Radiation Absorbed Dose Calculations for Samarium-153-EDTMP Localized in Bone

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Calculations have been undertaken to estimate the likely radiation dose received by patients undergoing treatment with samarium-153-EDTMP. Previously known bone structure parameters have been employed to partition correctly the energy absorbed in the bone matrix between red bone marrow, yellow marrow, and various types of mineral bone. Both uniform surface and volume distribution of the radioactivity are considered. The key findings of the calculations can be stated in terms of the MIRD "S-factors" for red bone marrow and the endosteal layer of cells on bone surfaces. In particular, the S-factor for red bone marrow is either 0.0276 mGy/MBq.h or 0.0077 mGy/MBq.h for surface and volume distributed radioactivity, respectively. For the endosteal layer of thickness (10 μm) on bone surfaces, the corresponding values are 0.0723 mGy/MBq.h and 0.0213 mGy/MBq.h, respectively.

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Samarium-153-labeled chelates have recently shown promise in the palliative treatment of bone metastases (*1–6*). The accurate prospective calculation of radiation dose to the total red bone marrow, based on skeletal retention of a trial dose of administered radioactivity, is an important component of any successful treatment regime since the red bone marrow dose ultimately dictates the amount of radioactivity that can be safely administered.

Recently, Logan et al. (*7*) produced "S-factors" for both bone surface and volume-distributed ^{153}Sm based on data in references 8 and 9. The absorbed fraction for red bone marrow was calculated assuming that any energy absorbed in the bone complex is deposited either in the mineral bone or in the red bone marrow; the energy lost to the yellow marrow is ignored. This may lead to an overestimate of the red marrow dose and while quite acceptable from the philosophy of radiation protection it is inappropriate when accurate dosimetry is required. We further believe that the bone structural data used in ICRP Reference Man (*10*) and a subsequent reference (*9*), specifically the total surface area of bone, should be modified on the basis of the work of Beddoe et al. (*11–14*).

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In view of the preceding discussion, we believe more relevant "S-factors" for ^{153}Sm are needed. Monte Carlo calculations of red marrow and endosteal bone surface dose factors for a number of representative bones have been performed by Spiers and his co-workers (*15–18*) for a number of β-ray emitters using the microscopic bone structure details generated by Beddoe et al. (*11–14*). In this paper, we have derived relevant "S-factors" for ^{153}Sm by interpolation from the dose factors in the work of Whitwell and Spiers (*15*) and Spiers et al. (*17*). Corrections are applied for the presence of conversion electrons and photon radiations.

DOSIMETRY CALCULATIONS

Adopting the MIRD notation (*8*), the absorbed dose to a target organ, t, from a source organ, s, can be written

$$D(t,s) = \tilde{A}_s \cdot S(t,s), \qquad \text{Eq. 1}$$

where $\tilde{A}_s$ is the cumulated activity in the source organ and the *S-factor* is given by:

$$S(t,s) = \Sigma_k \Delta_k \cdot \Phi_k(t,s). \qquad \text{Eq. 2}$$

The Δ_k term is the mean energy emitted per cumulated activity for radiation of type "k" and is a physical property of the radionuclide. $\Phi_k(t,s)$ is the *specific absorbed fraction* that depends implicitly on radiation type, the size, shape, and separation of the source and target organs. A related quantity is the *absorbed fraction*, $\phi_k(t,s)$ defined by:

$$\phi_k(t,s) = \Phi_k(t,s) \cdot M_t, \qquad \text{Eq. 3}$$

where M_t is the mass of the target organ. Physically, the absorbed fraction represents the fraction of the energy of type "k" emitted by the source organ that is absorbed in the target organ.

In the case of ^{153}Sm, we have to consider contributions from x-rays, γ-rays and atomic electrons (Auger and conversion) in addition to the dominant β-decays. All significant radiations are listed in Table 1.

β-emitters and Electrons

Surface Distribution of Activity. Spiers and his co-workers (*17, 18*) have calculated relevant dose factors for bone marrow and endosteal bone surfaces, of thickness 10 μm, for a number of radionuclides uniformly distributed on the trabecular surfaces of several human bones representative of the full skeleton. For each bone, their results are presented in terms of the mean absorbed tissue dose relative to that which would be experienced by mineral bone, D_b, the latter calculated as the energy released by the retained radionuclide on the trabecular bone surface of the par-

TABLE 1
Significant ^{153}Sm Emissions*

Radiation type	Energy (keV)	Intensity (%)	Δ (kg·mGy/MBq·h)
β-ray	225	100	0.12976
Atomic electrons†	7.4	49.4	0.00211
Atomic electrons†	21.0	24.5	0.00297
Atomic electrons†	59.4	60.9	0.02086
L x-ray	6.3	10.4	0.00038
$k_{\alpha 2}$ x-ray	40.9	18.0	0.00424
$k_{\alpha 1}$ x-ray	41.5	32.4	0.00775
k_{β} x-ray	47.8	12.2	0.00336
γ-ray	69.8	5.5	0.00221
γ-ray	103.1	29.0	0.01724

* Interpolated from reference 21.

† Several low-intensity groups of atomic electrons have been combined for computational purposes without loss of accuracy.

ticular bone divided by the total mass of trabecular bone. Tabulated values are denoted by ${}_{bs}D_m/D_b$ and ${}_{bs}D_e/D_b$, where the prefix refers to the origin of the radioactivity being on the bone surface and the subscripts m, e, and b refer to total marrow, endosteal layer, and bone, respectively. Recasting in terms of the MIRD terminology, the absorbed fraction for marrow, $\phi_\beta(m,b)$, is defined by:

$$\phi_\beta(m,b) = \frac{\text{Energy absorbed in marrow}}{\text{Total energy released}}$$

$$= \frac{{}_{bs}D_m \cdot M_m}{D_b \cdot M_b}$$

that is

$$\phi_\beta(m,b) = (M_m/M_b) \cdot ({}_{bs}D_m/D_b) \qquad \text{Eq. 4}$$

Similarly, the absorbed fraction for the endosteal layer, $\phi_\beta(e,b)$, is

$$\phi_\beta(e,b) = \frac{\text{Energy absorbed in 10 } \mu\text{m endosteal layer}}{\text{Total energy released}} = \frac{{}_{bs}D_e \cdot M_e}{D_b \cdot M_b},$$

where M_e is the mass of the endosteal layer of unit density. The mass ratio M_e/M_b is readily expressed in terms of the surface-to-volume ratio of the bone, $(S/V)_b$, viz.

$$M_e/M_b = (S/V)_b/1900 \qquad \text{Eq. 5}$$

and the above absorbed fraction becomes

$$\phi_\beta(e,b) = (S/V)_b \cdot ({}_{bs}D_e/D_b)/1900 \qquad \text{Eq. 6}$$

The density of mineral bone has been taken as 1.9 $g.cm^{-3}$ and the surface-to-volume ratio has units of cm^{-1}.

Results of calculations of dose factors and absorbed fractions for ^{153}Sm are listed in Table 2 along with pertinent bone structural data (*13*). For the atomic electrons with energy of ≤21 keV (see Table 1), absorbed fractions of 0.5 for both total marrow and the endosteal layer have been assumed. This is reasonable in view of the fact that these electrons have anticipated ranges of <10 μm and if emitted into the marrow cavity should be totally absorbed within the endosteal layer.

The absorbed fractions for red marrow have been estimated on the basis of the cellularity data of Cristy (*19*). One of the major differences between the present calculations and those of Logan et al. (*7*) is the latter's use of an absorbed fraction for red marrow of 0.5, an assumption inherent in the model for bone dosimetry adopted by the ICRP (*9*) for *radiation protection* purposes. From Table 2, all but two bones have absorbed fraction values for red marrow substantially lower than 0.5.

Usually, only the total trabecular uptake is known and the contributions from individual bones need to be weighted appropriately. Following Spiers et al. (*17*), we can estimate averaged red bone marrow and endosteal layer dose factors from known bone structure parameters (*13*) using

$${}_{bs}D_{rm}/D_{trab} = \Sigma_b\, f_{rm} \cdot ({}_{bs}D_m/D_b) \cdot (S/V)_b/(S/V)_{trab} \qquad \text{Eq. 7}$$

$${}_{bs}D_e/D_{trab} = \Sigma_b\, f_s \cdot ({}_{bs}D_e/D_b) \cdot (S/V)_b/(S/V)_{trab}, \qquad \text{Eq. 8}$$

where f_{rm} and f_s are the fractions of red marrow and endosteal surface area in each bone, respectively. The ratio $(S/V)_{trab}$ is the surface-to-volume ratio for all trabecular bone. The fractions, f_s, can be estimated from the expression:

$$f_s = (S/V)_b \cdot (M_b/M_{trab})/(S/V)_{trab}, \qquad \text{Eq. 9}$$

where the ratio of the individual trabecular bone mass to the skeletal trabecular bone mass, M_b/M_{trab}, is available in the literature (*10,20*). The related absorbed fractions are then

$$\phi_\beta(rm,trab) = (M_{rm}/M_{trab}) \cdot ({}_{bs}D_{rm}/D_{trab}) \qquad \text{Eq. 10}$$

and

$$\phi_\beta(e,trab) = (M_E/M_{trab}) \cdot ({}_{bs}D_e/D_{trab}), \qquad \text{Eq. 11}$$

where M_{rm} and M_E are the masses of total red bone marrow and endosteal surface layer of thickness (10 μm) associated with all trabeculation, respectively.

Using Spiers et al. classification of bones (*16*) and the red marrow distribution data of Cristy (*19*), weighted absorbed fractions from surface trabecular radioactivity have been estimated using Equations 10 and 11. Values are given in Table 2. The masses of red marrow and trabecular bone have been taken as 1.5 kg and 1 kg, respectively (*10*), while the mass of the endosteal surface layer associated with trabecular bone has been taken as 100 g, consistent with the findings of Beddoe et al. (*11–13*). The final value of the weighted red marrow absorbed fraction is relatively insensitive to the exact red marrow distribution data employed.

With one exception, dose factors for individual bones in Table 2 refer to ^{153}Sm distributed on the endosteal surfaces adjacent to trabeculation only. The contribution from cortically distributed surface radioactivity to the red bone marrow dose is <0.5% for ^{153}Sm electrons and β-rays and can safely be ignored. However, the absorbed dose to the endosteal surface lining Haversian canals and resorption cavities in the cortical bone cannot be discounted. Measurements of cortical bone structure have been reported and used to estimate the contribution to the endosteal layer absorbed dose from femoral cortex for a number of isotopes (*12,17*). The endosteal layer dose factor for the femoral cortex in Table 2 has been obtained by interpolation from this data. Since the work of Beddoe (*12*) and that of Spiers et al. (*14*) suggests that (at least for the long bones) the bone structural parameters are largely invariant, we adopted the absorbed fraction for the endosteal layer in the femoral cortex as representative of all endosteal surfaces associated with skeletal cortical bone. That is,

$$\phi_\beta(e,cort) = 0.055. \qquad \text{Eq. 12}$$

TABLE 2
Marrow and Endosteal Layer Dose Factors and Absorbed Fractions for ^{153}Sm β-rays and Atomic Electrons Interpolated from Reference 17 for Surface Distributed Radioactivity

Bone description	S/V cm^{-1}	M_m/M_b	$_{bs}D_m/D_b$	ϕ_β (m,b)	ϕ_β (rm,b)	$_{bs}D_e/D_b$	ϕ_β (e,b)
Parietal Bone	78	0.424	0.899	0.377	0.143	1.719	0.0706
Rib	185	4.53	0.162	0.733	0.513	0.656	0.0639
Cervical vertebra	166	1.85	0.324	0.600	0.420	0.849	0.0741
Lumbar vertebra	239	2.91	0.233	0.678	0.475	0.715	0.0899
Iliac crest	172	2.02	0.315	0.636	0.305	0.784	0.0710
Head/neck femur	177	3.03	0.224	0.679	0.170	0.750	0.0699
Total trabecular	190	3.00	0.272*	—	0.407	0.762	0.0762
Femoral cortex	29†	—	—	—	—	3.62	0.0553
Total cortical	23†	—	—	—	—	—	0.0553

* This dose factor is for *red* marrow, viz. $_{bs}D_{rm}/D_{trab}$.

† These values do not include periosteal surfaces of cortical bone but are consistent with a total cortical surface area (periosteal + endosteal) of 6 m^2 (*14*).

For completeness, we have estimated absorbed fractions for total mineral bone, treating the cortical and trabecular components separately. In particular,

$$\phi_\beta(\text{trab,trab}) = \Sigma_b f_s \cdot \phi_\beta(\text{trab,b}) = \Sigma_b f_s \cdot \{1\text{-}\phi_\beta(\text{m,b})\}, \quad \text{Eq. 13}$$

where ϕ_β(trab,b) and ϕ_β(trab,trab) are the absorbed fractions for trabecular bone from radioactivity in individual and total trabecular bone, respectively. Using the data in Table 2, the absorbed fraction for trabecular bone from ^{153}Sm uniformly distributed on trabecular surfaces is obtained as 0.34.

An estimate of the absorbed fraction in mineral cortical is obtained as follows. For the femoral cortex, approximately 26% of the total surface area is associated with the periosteal and medullary surfaces (*12*). For these surfaces, the absorbed fraction for ^{153}Sm distributed on the bone surface can be taken as 0.5, since half of the emitted electrons will be lost to soft tissue. An additional 5.5% of the electron energy is given up to the endosteal surfaces from electrons emitted internally (see above). Neglecting other small internal losses, the absorbed fraction for the femoral cortex will be 0.82. For the human tibia and humerus, similar arguments give absorbed fractions of 0.76 and 0.78, respectively. An appropriate weighted average for all cortical bone gives an absorbed fraction of 0.79.

Volume Distribution of Activity

We can apply the results of Whitwell et al. (*15,16*) to obtain the relevant dose factors for volume distributed radioactivity. Tabulated values (see Table 3) are denoted by $_vD_m/D_b$ and $_vD_e/D_b$, where the prefix refers to the origin of the radioactivity being volume distributed and the subscripts m, e, and b refer to marrow, endosteal layer, and bone, respectively. The skeletal averages are obtained by weighting each representative bone by its relative red marrow content or bone surface area and the absorbed fractions generated using the results:

$$_vD_{rm}/D_{trab} = \Sigma_b f_{rm} \cdot (_vD_m/D_b) \quad \text{Eq. 14}$$

$$_vD_e/D_{trab} = \Sigma_b f_s \cdot (_vD_e/D_b) \quad \text{Eq. 15}$$

$$\phi_\beta(\text{rm,trab}) = (M_{rm}/M_{trab}) \cdot (_vD_{rm}/D_{trab}) \quad \text{Eq. 16}$$

and

$$\phi_\beta(\text{e,trab}) = (M_E/M_{trab}) \cdot (_vD_e/D_{trab}), \quad \text{Eq. 17}$$

where all quantities are as previously defined.

From Spiers et al. (*16*), we estimate the dose from cortical bone to the red marrow and to the endosteal layer on trabecular bone as approximately 4% and 6%, respectively, of that due to the trabecular bone alone.

The absorbed fraction for all trabecular bone is:

$$\phi_\beta(\text{trab,trab}) = \Sigma_b \, \phi_\beta(\text{trab,b}) \cdot (M_b/M_{trab})$$

that is

$$\phi_\beta(\text{trab,trab}) = \Sigma_b \{1\text{-}\phi_\beta(\text{m,b})\} \cdot (M_b/M_{trab}), \quad \text{Eq. 18}$$

where the absorbed fractions relate to volume deposition. Using the anatomical data for reference man (*10*) and the results in Table 3, the absorbed fraction for trabecular bone from ^{153}Sm uniformly distributed throughout the trabecular bone is 0.51.

On the basis of the data in Table 3, for cortical bone the only small energy losses to bone surfaces, resorption cavities, Haversian canals, and the marrow should occur and, accordingly, a value of 0.95 is assigned to the absorbed fraction.

Photon Emissions

Specific absorbed fractions for photons of energy ≥10 keV for various combinations of source and target organs are available in the literature (*10,22*). Although strictly applicable only for uniform volume distributed activity, the penetrating nature of photon radiations allows for more universal application and relevant values have been used for both surface and volume distributed radioactivity in the present work. In any event, the contribution of photon radiations to the overall bone marrow and endosteal layer absorbed doses is only a few percent, justifying their use.

For the L x-rays of 6.3 keV energy, an adequate approximation is to assume an energy deposition pattern in the bone complex similar to that for the β-rays. That is, we assume the same absorbed fractions for L x-rays and β-rays.

RESULTS

Table 4 summarizes the findings of these calculations. Values of the absorbed dose per unit accumulated activity

TABLE 3
Marrow and Endosteal Layer Dose Factors and Absorbed Fractions for ^{153}Sm β-rays and Atomic Electrons Interpolated from Reference 15 for Volume Distributed Radioactivity

Bone description	S/V cm^{-1}	M_m/M_b	$_vD_m/D_b$	ϕ_β (m, b)	ϕ_β (rm, b)	$_vD_e/D_b$	ϕ_β (e, b)
Parietal bone	78	0.424	0.529	0.224	0.085	0.674	0.0277
Rib	185	4.53	0.125	0.569	0.398	0.335	0.0326
Cervical vertebra	166	1.85	0.243	0.450	0.315	0.430	0.0376
Lumbar vertebra	239	2.91	0.168	0.489	0.342	0.369	0.0464
Iliac crest	172	2.02	0.238	0.480	0.230	0.399	0.0359
Head/Neck femur	177	3.03	0.170	0.515	0.129	0.371	0.0346
Total trabecular	190	3.00	0.205*	—	0.307	0.382	0.0382
Femoral cortex	29†	—	—	—	—	0.925	0.0141
Total cortical	23†	—	0.0084*	—	0.0032	—	0.0147‡

* These dose factors are for *red* marrow, viz. $_vD/_{rm}/D_{trab}$ or $_vD_{rm}D/_{cort}$.

† These values do not include periosteal surfaces of cortical bone but are consistent with a total cortical surface area (periosteal + endosteal) of 6 m^2 (*14*).

‡ This value includes a small contribution to the endosteal layer of trabecular bone in addition to that to the cavity surface layer of cortical bone.

(S-factor) are given in SI units. Conversion to traditional units of rad/μCi.h, is achieved by multiplication of tabulated values by 0.0037. Values for *All Bone* as the source organ assume either uniform surface or volume deposition of radioactivity in bone.

DISCUSSION

Studies in this institution, using autoradiography and counting methods with a dog model, indicate that following administration of ^{153}Sm-EDTMP the radionuclide is localized on all bone surfaces. With few exceptions, the activity appears uniformly deposited to better than 20%. Given the short half-life of the nuclide, it is anticipated that there will be little diffusion of activity into the bone mineral and hence, that a uniform surface model of deposition is most appropriate to use.

Using this model, the estimated absorbed doses to key sites in the bone and marrow, referred to a *total bone surface* uptake of 1 MBq, are given in Table 5. When compared with the results of Logan et al. (*7*), substantial differences are evident. In particular, the absorbed dose for mineral bone is much lower in the present model. The major reason for this is the allowance for substantial "cross-fire" between the bone marrow and the mineral bone matrix (i.e., a fraction of the electrons has sufficient energy to penetrate the relatively thin trabecular bones and irradiate additional tissue in neighboring cavities). The marrow cavities, with the exception of parietal bone, are greater in dimension than the trabecular bone thicknesses (*11,13*), so the reverse process is less likely.

The excellent agreement with Logan et al. (*7*) for the red marrow absorbed dose is somewhat fortuitous. By accounting for the energy losses to the yellow marrow, the increase in absorbed dose expected on the basis of the cross-fire effect is more than negated. Indeed, the absorbed fraction for the red marrow from ^{153}Sm on the surface of trabecular bone is only 0.41 (see Table 2), resulting in a lower S-factor compared with Logan et al. (*7*). However, we have used a figure of 10 m^2 (*11,12*) for the trabecular bone surface area, resulting in preferential uptake of the radionuclide by trabecular bone compared with cortical bone. This offsets the lower S-factor and, consequently, the two models give comparable results for the red marrow absorbed dose.

Before applying these results, the assumptions implicit in the model should be recognized. First, ^{153}Sm-EDTMP is cleared rapidly from the vascular space to be uniformly and permanently bound without translocation on all bone surfaces. Any dose to the marrow during the brief uptake phase is neglected and once bound the effective half-life for dosimetry purposes is the physical half-life of ^{153}Sm.

TABLE 4
Summary of S-factors (mGy/MBq·h) for Surface and Volume Distributed ^{153}Sm

	Bone Type as Source Organ					
	Surface distribution			Volume distribution		
Target organ	Trabecular	Cortical	All	Trabecular	Cortical	All
Red bone marrow	4.36E-02	1.05E-03	2.76E-02	3.30E-02	1.38E-03	7.70E-03
Cortical bone	1.14E-03	3.20E-02	1.27E-02	1.14E-03	3.82E-02	3.08E-02
Trabecular bone	5.44E-02	1.14E-03	3.44E-02	8.06E-02	1.14E-03	1.70E-02
Endosteal layer	8.05E-02	5.87E-02	7.23E-02	4.09E-02	1.64E-02	2.13E-02

TABLE 5
Comparison of Absorbed Doses (mGy/MBq Bone Uptake) for ^{153}Sm-EDTMP Localized on Bone Surfaces

Target organ	Logan et al. (7)	Present work
Red bone marrow	1.80	1.86
Cortical bone	4.97	0.86
Trabecular bone	5.32	2.32
Endosteal layer	—	4.87

The red marrow doses represent average values; although some marrow may receive little or no radiation dose (*23*). Furthermore, normal marrow and bone masses associated with a 70-kg man are assumed. These may be quite inappropriate assumptions to make for patients who have recently received therapy for bone metastases.

For each patient, the activity administered should be decided on the basis of an accurate skeletal uptake of a trial dose. In determining the limiting amount of ^{153}Sm-EDTMP that can be safely administered to patients, a value of 1.86 mGy/MBq of *bone uptake* is suggested within the limitations of the model. For example, a clinical protocol *may* decide to limit the red bone marrow absorbed dose to 2.85 Gy (*6*). Under these circumstances, the maximum allowable activity in the mineral bone will be 1530 MBq, giving an estimated mean absorbed dose to the endosteal layer of 7.5 Gy. For tumor sites, where there may be an increased uptake of ^{153}Sm-EDTMP, perhaps by as much as five (*6*), the endosteal layer absorbed dose will be considerably higher. In fact, correction for this elevated tumor uptake may allow the absorbed dose for the endosteal layer to be used constructively as a guide to the potential benefit (i.e., pain relief) received by patients and ultimately may lead to the establishment of a dose-response relationship.

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REFERENCES

1. Turner JH, Claringbold PG, Hetherington EL, Sorby P, and Martindale AA. A phase I study of samarium-153 ethylenediaminetetramethylene phosphonate therapy for disseminated skeletal metastases. *J Clin Oncol* 1989;7:1926–1931.
2. Lattimer JC, Corwin LA, Stapleton J, et al. Clinical and clinicopathologic response of canine bone tumor patients to treatment with samarium-153-EDTMP. *J Nucl Med* 1990;31:1316–1325.
3. Ketring AR. ^{153}Sm-EDTMP and ^{168}Re-HEDP as bone therapeutic radiopharmaceuticals. *Int J Rad Appl Instrum [B]* 1987;14:223–232.
4. Holmes RA and Farhangi M. Dose tolerance of ^{153}Sm-EDTMP in metastatic bone cancer. *J Nucl Med* 1988;29:775.
5. Singh A, Holmes RA, Farhangi M, et al. Human pharmacokinetics of samarium-153 EDTMP in metastatic cancer. *J Nucl Med* 1989;30:1814–1818.
6. Turner JH, Martindale AA, Sorby P, et al. Samarium-153-EDTMP therapy of disseminated skeletal metastasis. *Eur J Nucl Med* 1989;15:784–795.
7. Logan KW, Volkert WA, and Holmes RA. Radiation dose calculations in persons receiving injection of samarium-153-EDTMP. *J Nucl Med* 1987;28:505–509.
8. Loevinger R and Berman M. A revised schema for calculating the absorbed dose from biologically distributed radionuclides. *MIRD pamphlet No. 1, revised.* New York: Society of Nuclear Medicine; 1976.
9. Limits for Intakes of Radionuclides by Workers. *International Commission on Radiological Protection, Publication 30, Part 1.* Oxford: Pergamon Press; 1979.
10. Reference Man: anatomical, physiological and metabolic characteristics. *International Commission on Radiological Protection, Publication 23.* Oxford: Pergamon Press; 1975.
11. Beddoe AH, Darley PJ, and Spiers FW. Measurements of trabecular bone structure in man. *Phys Med Biol* 1976;21:589–607.
12. Beddoe AH. Measurement of the microscopic structure of cortical bone. *Phys Med Biol* 1977;22:298–308.
13. Beddoe AH. Trabecular bone structure in man, rhesus monkey, beagle, and miniature pig. *Calcif Tiss Res* 1978;25:273–281.
14. Spiers FW, King SD, and Beddoe AH. Measurement of endosteal surface areas in human long bones: relationship to sites of occurrence of osteosarcoma. *Br J Radiol* 1977;50:769–776.
15. Whitwell JR and Spiers FW. Calculated beta-ray dose factors for trabecular bone. *Phys Med Biol* 1976;21:16–38.
16. Spiers FW, Beddoe AH, and Whitwell JR. Mean skeletal dose factors for beta-particle emitters in human bone. Part I. Volume-seeking radionuclides. *Br J Radiol* 1978;51:622–627.
17. Spiers FW, Whitwell JR, and Beddoe AH. Calculated dose factors for the radiosensitive tissues in bone irradiated by surface-deposited radionuclides. *Phys Med Biol* 1978;23:481–494.
18. Spiers FW, Beddoe AH, and Whitwell JR. Mean skeletal dose factors for beta-particle emitters in human bone. Part II. Surface-seeking radionuclides. *Br J Radiol* 1981;54:500–504.
19. Cristy M. Active bone marrow distributions as a function of age in humans. *Phys Med Biol* 1981;26:389–400.
20. Johnson LC. Morphologic analysis in pathology. In: Frost HM, ed. *Bone biodynamics.* New York: Little, Brown & Co.; 1964:543–654.
21. Browne E and Firestone RB. *Table of radioactive isotopes.* New York: Wiley; 1986.
22. Snyder WS, Ford MR, and Warner GG. Estimates of specific absorbed fractions for photon sources uniformly distributed in various organs of a heterogeneous phantom. *MIRD Pamphlet No. 5, Revised.* New York: Society of Nuclear Medicine; 1978.
23. Appelbaum FR, Sandmaier B, Brown PA, et al. Myelosuppression and mechanisms of recovery following administration of samarium-153-EDTMP. *Antibody Immunoconjugates & Radiopharmaceuticals* 1988; 1:263–270.