coconut, and meat. For coconut milk and coconut meat, the children are assumed to have an intake twice that of the adults, but until age 10 the rest of the dietary intake is assumed to be one-half that of the adults.

Table 3 lists the results for the six living patterns when pandanus and breadfruit are grown on southern islands only. As a result of this action, three living patterns fall within 50% of the FRC guide — Patterns 1, 2, and 5. When pandanus, breadfruit, coconut, and tacca are all confined to southern islands, then Living Pattern 3 also falls within the guide (Table 4). If the total diet is confined to the southern islands, then all living patterns are within FRC guide, and the only variation among living patterns is the result of the difference in external exposure for each of the situations (Table 5). For all the cases where there is a restriction on the agriculture and diet, it is assumed the village island will be plowed and graveled.

Similar results for whole-body exposure for the four different agricultural situations are presented in Tables 6-10. With no restrictions on the diet, Living Patterns 1, 2, and 5 are under FRC guides. Therefore, the bone-marrow is the more limiting feature. When the other agricultural conditions are used, the living patterns which fall below the FRC guide are the same as those for the bone-marrow dose.

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Table 1. Maximum annual bonemarrow dose (rem).

No restrictions on diet

Village island unmodified for external gamma

Living Pattern	Start January 1974		Start January 1984	
	Child."	Adult [a]	Child [b]	Adult
1	0.047	0.045	0.047	0.043
2	0.314	0.294	0.282	0.290
3	0.790	0.760	0.759	0.754
4	2.27	2.15	2.17	2.13
5	0.361	0.348	0.333	0.344
6	1.10	1.04	1.03	1.02

Living Pattern	Village island	Agriculture	Visitation
1	Enewetak-Parry	ALVIN-KEITH	Southern Is.
2	Enewetak-Parry	KATE-WILMA + LEROY	Northern Is.
3	JANET	JANET	Northern Is.
4	BELLE	BELLE	Northern Is.
5	JANET	KATE-WILMA + LEROY	Northern Is.
6	JANET	ALICE-IRENE	Northern Is.

[a] Diet change at 10 yr., i.e., 1984.

[b] Diet change at 10 yr., i.e., 1994.

Table 2. Maximum annual bonemarrow dose (rem).

No restrictions on diet

Village island graveled and plowed

Living Pattern	Start January 1974		Start Januarv 1984	
	Child [a]	Adult [a]	Child [b]	Adult
1	0.047	0.045	0.047	0.043
2	0.314	0.294	0.282	0.290
3	0.718	0.677	0.680	0.672
4	2.08	1.92	1.93	1.90
5	0.317	0.300	0.285	0.296
6	1.06	0.989	0.988	0.977

Table 3. Maximum annual bonemarrow dose (rem).

Pandanus and breadfruit from southern islands

Village island graveled and plowed

Living Pattern	Start January 1974		Start January 1984	
	Child. [a]	Adult [a]	Child [b]	Adult
1	0.047	0.045	0.047	0.043
2	0.148	0.149	0.200	0.142
3	0.293	0.294	0.418	0.284
4	0.786	0.774	1.16	0.749
5	0.151	0.178	0.201	0.148
6	0.428	0.437	0.574	0.419

[a] Diet change at 10 yr., i.e., 1984.

[b] Diet change at 10 yr., i.e., 1994.

Table 4. Maximum annual bonemarrow dose (rem).

Pandanus, breadfruit, coconut, tacca from southern islands

Village island graveled and plowed

	Start January 1974		Start January 1984	
Living Pattern	Child [a]	Adult [a]	Child [b]	Adult
1	0.047	0.045	0.047	0.043
2	0.122	0.130	0.092	0.101
3	0.168	0.204	0.138	0.166
4	0.415	0.516	0.325	0.392
5	0.121	0.135	0.094	0.106
6	0.253	0.354	0.202	0.254

Table 5. Maximum annual bonemarrow dose (rem).

Total diet from southern islands

Village island graveled and plowed

	Start January 1974		Start January 1984	
Living Pattern	Child [a]	Adult [a]	Child [b]	Adult
1	0.047	0.045	0.047	0.043
2	0.097	0.091	0.071	0.069
3	0.094	0.094	0.077	0.079
4	0.199	0.193	0.133	0.129
5	0.096	0.096	0.074	0.074
6	0.189	0.213	0.123	0.134

[a] Diet change at 10 yr., i.e., 1984.

[b] Diet change at 10 yr., i.e., 1994.

Table 6. Maximum annual whole-body dose (rem).

No restrictions on diet

Village island unmodified for external gamma

Living Pattern	Start January 1974		Start January 1984	
	Child[a]	Adult[a]	Child[b]	Adult
1	0.039	0.039	0.038	0.039
2	0.234	0.236	0.200	0. 233
3	0.619	0.630	0.531	0.628
4	1. 81	1. 80	1. 54	1. 79
5	0.285	0. 291	0. 252	0.291
6	0. 798	0. 812	0.674	0. 802

Living Pattern	Village island	Agriculture	Visitation
1	Enewetak-Parry	ALVIN-KEITH	Southern Is.
2	Enewetak-Parry	KATE-WILMA t LEROY	Northern Is.
3	JANET	JANET	Northern Is.
4	BELLE	BELLE	Northern Is.
5	JANET	KATE-WILMA t LEROY	Northern Is.
6	JANET	ALICE- IRENE	Northern Is.

[a]Diet change at 10 yr. , i. e. , 1984.

[b]Diet change at 10 yr., i. e. , 1994.

Table 7. Maximum annual whole-body dose (rem).

No restrictions on diet

Village island graveled and plowed

Living Pattern	Start January 1974		Start January 1984	
	Child[a]	Adult[a]	Child[b]	Adult
1	0.039	0.039	0.039	0.038
2	6.234	6.236	0.200	0.233
3	0.540	0.542	0.452	0.540
4	1.56	1.55	1.30	1.55
5	0.237	6.241	6.204	0.240
6	0.749	0.761	0.631	0.757

Table 8. Maximum annual whole-body dose (rem).

Pandanus and breadfruit from southern islands

Village island graveled and plowed

Living Pattern	Start January 1974		Start January 1984	
	Child[a]	Adult[a]	Child[b]	Adult,
1	0. 039	0. 039	.o. 039	0. 038
2	0. 125	0.128	0.146	0.127
3	0.245	0.252	0.304	0.249
4	0.662	0.663	0.846	0.656
5	0.128	0.133	0.149	0.132
6	~0,350	0.367	0.430	0. 363

[a]Diet change at 10 yr., i. e., 1984.

[b]Diet change at 10 yr., i. e. , 1994.

Table 9. Maximum annual whole-body dose (rem).

Pandanus, breadfruit, coconut, and tacca from southern islands

Village island graveled and plowed

Living Pattern	Start January 1974		Start January 1984	
	Child[a]	Adult[a]	Child[b]	Adult
1	0.040	0.039	0.039	0.039
2	0.091	0.122	0.078	0.093
3	0.146	0.187	0.119	0.151
4	0.357	0.475	0.280	0.355
5	0.093	0.127	0.080	0.098
6	0.246	0. 328	0.160	0.241

Table 10. Maximum annual whole-body dose (rem).

Total diet from southern islands

Village island graveled and plowed

Living Pattern	Start January 1974		Start January 1984	
	Child[a]	Adult[a]	Child[b]	Adult
1	0.040	0.039	0.039	0.039
2	0.090	0.083	0.065	0.066
3	0.087	0.097	0.070	0.076
4	0.192	0.191	0.126	0.126
5	0.089	0.094	0.066	0.071
6	0.182	0.211	0.116	0.131

[a]Diet change at 10 yr., i. e. , 1984.

[b]Diet change at 10 yr. , i. e. , 1994.