Bremsstrahlung Radiation Exposure From Pure β-Ray Emitters

Pat B. Zanzonico, Barbara L. Binkert and Stanley J. Goldsmith

Division of Nuclear Medicine, New York Hospital-Cornell Medical Center, New York, New York

With increasing therapeutic use of radionuclides that emit relatively high-energy (>1 MeV) β-rays and the production in vivo of bremsstrahlung sufficient for external imaging, the potential external radiation hazard warrants evaluation. **Methods:** The exposure from a patient administered β-ray-emitting radionuclides has been calculated by extending the National Council on Radiation Protection and Measurement model of a point source in air to account for biologic elimination of activity, the probability of bremsstrahlung production in vivo and its mean energy and the absorption by the patient's body of the bremsstrahlung thus produced. To facilitate such calculations, a quantity called the "specific bremsstrahlung constant" (in C/kg-cm²/MBq-h), Γ_{Br}, was devised and calculated for several radionuclides. The specific bremsstrahlung constant is the bremsstrahlung exposure rate (in C/kg/h) in air at 1 cm from a 1 MBq β-ray emitter of a specified maximum β-ray energy and frequency of emission in a medium of a specified effective atomic number. **Results:** For pure β-ray emitters, the retained activities at which patients can be released from medical confinement (i.e., below which the effective dose equivalent at 1 m will not exceed the maximum recommended value of 0.5 cSv for infrequently exposed members of the general public) are extremely large: on the order of hundreds of thousands to millions of megabecquerels. **Conclusion:** Radionuclide therapy with pure β-ray emitters, even high-energy β-ray emitters emitted in bone, does not require medical confinement of patients for radiation protection.

Key Words: bremsstrahlung; β-ray emitters; release criteria

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In the U.S., the Nuclear Regulatory Commission (NRC) and agreement state regulations (*1,2*) governing the release from medical confinement of patients who have received therapeutic amounts of radioactivity are based on the calculational model of the National Council on Radiation Protection and Measurement (NCRP) issued in 1970 (*3*). This model incorporates the contributions of only penetrating radiations (i.e., photons such as x- and γ-rays). Ideally, however, a therapeutic radionuclide should emit principally nonpenetrating radiations (i.e., particles such as β-rays) to maximize self-irradiation of the target region and minimize irradiation of nontarget regions. Increasingly, pure β-ray-emitters (Table 1 [*4*]) are being considered and used as therapeutic radionuclides (*5*). Because of their short ranges (typically less than 1 cm) in tissue, it has been implicitly assumed that there is no significant external radiation hazard from internally emitted β-rays. With the relatively low energy (on the order of 100 keV or less) of β-rays typically encountered in nuclear medicine and the low effective atomic number (~7.9 [*6,7*]) of soft tissue, there is virtually no bremsstrahlung ("brake radiation") produced in vivo, and the assumption of no external radiation hazard from β-rays is altogether reasonable. With increasing therapeutic use of relatively high-energy β-rays (on the order of 1 MeV or more emitted, for example, by ^{32}P, ^{89}Sr and ^{90}Y) and particularly in materials with high atomic numbers, such as bone (with an effective atomic number of ~20, equivalent to that of calcium), production in vivo of bremsstrahlung is sufficient for external detection and imaging. The resulting external radiation hazard may therefore be of some concern, at least theoretically, and should be systematically evaluated.

MATERIALS AND METHODS

Release Criteria for Patients Receiving Therapeutic Amounts of Radioactivity: The NCRP Model

The exposure from a radioactivity-containing patient may be estimated as follows:

$$D_\gamma(r,t) = \frac{34.6 Q_0 \Gamma_\gamma T_p (1 - e^{-0.693t/T_p})}{r^2}, \qquad \text{Eq. 1}$$

where $D_\gamma(r,t)$ is the photon exposure (in C/kg) at distance (in cm) r from the patient for an exposure time (in days) t; 34.6 is the conversion factor of 24 h/d times the multiplicative factor of 1.44 for calculating the integrated decay (i.e., cumulated activity) from activity and half-life; Q_0 is the initial activity (in MBq) in the point source (i.e., patient); Γ_γ is the specific γ-ray constant (in C/kg-cm²/MBq-h) of the radionuclide, that is, the photon (i.e., γ- or characteristic x-ray) exposure rate (in C/kg/h) at a distance of 1 cm from a 1-MBq point source; and T_p is the physical half-life (in days) of the radionuclide.

Implicit in the NCRP/NRC model (*1–3*) and equation 1 are the following assumptions: (a) The patient is a point source, and therefore exposure varies inversely as the square of the distance from the source and is not affected by attenuation and scatter by the patient's body, and (b) elimination of activity is only by physical

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For correspondence or reprints contact: Pat B. Zanzonico, PhD, Nuclear Medicine Service, Memorial Sloan-Kettering Cancer Center, 1275 York Ave., New York, NY 10021.

TABLE 1
Physical Properties of Pure β-Ray Emitters for Radionuclide Therapy

Radionuclide	Physical half-life, T_p	Specific γ-ray constant, Γ_γ C/kg-cm²/MBq-h	Specific γ-ray constant, Γ_γ R-cm²/mCi-h	Maximum β-ray energy, $[(E_{max})_\beta]$ MeV	Frequency of emission, $(f_\beta)_i$ / transformation	Specific bremsstrahlung constant, Γ_{Br}: Soft tissue Z_{eff} = 7.9 C/kg-cm²/MBq-h	Soft tissue Z_{eff} = 7.9 R-cm²/mCi-h	Bone (i.e., calcium) Z_{eff} = 21 C/kg-cm²/MBq-h	Bone (i.e., calcium) Z_{eff} = 21 R-cm²/mCi-h
^{32}P	14.3 d	0	0	1.71	1	1.01×10^{-4}	4.05×10^{-3}	2.70×10^{-4}	1.08×10^{-2}
^{33}P	25.4 d	0	0	0.25	1	1.65×10^{-5}	6.58×10^{-4}	4.38×10^{-5}	1.75×10^{-3}
^{35}S	87.4 d	0	0	0.167	1	2.80×10^{-5}	1.12×10^{-3}	7.45×10^{-5}	2.98×10^{-3}
^{45}Ca	163 d	0	0	0.257	1	1.71×10^{-5}	6.85×10^{-4}	4.55×10^{-5}	1.82×10^{-3}
^{89}Sr	50.5 d	0	0	1.49	1	7.85×10^{-5}	3.14×10^{-3}	2.11×10^{-4}	8.43×10^{-3}
^{90}Y	64.1 h	0	0	2.28	1	1.41×10^{-4}	5.64×10^{-3}	3.75×10^{-4}	1.50×10^{-2}
^{143}Pm	13.6 d	0	0	0.93	1	2.75×10^{-5}	1.10×10^{-3}	7.33×10^{-5}	2.93×10^{-3}
^{169}Er	9.4 d	0	0	0.35	1	1.38×10^{-5}	5.53×10^{-4}	3.65×10^{-5}	1.46×10^{-3}
^{210}Bi	5.01 d	0	0	1.16	1	3.83×10^{-5}	1.53×10^{-3}	1.02×10^{-4}	4.06×10^{-3}

decay in situ; that is, there is no biologic elimination, or excretion, of activity.

In practice, the following additional assumptions are introduced: (a) An exposure of 2.58×10^{-4} C/kg (1 R) is equivalent to an absorbed dose of 1 cGy (1 rad), a dose equivalent of 1 cSv (1 rem) and an effective dose equivalent of 1 cSv (1 rem); (b) the maximum exposure to an individual from the patient corresponds to complete decay of activity in the patient, (the term, $1 - e^{-0.693\,t\,/\,T_p}$, then becomes unity); and (c) the occupancy factor, E, at a distance of 1 m from the patient is 0.25; that is, the maximum fraction of time an individual would be 1 m from a patient is 0.25.

Therefore, at a distance r = 100 cm from the patient, the total photon effective dose equivalent, D_γ (1 m, ∞), is given by:

$$D_\gamma(1\text{ m},\infty) = \frac{34.6Q_o\Gamma_\gamma T_p 0.25}{(100\text{ cm})^2}. \qquad \text{Eq. 2}$$

The general criterion in NCRP Report No. 37 (*3*) and in NRC Regulatory Guide 8.39 (*2*) for release of a patient from medical confinement is that the total effective dose equivalent at 1 m from the patient shall not exceed 0.5 cSv. This corresponds to the prevailing annual maximum recommended effective dose equivalent to a member of the general public (i.e., a nonoccupationally exposed individual) for an "infrequent" exposure (*8*). Thus, a patient administered a therapeutic amount of a radionuclide shall remain hospitalized on the basis of the projected photon effective dose equivalent at 1 m until the activity (in MBq) remaining in the patient has decreased to that given by:

$$(A_{release})_\gamma = \frac{580}{\Gamma_\gamma T_p}. \qquad \text{Eq. 3}$$

Patients receiving therapeutic amounts of radionuclides may be released from medical confinement with activity in excess of that determined on the basis of equations 1 to 3 by taking into account the effective half-life (i.e., biologic as well as physical elimination) of the radioactive material as well as other mitigating factors relevant to a specific case such as shielding by the patient himself (*1–3*):

$$D_\gamma(r,t) = \frac{34.6Q_o\Gamma_\gamma T_e(1 - e^{-0.693t/T_p})}{r^2} \times [1 - \overline{\phi}_\gamma(TB \leftarrow TB)] \qquad \text{Eq. 4}$$

$$D_\gamma(1\text{m},\infty) = \frac{34.6Q_o\Gamma_\gamma T_e 0.25}{(100\text{ cm})^2}[1 - \overline{\phi}_\gamma(TB \leftarrow TB)] \qquad \text{Eq. 5}$$

$$(A_{release})_\gamma = \frac{580}{\Gamma_\gamma T_e[1 - \overline{\phi}_\gamma(TB \leftarrow TB)]} \qquad \text{Eq. 6}$$

where T_e is the effective half-life (in days) of the radionuclide:

$$T_e = \frac{T_p T_b}{T_p + T_b}. \qquad \text{Eq. 7}$$

T_b is the empirically determined biologic half-life (in days) of the radionuclide in a specific patient, and

$$\overline{\phi}_\gamma(TB \leftarrow TB) = \overline{\phi}_\gamma(TB \leftarrow TB)(\overline{E}_\gamma)$$

is the average total body (TB)-to-TB absorbed fraction for photons of average energy (in MeV) $\overline{E}_\gamma$, that is, the fraction of photon energy emitted uniformly in the TB that is absorbed by the TB.

The term $1 - \overline{\phi}_\gamma(TB \leftarrow TB)(\overline{E}_\gamma)$ is the fraction of photon energy of energy $\overline{E}_\gamma$, which is not absorbed within the TB, and is thus used to approximate the effect of shielding by the patient. A compilation of TB/TB absorbed fractions as a function of photon energy and TB mass is presented by Zanzonico et al. (*9*) as adapted from Christy and Eckerman (*10*); absorbed fractions for photon energies and TB masses not tabulated may be estimated by interpolation between the appropriate table entries.

Release Criteria for Patients Receiving Therapeutic Amounts of Radioactivity: Adaptation of the NCRP Model to β-Emitters

In adapting the foregoing formalism for photons to the bremsstrahlung external radiation hazard from β-rays, the subscript

"γ" (for x- and γ-rays) is replaced with the subscript "Br" (for bremsstrahlung):

$$D_{Br}(r,t) = \frac{34.6Q_o\Gamma_{Br}T_e(1 - e^{-0.693t/T_P})}{r^2} \times [1 - \overline{\phi_{Br}}(TB \leftarrow TB)] \quad \text{Eq. 8}$$

$$D_{Br}(1m,\infty) = \frac{34.6Q_o\Gamma_{Br}T_e0.25}{(100\ cm)^2}[1 - \overline{\phi_{Br}}(TB \leftarrow TB)] \quad \text{Eq. 9}$$

$$(A_{release})_{Br} = \frac{580}{\Gamma_{Br}T_e[1 - \overline{\phi_{Br}}(TB \leftarrow TB)]} \quad \text{Eq. 10}$$

where $D_{Br}(r,t)$ equals bremsstrahlung exposure (in R) at distance (in cm) r from the patient for an exposure time (in days) t; $D_{Br}(1\ m, \infty)$ equals total bremsstrahlung effective dose equivalent (in cSv) at a distance of 1 m from the patient; $(A_{release})_{Br}$ equals activity (in MBq) above which a patient shall remain hospitalized on the basis of the projected bremsstrahlung effective dose equivalent; and Γ_{Br} equals "specific bremsstrahlung constant" (in C/kg-cm^2/MBq-h) of the radionuclide, that is, the bremsstrahlung exposure rate (in C/kg/h) at a distance of 1 cm from a 1-MBq β-ray point source.

The specific bremsstrahlung constant, Γ_{Br}, is a newly devised quantity analogous to the specific γ-ray constant, Γ_γ, for photons, and it can be estimated as follows. First, the probability of a radiative energy loss (i.e., bremsstrahlung interaction) by each β-ray is calculated (*11*):

$$[(P_{Br})\beta]_i = \frac{Z_{eff}[(E_{max})\beta]_i}{3000}, \quad \text{Eq. 11}$$

where $[(P_{Br})_\beta]_i$ equals the probability of a radiative energy loss by β-ray i; Z_{eff} equals the effective atomic number of the stopping material (i.e., tissue); and $[(E_{max})_\beta]_i$ equals the maximum initial kinetic energy (in MeV) of β-ray i.

Second, the mean energy of the resulting bremsstrahlung radiation is calculated. The mean energy is dependent on many factors, including the maximum initial kinetic energy of the β-ray and the composition and geometry of the stopping material, and is therefore difficult to calculate precisely. From Figure 1, the bremsstrahlung energy spectrum of a patient administered ^{89}Sr-strontium chloride (Metastron; Medi-Physics, Arlington Heights, IL), the maximum energy of the spectrum in vivo is essentially equivalent to one-third of the maximum initial kinetic energy of the β-ray; actually, a long "tail" from this energy to the maximum initial kinetic energy of the β-ray is also present but is generally so small (i.e., represents such a small proportion of the total radiative energy losses) in vivo that it may be ignored. For such a distribution, the mean energy equals one-third of the spectrum's maximum energy (which is itself one-third of the maximum initial kinetic energy of the β-ray) and therefore one-ninth of the maximum initial kinetic energy of the β-ray:

$$[(\overline{E}_{Br})\beta]_i = 0.11[(E_{max})\beta]_i, \quad \text{Eq. 12}$$

where $[(\overline{E}_{Br})_\beta]_i$ equals the mean energy (in MeV) of bremsstrahlung for β-ray i emitted by a radionuclide. The spectrum, which indicates the energy window of 160 keV ± 25% used for imaging,

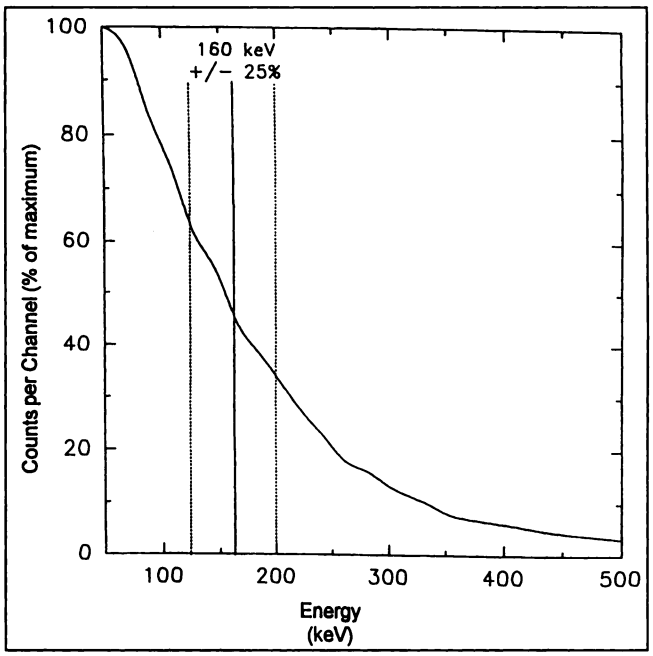

FIGURE 1. Posterior gamma camera pulse height spectrum of chest of patient with metastatic prostate cancer 1 wk after intravenous injection of 148 MBq (4 mCi) of ^{89}Sr-strontium chloride (Metastron).

was acquired using a General Electric 500A gamma camera (General Electric Medical Systems, Milwaukee, WI) without collimation (Fig. 1).

Finally, using equations 11 and 12, the specific bremsstrahlung constant of the radionuclide can be approximated:

$$\Gamma_{Br} = \sum_{i=1}^{n} (f_\beta)_i[(P_{Br})_\beta]_i\Gamma_{Br}[(\overline{E}_{Br})_\beta]_i, \quad \text{Eq. 13}$$

where $(f_\beta)_i$ equals the frequency of emission (i.e., the number per nuclear transformation) of β-ray i and $\Gamma_{Br}([(\overline{E}_{Br})_\beta]_i)$ equals the specific bremsstrahlung constant (in C/kg-cm^2/MBq-h) of β-ray i yielding bremsstrahlung of mean energy $[(\overline{E}_{Br})_\beta]_i$.

Of course, the estimation of the specific bremsstrahlung constant based on the bremsstrahlung mean energy, rather the actual bremsstrahlung energy spectrum, is a gross approximation.

The energy-dependent specific bremsstrahlung constant of β-ray i, $\Gamma_{Br}([(\overline{E}_{Br})_\beta]_i)$, corresponds to the conventional energy-dependent specific γ-ray constant (*12*) for photon energy $[(\overline{E}_{Br})_\beta]_i$. The resulting specific bremsstrahlung constants, $\Gamma_{Br}([(\overline{E}_{Br})_\beta]_i)$, in soft tissue or in bone for one β-ray (i = 1) of frequency $(f_\beta)_i = 1$ and maximum initial kinetic energy $[(E_{max})_\beta]_i$ are shown in Figure 2.

Using the foregoing formalism, the activities, $A_{release}$, of current and potential therapeutic radionuclides below which patients can be released from medical confinement have been calculated for the 70-kg Standard Man and are presented in Table 2. Not surprisingly, the activities of pure β-ray-emitters at which patients can be released from medical confinement are extremely large: on the order of hundreds of thousands to millions of megabecquerels (tens of thousands to hundreds of thousands of millicuries). For localization in bone, where the production of bremsstrahlung is greater than in soft tissue because of the calcium content and resulting high effective atomic number, these activities are several times higher than they are in soft tissue. And, depending on the β-ray and

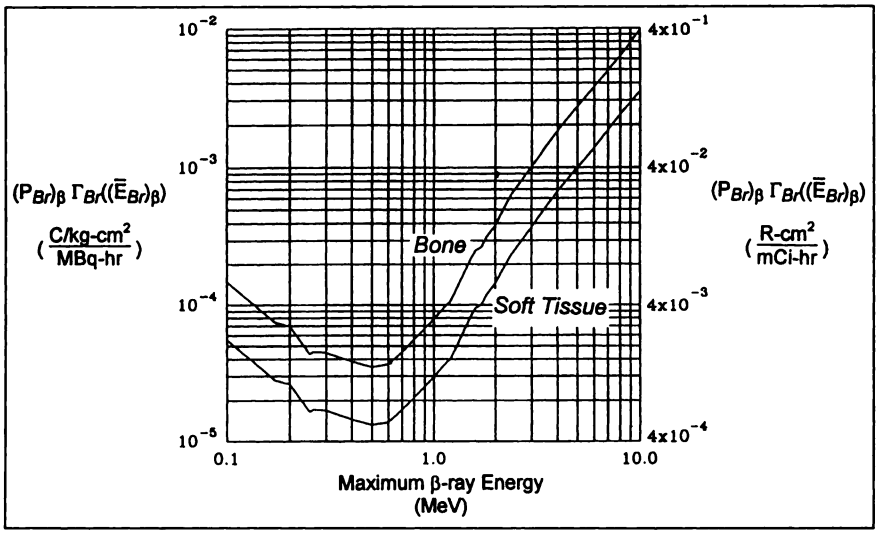

FIGURE 2. Specific bremsstrahlung constant (in C/kg-cm²/MBq-h on left ordinate scale and in R-cm²/mCi-h on right ordinate scale), $(P_{Br})_\beta \Gamma_{Br}([E_{Br}]_\beta)$, of β-ray with probability $(P_{Br})_\beta$ of radiative energy loss and mean bremsstrahlung energy (in MeV) $(E_{Br})_\beta$ in soft tissue (effective atomic number: Z_{eff} = 7.9) and in bone (i.e., calcium; effective atomic number: Z_{eff} = 21).

resulting bremsstrahlung energies, the effect of shielding by the patient increases these activities by up to several times.

DISCUSSION

The activities of current and potential therapeutic radionuclides below which patients can be released from medical confinement (based on a total effective dose equivalent at 1 m of 0.5 cSv) have been calculated (Table 2). These activities have been calculated assuming no biologic elimination of the radionuclide (i.e., the effective half-life, equals the physical half-life) and an exposure factor of 0.25 at a distance from the patient of 1 m. For systemic radionuclide therapy, in which the radionuclide is biologically distributed and eliminated, the physical half-life generally overestimates the effective half-life and therefore the calculated activities overestimate the activities at which patients systemically administered therapeutic radionuclides may actually be released from medical confinement. In addition, as noted, these activities are approximate in that they were calculated simply using the bremsstrahlung mean energy to represent the bremsstrahlung energy spectrum. A more accurate estimate would be obtained by replacing the bremsstrahlung

TABLE 2
Retained Activities of Pure β-Ray Emitters Below Which Patients Can Be Released from Medical Confinement Based on Total Dose Equivalent of 0.5 rem at 1 m

	$A_{release}$*							
	Ignoring shielding by patient†				Including shielding by patient‡			
	In soft tissue Z_{eff} = 7.9		In bone (i.e., calcium) Z_{eff} = 21		In soft tissue Z_{eff} = 7.9		In bone (i.e., calcium) Z_{eff} = 21	
Radionuclide	MBq	mCi	MBq	mCi	MBq	mCi	MBq	mCi
^{32}P	370,000	10,000	139,000	3,770	1,060,000	28,600	400,000	10,800
^{33}P	1,280,000	34,700	481,000	13,000	1,610,000	43,400	603,000	16,300
^{35}S	219,000	5,930	82,500	2,230	241,000	6,520	90,700	2,450
^{45}Ca	192,000	5,200	72,500	1,960	235,000	6,340	88,100	2,380
^{89}Sr	135,000	3,660	51,100	1,380	389,000	10,500	145,000	3,930
^{90}Y	1,420,000	38,500	537,000	14,500	4,180,000	113,000	1,580,000	42,600
^{143}Pm	1,430,000	38,700	540,000	14,600	3,890,000	105,000	1,450,000	39,300
^{169}Er	4,140,000	112,000	1,550,000	42,000	6,070,000	164,000	2,280,000	61,700
^{210}Bi	2,800,000	75,800	1,050,000	28,500	8,030,000	217,000	3,020,000	81,500

*Calculated assuming no biologic elimination of the radionuclide (i.e., the effective half-life equals the physical half-life) and an exposure factor of 0.25 at a distance from the patient of 1 m.

†Calculated assuming no effect of attenuation and scatter of bremsstrahlung by the patient's body, generally more typical of regionally administered and therefore localized radionuclides.

‡Calculated incorporating the effects of attenuation and scatter of bremsstrahlung by the patient's body, generally more typical of systemically administered and therefore distributed radionuclides, assuming a total body mass of 70 kg.

Z_{eff} = effective atomic number.

mean energy with the bremsstrahlung energy spectrum (represented as a weighted sum of photon energies) for standard anatomic models (*4*) and the mean TB/TB absorbed fraction for the bremsstrahlung mean energy with the corresponding energy-dependent TB/TB absorbed fractions. A further refinement in the estimation of such activities would be the use of calculated exposures per unit activity at 1 m from anthropomorphic phantoms based on Monte Carlo simulations (*13*), rather than the use of TB/TB absorbed fractions.

As noted, the specific bremsstrahlung constant is a newly devised quantity analogous to the specific γ-ray constant for photons. Conceptually, the specific bremsstrahlung constant is the exposure rate at a unit distance from a unit-activity point source of bremsstrahlung in air emitting one β-ray of the specified maximum energy $(E_{max})_\beta$ per nuclear transformation and yielding bremsstrahlung of mean energy $(\overline{E}_{Br})_\beta$. Of course, bremsstrahlung is a result of scattering of electrons and therefore would not actually be emitted from a point source of β-rays, the term "point source" referring to the geometry of the bremsstrahlung, not the actual β-ray, source. The term "specific bremsstrahlung constant" is thus an artificial, but useful, calculational construct.

In principle, for radionuclides that emit photon (i.e., γ- or characteristic x-rays) radiations and bremsstrahlung, the contributions of both such radiations should be considered in determining the activity of such a radionuclide below which a patient can be released from medical confinement. In practice, however, the specific γ-ray constant is several orders of magnitude greater than the specific bremsstrahlung constants, and the negligibly small contribution of bremsstrahlung may be ignored. It must be emphasized, then, that while the assumptions and computational methods used are reasonable and appropriately conservative for estimating the external radiation hazard from pure β-ray-emitters, they may not be applicable generally.

CONCLUSION

For pure β-ray-emitting radionuclides, the activities requiring medical confinement are very high: on the order of hundreds of thousands to millions of megabecquerels (tens of thousands to hundreds of thousands of millicuries). Of course, patients receiving such radionuclides would never receive activities even remotely approaching such values because of prohibitive radiation toxicity to the patient. For example, when using ^{89}Sr-strontium chloride for the palliation of bone pain, the standard administered activity, limited by hematologic toxicity secondary to marrow irradiation, is only 148 MBq (4 mCi). In contrast, ^{89}Sr activities requiring medical confinement are at least 145,000 MBq (3,900 mCi) (Table 2). Thus, consistent with prevailing practice, patients receiving pure β-ray-emitting radionuclides do not have to be hospitalized for radiation precautions.

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