MIRD Pamphlet No. 14: A Dynamic Urinary Bladder Model for Radiation Dose Calculations

Stephen R. Thomas, Michael G. Stabin, Chin-Tu Chen, and R.C. Samaratunga

Department of Radiology, College of Medicine, University of Cincinnati, Cincinnati, Ohio; Oak Ridge Associated Universities, Oak Ridge, Tennessee, and University of Chicago, Chicago, Illinois
A task group of the MIRD Committee, Society of Nuclear Medicine

The constant-volume urinary bladder model in the standard MIRD phantom has recognized limitations. Various investigators have developed detailed models incorporating more physiologically realistic features such as expanding bladder contents and residual volume, and variable urinary input rate, initial volume and first void time. We have reviewed these published models and have developed a new model incorporating these factors. The model consists of a spherical source with variable volume to simulate the bladder contents and a wall represented by a spherical shell of constant volume. The wall thickness varies as the source expands or contracts. The model provides for variable urine entry rate (three different hydration states), initial bladder contents volume, residual volume and first void time. The voiding schedule includes an extended nighttime gap during which the urine entry rate is reduced to one-half the daytime rate. Radiation dose estimates have been calculated for the bladder wall surface (including photon and electron components) and at several depths in the wall (electron component) for [^{18}F]FDG, ^{99m}Tc-DTPA, ^{99m}Tc-HEDP, [^{99m}Tc]pertechnetate ^{99m}Tc-RBCs, ^{99m}Tc-glucoheptonate, ^{99m}Tc-MAG3, [^{123}I]/[^{124}I]/[^{131}I]OIH and sodium [^{131}I]iodide(NaI). The initial bladder volume and first void time that provide the lowest radiation dose to the bladder wall are determined separately for each compound to give guidance for establishing dose reduction protocols.

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Calculation of radiation dose to the inner mucosal surface and at depth in the urinary bladder wall from radioactivity distributed within the bladder contents is of importance for: (a) evaluating new or existing radiopharmaceuticals for human use and (b) designing patient protocol strategies intended to minimize the radiation dose for a specific radiopharmaceutical. Accurate dose estimates may hold particular significance for those agents that are excreted rapidly such as [^{18}F]FDG and ^{99m}Tc-DTPA (*1,2*).

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For reprints contact: David A. Weber, PhD, Chairman, MIRD Committee, Brookhaven National Laboratories, Nuclear Medicine Division, Medical Department, Bldg. 490, Upton, NY 11973.

Most dose estimates to the bladder wall are based on the standard MIRD phantom in which the bladder has a constant volume (*3*). No provision is made for dynamic variation or incorporation of other variables (such as filling rate, initial volume, residual volume, first voiding time, wall thinning) which may be expected to have an effect on the dose. The limitations of this bladder model have long been recognized and various alternative models have been proposed. In this paper, the published models for the urinary bladder are reviewed and the results compared with those provided under equivalent conditions by the MIRD model. A new model was developed that incorporates the complexities of urinary function into a practical algorithmic representation for calculating the radiation dose to the bladder wall.

A REVIEW OF PREVIOUSLY PUBLISHED URINARY BLADDER MODELS FOR DOSIMETRY CALCULATIONS

Table 1 contains definitions of symbols used in the algorithms of four previously published urinary bladder models for dose calculations that are described in Table 2 along with the new model. Model A in Table 2 is associated with the standard MIRD phantom (*3*). (Other publications relevant to the MIRD schema and model descriptions are provided in references *4–8*.) A limitation of the model is that the volume of the bladder contents remains constant at 202.6 ml (200 g). The surface electron dose rate is derived from the approximation that the dose rate at the surface of a large sphere is one-half of the dose rate in an infinite medium that has the same radioactive concentration as within the sphere (*9*). The photon dose is derived using Monte Carlo techniques. Bladder wall dose per unit cumulated activity in various source organs, including bladder contents, has been calculated for many radionuclides with this model (*8*). Cumulated activity in bladder contents is derived using a bladder radioactivity input model which is generally obtained from the whole-body retention curve determined through knowledge of the pharmaceutical biokinetics. No attempt is made to represent the physical dynamics of bladder filling and emptying.

Snyder and Ford (*10*) developed a model in which the

TABLE 1
Definition of Symbols Used in the Calculational Methods Described in Table 2

Symbol	Name/Description	Units	
		Traditional	S.I.
$\tilde{A}$	Cumulated activity $\tilde{A} = \int A(t)dt$	μCi h	MBq s
A(t)	Activity within the bladder as a function of time	μCi [or mCi]	Bq [or MBq]
$A_v(t)$	Bladder activity per unit volume at time, t	$\mu Ci/cm^3$ [or mCi/cm^3]	Bq/cm^3 [or MBq/cm^3]
$\bar{D}/A_0$ [D_s/A_0]	Average dose to the bladder wall [or dose to the inner surface] per unit administered activity	rad/μCi [or rad/mCi]	mGy/MBq
$D\gamma(V)$	Photon dose to the bladder wall at bladder volume, V	rad	mGy
f [f_i]	Residual bladder volume fraction following a void [the i^{th} void]	—	—
g_s	Geometrical factor for a point on the surface of a sphere	cm	m
r(t)	Bladder radius at time, t	cm	m
$R_{\beta s}$	Electron dose rate at the bladder wall inner surface per unit activity in the bladder contents volume	rad/mCi h	Gy/MBq s
$R_{\gamma s}$	Photon (gamma) dose rate at the bladder wall inner surface per unit activity in the bladder contents volume	rad/mCi h	Gy/MBq s
$R_{\gamma w}$	Average photon (gamma) dose rate within the bladder wall per unit activity in the bladder contents volume	rad/mCi h	Gy/MBq s
S	S value for the bladder contents (source) to the bladder wall (target)	rad/μCi h	Gy/MBq s [or μGy/MBq s]
T_v	Regular voiding interval	h	s
T_i	Void time for the i^{th} void	h	s
T_1	Time of first void	h	s
U(t)	Urine volume rate of entry into the bladder	ml/min [or cm^3/min]	ml/s [or cm^3/s]
V(t)	Bladder volume at time, t	ml [or cm^3]	ml [or cm^3]
V_0	Initial bladder contents volume	ml [or cm^3]	ml [or cm^3]
V_r	Residual volume following void	ml [or cm^3]	ml [or cm^3]
X(t)	Gamma ray exposure rate at the inner bladder wall surface at time, t	R/h	C/kg s
α_j	Biologic coefficients representing the fraction of the administered activity entering the bladder for the j-th component	—	—
Δ_β	Mean electron particle energy emitted per nuclear transition (formerly, equilibrium dose constant)	g rad/μCi h	Gy kg/Bq s
λ_j	Biologic rate constant for entry of the j-th component into the bladder	h^{-1}	s^{-1}
λ	Physical decay constant	h^{-1}	s^{-1}
ρ	Density of the medium	g/ml [or g/cm^3]	g/cm^3
τ	Residence time in the bladder contents	h	s
Γ	Exposure rate constant	R cm^2/mCi h	C cm^2/kg MBq s
Γ'	Exposure rate constant converted to dose in tissue using the Roentgen-to-rad conversion factor	rad cm^2/mCi h	Gy cm^2/MBq s
μ	Effective absorption coefficient for water at a given energy	cm^{-1}	m^{-1}

bladder is represented as an ellipsoid with axes in the ratio of 4:3:3 (left-right:front-back:top-bottom) that remains fixed as the bladder fills (Model B in Table 2). The surface electron dose rate is also derived using the asssumption that the dose rate at the surface of a sphere is one-half of the dose rate in the infinite medium. The variation of electron dose rate with depth is estimated using an integration of Berger's (*11,12*) point kernel for an infinite slab of finite thickness with a semi-infinite source on one side. An average electron dose to the wall was calculated as well as a surface electron dose. Photon dose is determined using a Monte Carlo technique for several discrete bladder content volumes. Photon dose for zero volume is calculated as for a point source. The bladder wall mass remains fixed at 45 g, while the wall thickness decreases regularly (maintaining the 4:3:3 directional ratio) as the bladder volume increases. The filling rate is assumed to be linear. The voiding schedules are uniform. The model allows for residual volumes after voiding. The radionuclide input is an exponential function of one or more components. The dose per photon is given as a function of bladder volume for several discrete photon energies. These curves are fitted by two-component exponential functions, and the coefficients of the curves are provided. Total dose to the bladder wall is tabulated for intravenous injections of ^{131}I(NaI) and [^{99m}Tc]pertechnetate for three filling rates, three uniform voiding schedules and four values of residual volume. Photon dose is presented separately from both surface and average electron dose. In addition, estimates are given for ^{123}I(NaI) for the same filling rates and voiding schedules without consideration of residual volume. In a separate paper, Smith and Warner (*13*) presented the bladder dose reduction calculated from Model B for seven radionuclides. Several parameters including voiding schedule (irregular), effective half-time of the activity entering the bladder and initial urine volume at time of injection are varied.

In Model C by Diffey and Hilson (*14*), the bladder is taken as a sphere of variable radii. The electron dose rate to the surface of the bladder wall is derived using the same assumptions as those in Model A. The photon dose rate is derived theoretically for the spherical volume. The filling rate is assumed to be linear with uniform voiding intervals. The model does not allow for residual urine volume after voiding. Dose was calculated only for ^{99m}Tc-DTPA with a single exponential input function assumed. The dose rate for a given interval is found by numerical integration. The electron, photon, and total dose are plotted as a function of voiding interval for a fixed filling rate. In addition, total dose is plotted as a function of voiding interval for several filling rates.

Model D was developed by Chen, Harper and Lathrop (*1,2*). The bladder is a sphere of varying radii. The electron dose rate calculations follow the standard assumptions of Model A. An analytical expression is derived for the photon dose rate to the inner surface of a sphere. The filling rate is assumed to be linear with nonuniform voiding schedules possible. The model allows for a fractional residual volume after each void. The activity input is represented by an exponential function with one or more components. Bladder wall doses for [^{18}F]FDG and ^{99m}Tc-DTPA are calculated as separate functions of voiding interval, residual urine fraction, urine production rate, or initial bladder volume with other parameters specified (i.e., fixed) within a given calculation. The authors also provide the total dose as a function of first void time after radiopharmaceutical administration for several initial volumes. As an extension of this work, Powell and Chen (*15*) calculated the absorbed dose as a function of depth into the bladder wall. The dose from electrons is estimated through approximation of the spherical source volume by a large number of line segment sources. The dose from each line source was estimated through integration of the point source functions of Loevinger et al. (*9*) or Bochkarev et al. (*16*). The dose from photons was estimated using the specific gamma constant for the radionuclide studied and geometrical factors from Loevinger (*9*). The bladder wall dose for the positron emitter ^{18}F is presented along with correlative results from thermoluminescent dosimeter (TLD) phantom experiments.

Several publications not included in Table 2 are discussed briefly. Unnikrishnan (*17*) described a bladder model involving a sphere of variable radius. The electron dose rate at the surface of the bladder contents volume (assumed to represent the maximum dose rate) is derived from integration of Berger's scaled absorbed dose distributions (*11*) to represent a spherical volume source. The photon dose is taken directly from Snyder and Ford's work (*10*). The urine filling rate is linear with an initially empty bladder assumed. Dose to the bladder wall is calculated for [^{131}I]OIH under the assumption of activity entering the bladder either with: (a) a constant rate or (b) instantaneously at time zero. The electron and photon dose rates are given as a function of final bladder volume for both sets of assumptions.

Dimitriou et al. (*18*) modified the model of Diffey and Hilson (*14*) for calculation of dose from ^{99m}Tc cystography studies. Here, the bladder volume increases only as a result of saline flow, and all of the activity injected into the catheter is assumed to be in the bladder during the entire filling phase. Complete bladder emptying is assumed. The total dose to the bladder wall is expressed as a function of filling time for a variety of filling rates and for two different delay times between initiation of saline flow and radionuclide injection.

Cloutier et al. (*5*) described a dynamic bladder model that was used for calculating the dose to the fetus from activity in the mother's bladder. Dose to the bladder wall was not calculated. The ellipsoidal bladder is assumed to fill at a constant rate to 300 ml and to be displaced downward as it fills. Monte Carlo calculations are used to select time points at random from the time-activity distri-

TABLE 2
Description Details of Urinary Bladder Models for Dosimetry Calculations

Model	Anatomic configuration	Physiologic aspects	Calculational methods	Comments
A. MIRD model (1978) *(3)*	1. Ellipsoid of constant volume (bladder contents): 202.6 ml (200 g). 2. Wall mass: 45.13 g (Volume: 45.73 ml). 3. Wall thickness: Constant in time but varies geometrically according to position relative to ellipse axes (i.e., thickest along the direction of the major axis).	1. Activity input is derived from the whole-body retention curve. 2. Variable but regularly spaced void intervals traditionally taken as 2.4 hr or 4.8 hr (correspond to 10 or 5 equally spaced voiding times over a 24-hr period).	1. $R_{\beta S} = 10^3\,\Delta_\beta/(2\rho V(t))$ 2. $R_{\gamma W}$: Derived empirically using Monte Carlo calculations 3. $\tau = \tilde{A}/A_0 = \sum_i \alpha_i \left(\frac{1 - e^{-\lambda T_v}}{\lambda} - \frac{1 - e^{-(\lambda_i+\lambda)T_v}}{\lambda_i + \lambda}\right) \times \left(\frac{1}{1 - e^{-(\lambda_i+\lambda)T_v}}\right)$ 4. $\bar{D}/A_0 = S\,\tau$	1. The beta dose rate is derived from the standard assumption that the dose rate at the surface of a sphere is one-half of the dose rate in the infinite medium. 2. Cumulated activity is derived from the whole-body retention curve and the described regular-voiding-schedule model. 3. No attempt is made to model the physical dynamics of bladder filling and emptying.
B. Snyder and Ford *(10)*	1. Ellipsoid with axes in ratio of 4:3:3 (left-right: front-back: top-bottom). 2. Volume range (bladder contents): 0 to 500 ml. 3. Wall mass: 45 g. 4. Wall thickness: Varies geometrically according to position relative to ellipse axes, thinning with increasing bladder volume to maintain the constant 45-g mass.	1. Urine volume entry rate into the bladder, U(t): 0.69, 0.97, 1.39 ml/min (1000, 1400, 2000 ml/day). 2. Initial bladder contents volume, V_0: 20, 40, 60, 80% of the regular void volume. 3. Residual volume, V_r: 0%, 10%, 20%, 30% "carry-over" from regular void volume. 4. Uniform activity distribution within bladder volume. 5. Voiding schedule: variable; 4, 7, 10 voids/day spaced regularly.	1. $R_{\beta S} = 10^3\Delta_\beta/(2\rho V(t))$ 2. $D_\gamma(V) = ae^{-cV} + be^{-dV}$: Empirical function with coefficients a, b, c, d derived from a fit to Monte Carlo calculations for the photon dose as a function of volume, V.	1. The variation of electron dose rate with depth was estimated using an integration of Berger's point kernel for an infinite slab of finite thickness with a semi-infinite source on one side; thus, the average electron dose in the wall was calculated as well as the surface dose. 2. The empirical functions for photon dose are expressed as a function of energy at discrete intervals; thus, interpolation is required for the specific radionuclides. 3. Photon dose for zero volume is calculated as for a point source.
C. Diffey and Hilson *(14)*	1. Expanding sphere. 2. Volume range (bladder contents): not specified.	1. Urine volume entry rate into bladder, U(t): 0.5–2.5 ml/min. 2. Initial bladder contents volume, V_0: 0 ml. 3. Residual volume, V_r: 0 ml (complete bladder voiding assumed). 4. Uniform activity distribution within bladder contents. 5. Voiding schedule: regular periods from 1 to 20 hr.	1. $R_{\beta S}$ [Standard assumption; however, expressed differently] 2. $X(t) = \Gamma A_v(t) g_s$ 3. $g_s = \frac{2\pi}{\mu}\left[1 - \frac{1 - e^{-2\mu r(t)}}{2\mu r(t)}\right]$ 4. $R_{\gamma S} = 0.96X(t)$	1. The photon dose rate is expressed similar to that of Model D but contains a different geometrical factor. 2. Roentgen-to-rad conversion factor of 0.96 was used to convert the exposure rate to dose rate. 3. The dose rate for a given interval was found by numerical integration using Simpson's rule.

TABLE 2 (continued)

Model	Anatomic configuration	Physiologic aspects	Calculational methods	Comments
D. Chen, Harper and Lathrop *(1,2)*	1. Expanding sphere. 2. Volume range (bladder contents): 10 to 500 ml.	1. Urine volume entry rate into bladder, U(t): 1.25 ml/min. 2. Initial bladder contents volume, V_0: 10 to 500 ml (in steps). 3. Residual volume, V_r: held as a fixed fraction (0.07) of the bladder volume at that voiding time. 4. Uniform activity distribution within bladder contents. 5. Voiding schedule: variable first voiding time, T_1; regular voiding periods of 3 hr thereafter.	1. $R_{\beta S} = 10^3\Delta_\beta/(2\rho V(t))$ 2. $R_{\gamma S} = 10^3 \rho \Gamma g_s / V(t)$ 3. $g_s = (6\pi^2 V(t))^{1/3}$, for $\mu r(t) \ll 1$ 4. $V(t) = \left(\prod_{i=1}^{n} f_i\right) V_0 + \sum_{i=1}^{n}\left(\prod_{i=1}^{n} f_i\right)\int_{T_{i-1}}^{T_i} U(t)dt + \int_{T_n}^{t} U(t)dt$ for $T_n \le t < T_{n+1}$ 5. $A(t) = A_0 e^{-\lambda(t-T_1)} \sum_{j=1}^{m} \alpha_j[1 - e^{-\lambda_j(t-T_1)}] - \sum_{i=2}^{n} (1 - f_i)A(T_i)\, e^{-\lambda(t-T_i)}$ for $T_n \le t < T_{n+1}$ 6. $D_s/A_0 = \frac{1}{60}\int_{T_1}^{\infty}\left[\frac{3.9 \times 10^{-3}\Gamma A(t)}{[V(t)]^{1/3}} + \frac{\Delta_\beta A(t)}{2V(t)}\right] dt$	1. Both the electron and photon dose rates are calculated to the inner surface of the bladder wall only.
E. Dynamic Bladder Model (This report)	1. Expanding sphere. 2. Volume range (bladder contents): 10 to 770 ml. 3. Wall mass: 45 g (volume: 45 cm^3). 4. Wall thickness: Uniform thinning as bladder contents expand while maintaining a constant 45-g mass (45 cm^3).	1. Urine volume entry rate into bladder, U(t): Variable corresponding to three different hydration states with the nighttime entry rate being one-half the daytime rate: 0.5 (0.25), 1.0 (0.5), 1.5 (0.75), ml min^{-1} (day/night). 2. Initial bladder contents volume, V_0: 10 to 500 ml. 3. Residual volume, V_r : 10 ml. Fixed following each void. 4. (a) Uniform activity distribution within bladder contents. (b) Variable activity rate of entry into the bladder per specific radiopharmaceutical biologic data. (c) Radiopharmaceutical administration constrained to occur at 9:00 a.m. 5. Voiding schedule: Variable first void time T_1; regular voiding period of 3 hr thereafter with the exception of the shortened period preceding the 6 hr nighttime gap (constrained to begin at 12:00 a.m.).	1. Dose to the inner surface of the bladder wall is calculated similarly to the method of Model D: $R_{\beta S}$, $R_{\gamma S}$, g_s. 2. $V(t) = V_o + \int U(t)dt$; $0 \le t < T_1$(1^{st} void) $= V_r + \int U(t)dt$; $T_{n-1} \le t < T_n$ 3. $A(t) = A_0 e^{-\lambda t} \sum_{1}^{j} \alpha_j(1 - e^{-\lambda_j t}) - \sum_{1}^{n} [1 - V_r/V(T_i)]A(T_i)e^{-\lambda(t-T_i)}$ 4. D_S/A_0: Same expression as for Model D. 5. Electron dose at depth into the bladder wall is calculated using an extension of the solution for point sources to spherical volume geometry: X_{50}, X_{90}.	1. Electron and photon dose rates are calculated to the inner surface of the bladder wall. 2. Electron depth dose values are calculated for the X_{50} and X_{90} percentile distance parameters.

bution in the bladder. Because activity is assumed to enter the bladder linearly with time and the volume of the bladder contents also increases linearly with time, this Monte Carlo method weights the calculation according to both activity and bladder size. The activity in the bladder is calculated from the total-body retention function, the excretion rate through the kidney, and the time elapsed since the bladder was emptied. The model provides for voiding intervals of equal or varied time periods. The bladder is assumed to be completely emptied at each void.

Smith, Veall and Wotton (*19*) employed the same geometric model and methods for calculating electron and photon dose as Snyder and Ford (*10*). The filling rate is taken as constant with a uniform voiding schedule. Complete emptying is assumed at each void. Radionuclide input is represented by exponential functions with one or more components. Total dose as a function of volume is calculated for 31 radionuclides and fitted with three-component exponential curves. A table of the coefficients for these curves is provided. Dose to the bladder wall is expressed as a function of bladder volume for [^{131}I]OIH and ^{99m}Tc-DTPA. Dose to the bladder wall is shown also as a function of bladder voiding interval for several filling rates and for initial volumes of 0 and 100 ml.

DESCRIPTION OF THE NEW DYNAMIC BLADDER MODEL

The new model incorporates desirable features of the previous methods while introducing innovations that take into consideration some of the complexities of the dynamic situation.

Anatomic Configuration

1. Expanding sphere: A spherical model is modified from that of Chen et al. (*2*) which facilitates description by analytical techniques. X-ray images of a contrast-filled bladder demonstrate that the spherical approximation is appropriate for relatively large bladder volumes (*2*). For smaller volumes, the bladder assumes an irregular shape deviating from both the spherical model and the ellipsoidal configuration adopted in some of the previous methods (Table 2). However, as Chen et al. point out, the dose to the bladder wall from nonpenetrating radiation (the major fraction of total radiation dose) is relatively independent of the actual bladder shape. Thus, the accuracy of the geometrical description at small volumes is not critical.
2. Volume range for the bladder contents: 10 to 770 ml. The upper bound of 770 ml results from the dynamic physiologic aspects of the model as listed below, including maximum urine entry rate, initial volume, and first voiding time.
3. Wall characteristics: Uniform thinning with bladder contents expansion while maintaining a constant 45-g mass (45 cm^3).

Physiologic Aspects

1. Variable urine volume entry rate into the bladder (U(t)) corresponding to three different hydration states: (a) 0.5 ml/min^{-1}, (b) 1.0 ml/min^{-1} and (c) 1.5 ml/min^{-1}. For the 6 hr nighttime gap, the entry rate is reduced to one-half the daytime rate; namely, 0.25, 0.5 and 0.75 ml/min^{-1}, respectively.
2. Variable activity rate of entry into the bladder (A(t)): Specific radiopharmaceuticals are evaluated according to published biologic parameters. Table 3 contains physical and biologic data for the various radiopharmaceuticals. Administration of the radiopharmaceutical is constrained to take place at 9:00 a.m.
3. Initial bladder contents volume (V_0) range: 10–500 ml.
4. Residual bladder contents volume (V_r): fixed at 10 ml following each void.
5. Activity: uniformly distributed within the urine.
6. Voiding schedule: (a) first (initial) voiding time (T_1) variable from 20 min to 3 hr (evaluation of this parameter for minimum dose is provided for each radiopharmaceutical); (b) three-hour void intervals following the initial void with a shortened period leading up to midnight depending upon the time available within the three-hour sequence pattern; and (c) a 6-hr nighttime gap beginning at midnight.

Calculational Methods

1. Radiation dose to the inner surface of the bladder wall calculated using a modification of the expanding spherical model of Chen et al. (*2*). (Refer to Table 1 for definition of terms).
   a. Time-dependent bladder-contents volume, V(t), with radiopharmaceutical administration taking place at time t = 0:

$$V(t) = V_0 + \int U(t)dt;\ 0 \le t < T_1\ (1^{st}\ \text{void})$$
$$= V_r + \int U(t)dt;\ T_{n-1} \le t < T_n. \qquad \text{Eq. 1}$$

   b. Time-dependent bladder contents activity, A(t):

$$A(t) = A_0 e^{-\lambda t} \sum_{1}^{j} \alpha_j (1 - e^{-\lambda j t})$$
$$- \sum_{1}^{n} [1 - V_r/V(T_i)] A(T_i) e^{-\lambda j t (t - T_i)}, \qquad \text{Eq. 2}$$

where n is the void number (i.e., first void, n = 1, etc.). The first term of Equation 2 represents the input into the bladder from the whole body. The expression after the summation sign of the second

TABLE 3
Physical and Biologic Parameters for the Radiopharmaceuticals Used in the Bladder Wall Dose Calculations

	Physical Parameters			Biologic Parameters for the Bladder Contents		
Radiopharmaceutical	Δ_β (Gy kg/MBq s) (ref. *28*)	$\Gamma' = 0.96\,\Gamma$ (mGy cm²/MBq s)	λ (min⁻¹)	Fraction* α_j	Rate constant λ_j (min⁻¹)	Reference†
[¹⁸F]FDG	4.00×10^{-8}	4.13×10^{-4}	6.36×10^{-3}	0.19	3.85×10^{-2}	20
				0.06	1.24×10^{-3}	
^{99m}Tc-DTPA	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	0.579	1.15×10^{-2}	21
				0.421	1.25×10^{-3}	
[^{99m}Tc]pertechnetate	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	0.0168	1.331×10^{-1}	22
				0.138	9.220×10^{-3}	
				0.125	1.919×10^{-3}	
				0.070	4.101×10^{-4}	
^{99m}Tc-HEDP	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	−0.0048	4.368×10^{-1}	23
				−0.283	9.096×10^{-2}	
				0.302	8.073×10^{-2}	
				0.278	1.041×10^{-2}	
				0.734	8.686×10^{-4}	
^{99m}Tc-glucoheptonate	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	0.35	3.469×10^{-2}	24
				0.30	5.663×10^{-3}	
				0.35	1.298×10^{-4}	
^{99m}Tc-RBCs	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	0.0071	9.627×10^{-6}	25
				0.0518	1.916×10^{-3}	
				0.0482	4.097×10^{-4}	
^{99m}Tc-MAG3	2.59×10^{-9}	5.63×10^{-5}	1.92×10^{-3}	0.51	3.016×10^{-1}	(Wooten W, *personal communication*)
				0.49	4.053×10^{-2}	
[¹³¹I]OIH	3.04×10^{-8}	1.61×10^{-4}	5.99×10^{-5}	0.51	2.947×10^{-1}	26
				0.49	4.053×10^{-2}	
¹³¹I(NaI)	3.04×10^{-8}	1.61×10^{-4}	5.99×10^{-5}	0.729	1.903×10^{-3}	27
				0.271	7.405×10^{-6}	
[¹²³I]OIH	4.51×10^{-9}	1.17×10^{-4}	8.75×10^{-4}	0.51	2.947×10^{-1}	26
				0.49	4.053×10^{-2}	
[¹²⁴I]OIH	3.10×10^{-8}	3.87×10^{-4}	1.15×10^{-4}	0.51	2.947×10^{-1}	26
				0.49	4.053×10^{-2}	

* For radiopharmaceuticals with excretion through the urinary tract only, the coefficients α_j will be the same as those for the total body.
† Reference from which the biologic parameters were taken or derived.

term represents the activity which leaves the bladder at void time T_i. (The second term is zero before the first void.) Thus, this second term is the sum of administered activity that has been previously voided. Physical decay for each term is included through the exponential function containing the physical decay constant.

c. Dose per unit administered activity to the bladder wall inner surface:

$$\bar{D}/A_0 = (1/60)\int_0^\infty [3.9 \times 10^{-3}\,\Gamma\, A(t)/V(t)^{2/3} + \Delta_\beta A(t)/(2V(t))]dt. \qquad \text{Eq. 3}$$

Considerations leading to this analytical expression as derived by Chen, Harper, and Lathrop (*2*) were described earlier in the text and Table 2 as Model D. The calculations as carried out by numerical integration were terminated when the ratio of the dose in a given interval between voids to the total dose including that interval was less than 0.01%, i.e., $D(n \rightarrow n+1)/D(1 \rightarrow n+1) \leq 0.0001$. (A value of 0.1% was used for ^{99m}Tc-MAG3, [¹³¹I]OIH, [¹²³I]OIH and [¹²⁴I]OIH to avoid unnecessary integration time.)

2. Electron dose at depth into the bladder wall: Depth dose characteristics for point sources or discrete distributions of radionuclides may be described through use of the percentile distance parameter which denotes the fraction of emitted energy absorbed in a sphere of radius x around the source. Thus, x_{90}(or x_{50}) specifies the distance from the source within which 90% (or 50%) of the energy is absorbed. The values of these parameters, as given by Berger (*11*), for the radionuclides evaluated in this report, are given in Table 4. For beta emitters, the values are taken directly from reference 11. For nuclides with a

series of electron emissions, the percentile distance values are determined through consideration of the energies and abundances of the various emissions and the values given in reference 11 for the individual energies. Formulas for extension of these solutions for point sources to the spherical volume source geometry assumed for the bladder are taken from reference 12. Bladder size is determined at each time step by solution of the time-dependent bladder-contents volume expression (Equation 1) using the optimal first void time (as determined by average bladder-wall dose) and three different values of initial volume. Integration of the final expression is accomplished by use of the trapezoidal integration method.

RESULTS

A variety of commonly used radiopharmaceuticals was studied to provide a comparison among bladder wall dosimetry models and to evaluate the new model. These include: [^{18}F]FDG (*20*), ^{99m}Tc-DTPA (*21*), [^{99m}Tc]pertechnetate (*22*), ^{99m}Tc-HEDP (*23*), ^{99m}Tc-glucoheptonate (*24*), ^{99m}Tc-RBCs (*25*), ^{99m}Tc-MAG3 (Wooten W, VA Medical, University of Utah, *personal communication*), [^{131}I]OIH (*26*), [^{123}I]OIH (*26*), [^{124}I]OIH (*26*), ^{131}I(NaI) (*27*). The biological parameters for these radiopharmaceuticals, taken from the references cited, are listed in Table 3.

The dose per unit administered activity ($\bar{D}/A_0$) to the inner bladder wall surface was calculated for each radiopharmaceutical as a function of initial bladder contents volume (V_0) and first void time (T_1). As a function of these parameters, families of dose curves as well as tabular data were generated for each model. For the previously published models (Table 2), 3-hr voiding intervals were assumed following the variable first void time. In the Appendix, Figures A1–A4 provide examples of the ^{99m}Tc-DTPA results for these models with the calculations presented in Tables A1–A4.

Similar calculations for the new model are shown in Figures A5–A15 and are presented in Tables A5–A15. For the figures, only the results for a bladder urine input function U(t) = 1.0/0.5 ml min^{-1} (day/night) are shown. The tables provide data for the other entry rates evaluated (i.e., 0.5/0.25 and 1.5/0.75 ml min^{-1}). Examples of the bladder activity curves for two radiopharmaceuticals are shown in Figures 16A–17A for U(t) = 1.0/0.5 ml min^{-1}, V_0 = 100 ml and T_1 = 60 min.

A comparison of the absorbed dose per unit administered activity at the bladder wall inner surface is contained in Table 5 for all models. Values are given for the initial void time which results in minimum dose (T_{1m}) for the initial bladder volume specified.

Table 6 provides the electron absorbed dose in the bladder wall (x_{50} and x_{90}) as calculated for the new model at the optimal first void time (T_{1m} as determined by the surface dose evaluation) for three different V_0 and U(t) values.

TABLE 4
Percentile Distance Within Which 50% (x_{50}) and 90% (x_{90}) of the Electron Energy Is Absorbed in the Bladder Wall (Soft Tissue) (*11*)*. (For comparison, the bladder wall thickness as a function of bladder-contents volume for the new model is provided below)

Radionuclide	x_{50} (cm)	x_{90} (cm)
^{18}F	0.038	0.0939
^{99m}Tc	0.0090	0.0148
^{123}I	0.0093	0.0166
^{124}I	0.182	0.431
^{131}I	0.0285	0.0822

* Values for ^{18}F, ^{124}I and ^{131}I are taken directly from reference 11. Values for ^{99m}Tc and ^{123}I are derived from results of reference 11 for monoenergetic electrons and known abundances of the emissions of these nuclides.

	Bladder-contents volume (cm^3)				
	50	100	300	500	800
Bladder wall thickness (cm)†	0.55	0.38	0.20	0.14	0.11

† Spherical-shell bladder-wall volume remains constant at 45 cm^3.

DISCUSSION AND CONCLUSIONS

The published models for urinary bladder wall dose have provided a useful framework for development of the new comprehensive dynamic bladder model. Provisions for an expanding/contracting bladder with variable initial volume, first void time, and rate of urine entry along with options for residual volume allow a more detailed understanding of bladder wall dosimetry than offered by the standard MIRD model.*

Inspection of the comparative results in Table 5 indicates that generally the highest dose to the bladder wall surface is given by the model of Chen et al. (D) with values averaging approximately 44% higher at V_0 = 200 ml than those of the previous MIRD model (A) (range 0 to 82% higher). The Snyder/Ford (B) and Diffey/Hilson (C) models provide roughly identical results for dose to the bladder wall and optimal time for the first void with dose values averaging approximately 26% to 31% higher respectively than for Model A (range −7% to +71% inclusive for Models B and C). The new model provides dose values comparable but generally somewhat lower than those of the original MIRD approach with the exception of [^{18}F] FDG, ^{131}I(NaI) and OIH. The average dose values are approximately 9% lower (range −41% to +25%).

* Computer code for the new dynamic urinary bladder model has been installed at the Radiopharmaceutical Internal Dose Information Center, Oak Ridge Associated Universities, Oak Ridge, TN. Human dose-estimate calculations are performed as a national service at this facility.

TABLE 5
A Comparison of the Absorbed Dose per Unit Administered Activity at the Bladder Wall Surface for the Various Models

	Initial volume	Bladder Model									
		Model A MIRD (3)		Model B Snyder/Ford (7)		Model C Diffey/Hilson (13)		Model D Chen et al. (2)		This Report (1.0/05 ml/min)	
	V_0 ml	T_{1m}* (min)	$\bar{D}/A_0$ (mGy/MBq)	T_{1m}* (min)	$\bar{D}/A_0$ (mGy/MBq)	T_{1m}* (min)	$\bar{D}/A_0$ (mGy/MBq)	T_{1m}* (min)	$\bar{D}/A_0$ (mGy/MBq)	T_{1m}* (min)	$\bar{D}/A_0$ (mGy/MBq)
[^{18}F]FDG	10	—	—	40	0.22	40	0.13	40	0.25	40	0.25
	200	40	0.059	60	0.081	80	0.065	60–80	0.084	80	0.065
	500	—	—	0	0.049	100	0.038	80–120	0.038	100	0.035
^{99m}Tc-DTPA	10	—	—	80	0.076	80	0.076	80	0.084	80	0.059
	200	60	0.030	120	0.049	140	0.046	140	0.051	180+	0.030
	500	—	—	180+	0.035	180+	0.032	160–180+	0.038	180+	0.021
[^{99m}Tc]pertechnetate	10	—	—	40–60	0.024	40–60	0.024	40–60	0.026	60–80	0.019
	200	60–80	0.012	100–160	0.016	140–160	0.015	120–160	0.016	180+	0.0095
	500	—	—	180+	0.011	180+	0.011	180+	0.012	180+	0.0070
^{99m}Tc-HEDP	10	—	—	60–100	0.051	60–100	0.051	40–120	0.057	80	0.041
	200	100	0.038	120–140	0.035	100–180+	0.035	120–180+	0.038	180+	0.024
	500	—	—	180+	0.027	180+	0.027	140–180+	0.030	180+	0.019
^{99m}Tc-glucoheptonate	10	—	—	40–60	0.068	40–60	0.070	40–60	0.076	60	0.057
	200	40–80	0.030	80–100	0.038	60–140	0.038	100–120	0.041	120	0.023
	500	—	—	160–180+	0.030	120	0.026	80–160	0.030	180+	0.015
^{99m}Tc-RBCs	10	—	—	60–160	0.0035	60–180+	0.0035	60–160	0.0038	140–160	0.0028
	200	80	0.0021	160–180+	0.00027	180+	0.0026	100–180+	0.0030	180+	0.0019
	500	—	—	180+	0.0023	180+	0.0022	180+	0.0025	180+	0.0018
^{99m}Tc-MAG3	10	—	—	20	0.11	20	0.12	20	0.12	40	0.12
	200	20	0.032	40	0.046	40–60	0.046	40	0.049	60	0.027
	500	—	—	60	0.030	40–80	0.030	60	0.032	80	0.014
^{131}I(NaI)	10	—	—	180+	0.81	180+	0.81	180+	0.86	140	0.76
	200	180+	0.46	180+	0.78	180+	0.78	180+	0.84	180+	0.64
	500	—	—	180+	0.76	180+	0.76	180+	0.81	180+	0.60
[^{131}I]OIH	10	—	—	20	1.03	20	1.03	20	1.16	40	1.60
	200	20–40	0.30	60	0.35	60	0.35	40–60	0.43	60	0.37
	500	—	—	60	0.22	60	0.22	60–80	0.27	80	0.19
[^{124}I]OIH	10	—	—	20	1.22	20	1.27	20	1.43	40	1.62
	200	20–40	0.43	40–60	0.49	40–60	0.49	40	0.57	60	0.37
	500	—	—	60	0.30	60	0.30	40–80	0.41	80	0.20
[^{123}I]OIH	10	—	—	20	0.18	20	0.18	20	0.25	40	0.22
	200	20–40	0.065	40	0.073	40–60	0.070	40	0.10	60	0.05
	500	—	—	60	0.046	60	0.043	60	0.068	80	0.027

* T_{1m} represents the initial (first) void time which provides minimum dose for the given initial volume V_0.
Explanatory points for T_{1m}: (a) a value of 40–80 indicates that the same minimum dose value as shown in the adjacent column was obtained for initial void times of 40, 60, 80 min; (b) a value of 100–180+ indicates that the same minimum dose value was obtained for initial void times from 100 to 180 min; and (c) a value of 180+ indicates that the minimum dose value calculated occurred at the 180-min void point and is that value shown in the adjacent column. The actual dose minimum may occur at longer initial void times.

Each radiopharmaceutical has a unique time-activity curve for bladder activity. This variability, when combined with a nonuniform voiding schedule and analyzed in terms of initial bladder volume and first bladder voiding time, may be used to predict the optimum first voiding time and most desirable hydration states. Large initial bladder volumes and higher rates of urine flow into the bladder result in lower total bladder wall dose. Earlier first voiding times do not necessarily result in lower total bladder wall doses. In fact, the results indicate that the optimum first voiding time is from 40 min to 3 hr after injection, depending on the radiopharmaceutical. The optimum first void time (T_{1m}) does not appear to be sensitive to the model used.

Electron dose decreases rapidly with increasing depth in the wall at a gradient determined by the electron energy spectrum. For most nuclear medicine radiopharmaceuticals, 90% of the energy is deposited within 0.1 cm of the bladder interior wall surface. An exception is ^{124}I, potentially a contaminant in ^{123}I. Other high-energy beta emitters such as ^{90}Y or other therapy agents, however, might contribute a significant dose deep into the bladder wall and possibly even into surrounding tissues.

TABLE 6
Electron Depth-Dose per Unit Administered Activity to the Bladder Wall at x_{50} and x_{90}

Radiopharmaceutical	Initial volume (ml)	Bladder fill rate (ml/min)	Absorbed dose/Administered activity rad/mCi at x_{50}	rad/mCi at x_{90}	mGy/MBq at x_{50}	mGy/MBq at x_{90}
[^{18}F]FDG	10	0.5	0.32	0.027	0.086	0.0073
	10	1.0	0.18	0.015	0.049	0.0041
	10	1.5	0.12	0.11	0.32	0.0030
	200	0.5	0.073	0.062	0.020	0.0017
	200	1.0	0.050	0.0043	0.014	0.0012
	200	1.5	0.040	0.0034	0.011	0.00092
	500	0.5	0.039	0.0033	0.011	0.00089
	500	1.0	0.027	0.0023	0.0073	0.00062
	500	1.5	0.023	0.0019	0.0062	0.00051
^{99m}Tc-DTPA	10	0.5	0.061	0.0048	0.016	0.0013
	10	1.0	0.032	0.0025	0.0086	0.00068
	10	1.5	0.022	0.0017	0.0059	0.00046
	200	0.5	0.033	0.0026	0.0089	0.00070
	200	1.0	0.018	0.0014	0.0049	0.00038
	200	1.5	0.013	0.0010	0.0035	0.00027
	500	0.5	0.032	0.0025	0.0086	0.00068
	500	1.0	0.017	0.0013	0.0046	0.00035
	500	1.5	0.012	0.00089	0.0032	0.00024
[^{99m}Tc]pertechnetate	10	0.5	0.019	0.0015	0.0051	0.00041
	10	1.0	0.010	0.00078	0.0027	0.00021
	10	1.0	0.0068	0.00053	0.0018	0.00014
	200	0.5	0.011	0.00086	0.0030	0.00023
	200	1.0	0.0060	0.00047	0.0016	0.00013
	200	1.5	0.0043	0.00033	0.0012	0.00008
	500	0.5	0.0062	0.00048	0.0017	0.00013
	500	1.0	0.0037	0.00029	0.0010	0.00007
	500	1.5	0.0028	0.00022	0.00076	0.00005
^{99m}Tc-HEDP	10	0.5	0.044	0.0034	0.012	0.00092
	10	1.0	0.023	0.0018	0.0062	0.00049
	10	1.5	0.016	0.0012	0.0043	0.00032
	200	0.5	0.028	0.0022	0.0076	0.00059
	200	1.0	0.015	0.0012	0.0041	0.00032
	200	1.5	0.011	0.00085	0.0030	0.00023
	500	0.5	0.018	0.0014	0.0049	0.00038
	500	1.0	0.011	0.00083	0.0030	0.00022
	500	1.5	0.0078	0.00061	0.0021	0.00016
^{99m}Tc-glucoheptonate	10	0.5	0.057	0.0045	0.015	0.0012
	10	1.0	0.030	0.0023	0.0081	0.00062
	10	1.5	0.021	0.0016	0.0057	0.00043
	200	0.5	0.023	0.0018	0.0062	0.00049
	200	1.0	0.013	0.0010	0.0035	0.00027
	200	1.5	0.0099	0.00077	0.0027	0.00021
	500	0.5	0.018	0.0014	0.0049	0.0038
	500	1.0	0.010	0.00078	0.0027	0.00021
	500	1.5	0.0073	0.00057	0.0020	0.00015

TABLE 6 (Continued)

Radiopharmaceutical	Initial volume (ml)	Bladder fill rate (ml/min)	Absorbed dose/Administered activity rad/mCi		mGy/MBq	
			at x_{50}	at x_{90}	at x_{50}	at x_{90}
^{99m}Tc-MAG3	10	0.5	0.12	0.0096	0.032	0.0026
	10	1.0	0.066	0.0052	0.018	0.0014
	10	1.5	0.046	0.0035	0.012	0.00095
	200	0.5	0.025	0.0020	0.0068	0.00054
	200	1.0	0.016	0.0012	0.0043	0.00032
	200	1.5	0.012	0.00097	0.0032	0.00026
	500	0.5	0.014	0.0011	0.0038	0.00030
	500	1.0	0.0087	0.00068	0.0024	0.00018
	500	1.5	0.0069	0.00054	0.0019	0.00015
[^{123}I]OIH	10	0.5	0.25	0.022	0.068	0.0059
	10	1.0	0.13	0.012	0.035	0.0032
	10	1.5	0.091	0.0081	0.025	0.0022
	200	0.5	0.052	0.0047	0.014	0.0013
	200	1.0	0.033	0.0029	0.0089	0.00078
	200	1.5	0.025	0.0023	0.0068	0.00062
	500	0.5	0.027	0.0024	0.0073	0.00065
	500	1.0	0.017	0.0015	0.0046	0.00041
	500	1.5	0.014	0.0012	0.0038	0.00032
[^{124}I]OIH	10	0.5	1.8	0.078	0.49	0.021
	10	1.0	0.94	0.042	0.25	0.011
	10	1.5	0.64	0.029	0.17	0.0078
	200	0.5	0.35	0.016	0.095	0.043
	200	1.0	0.23	0.010	0.062	0.0027
	200	1.5	0.18	0.0082	0.049	0.0022
	500	0.5	0.20	0.0092	0.054	0.0025
	500	1.0	0.13	0.0058	0.035	0.0016
	500	1.5	0.10	0.0047	0.027	0.0013
[^{131}I]OIH	10	0.5	2.5	0.20	0.67	0.054
	10	1.0	1.3	0.11	0.35	0.030
	10	1.5	0.90	0.072	0.24	0.019
	200	0.5	0.54	0.043	0.15	0.012
	200	1.0	0.33	0.027	0.089	0.0073
	200	1.5	0.26	0.021	0.070	0.0057
	500	0.5	0.29	0.023	0.078	0.0062
	500	1.0	0.18	0.014	0.049	0.0038
	500	1.5	0.14	0.011	0.038	0.0030
^{131}I(NaI)	10	0.5	1.4	0.11	0.38	0.030
	10	1.0	0.69	0.055	0.19	0.015
	10	1.5	0.46	0.037	0.12	0.010
	200	0.5	1.1	0.089	0.30	0.024
	200	1.0	0.58	0.046	0.16	0.012
	200	1.5	0.40	0.032	0.11	0.0086
	500	0.5	1.1	0.085	0.30	0.023
	500	1.0	0.55	0.044	0.15	0.012
	500	1.5	0.38	0.030	0.10	0.0081

APPENDIX

DTPA calculations for the various models are shown in Figures A1–A4 and Tables A1–A4. Calculations for the new model are shown Figures A5–A17 and Tables A5–A15.

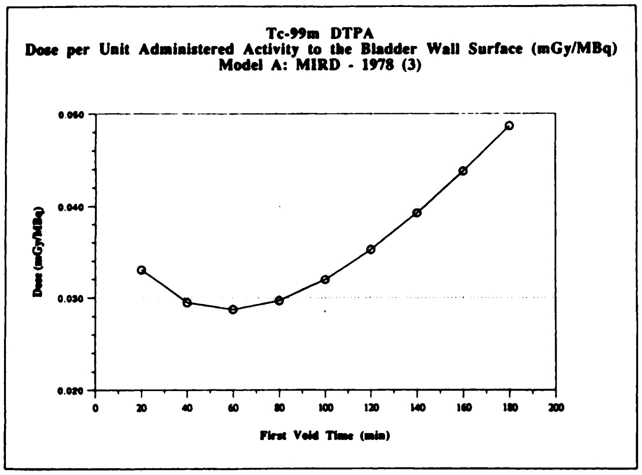

FIGURE A1. Model A (MIRD (*3*)), ^{99m}Tc-DTPA. Dose per unit administered activity to the urinary bladder wall surface as a function of first void time (T_1) (Constant volume). Urine entry rate (U(t)): 1.25 ml/min (constant at all times). Voiding schedule: Every 3 hr after initial void, 10 voids total included in the dose calculation, no nighttime gap.

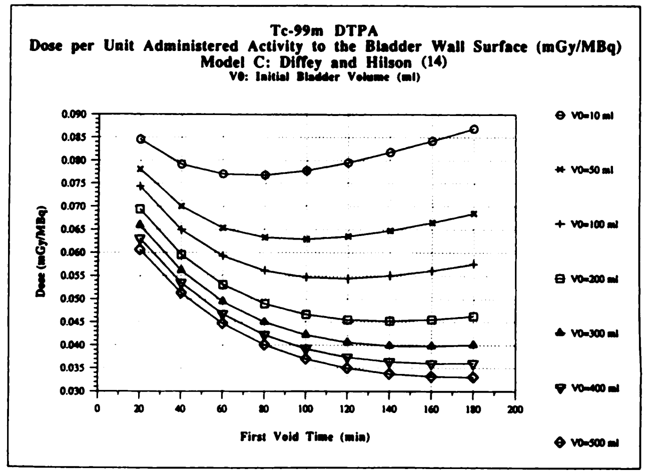

FIGURE A3. Model C (Diffey and Hilson (*14*)), ^{99m}Tc-DTPA. Dose per unit administered activity to the urinary bladder wall surface as a function of first void time (T_1) for various values of initial bladder contents (V_0). Urine entry rate (U(t)) and voiding schedule as for Figure A1.

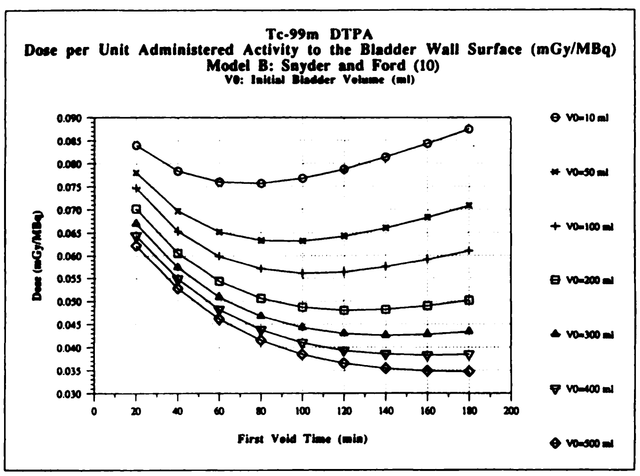

FIGURE A2. Model B (Snyder and Ford (*10*)), ^{99m}Tc-DTPA. Dose per unit administered activity to the urinary bladder wall surface as a function of first void time (T_1) for various values of initial bladder contents (V_0). Urine entry rate U(t) and voiding schedule as for Figure A1.

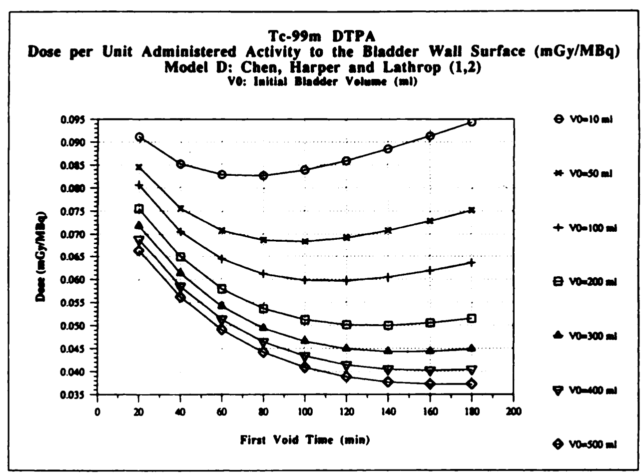

FIGURE A4. Model D (Chen, Harper and Lathrop (*1,2*)), ^{99m}Tc-DTPA. Dose per unit administered activity to the urinary bladder wall surface as a function of first void time (T_1) for various values of initial bladder contents (V_0). Urine entry rate (U(t)) and voiding schedule as for Figure A1.

TABLE A1

Tc-99m DTPA
Dose per Unit Administered Activity to the Bladder Wall Surface (mGy/MBq)
Model A: MIRD - 1978 (3)

Dose per administered activity (mGy/MBq)

First Void Time (min)

20	40	60	80	100	120	140	160	180
0.0331	0.0295	0.0288	0.0297	0.0319	0.0352	0.0392	0.0438	0.0487

TABLE A2

Tc-99m DTPA
Dose per Unit Administered Activity to the Bladder Wall Surface (mGy/MBq)
Model B: Snyder and Ford (10)
V0: Initial Bladder Volume (ml)

Dose per administered activity (mGy/MBq)

First Void Time (min)

V0 (ml)	20	40	60	80	100	120	140	160	180
10	0.0840	0.0784	0.0760	0.0757	0.0768	0.0787	0.0814	0.0843	0.0875
50	0.0781	0.0697	0.0652	0.0633	0.0631	0.0642	0.0660	0.0683	0.0708
100	0.0746	0.0653	0.0598	0.0570	0.0560	0.0563	0.0574	0.0590	0.0610
200	0.0702	0.0605	0.0543	0.0506	0.0487	0.0480	0.0482	0.0490	0.0502
300	0.0670	0.0573	0.0508	0.0467	0.0442	0.0430	0.0426	0.0428	0.0434
400	0.0644	0.0548	0.0482	0.0438	0.0410	0.0393	0.0385	0.0383	0.0385
500	0.0621	0.0527	0.0461	0.0415	0.0384	0.0365	0.0354	0.0348	0.0347

TABLE A3

Tc-99m DTPA
Dose per Unit Administered Activity to the Bladder Wall Surface (mGy/MBq)
Model C: Diffey and Hilson (14)
V0: Initial Bladder Volume (ml)

Dose per administered activity (mGy/MBq)

First Void Time (min)

V0 (ml)	20	40	60	80	100	120	140	160
10	0.0845	0.0791	0.0770	0.0768	0.0778	0.0795	0.0818	0.0843
50	0.0781	0.0700	0.0653	0.0633	0.0628	0.0635	0.0648	0.0665
100	0.0743	0.0649	0.0592	0.0561	0.0547	0.0545	0.0550	0.0561
200	0.0694	0.0595	0.0531	0.0490	0.0466	0.0455	0.0452	0.0455
300	0.0658	0.0561	0.0494	0.0450	0.0422	0.0406	0.0399	0.0398
400	0.0630	0.0534	0.0467	0.0422	0.0392	0.0374	0.0364	0.0359
500	0.0606	0.0512	0.0447	0.0401	0.0370	0.0349	0.0338	0.0332

TABLE A4

Tc-99m DTPA
Dose per Unit Administered Activity to the Bladder Wall Surface (mGy/MBq)
Model D: Chen, Harper and Lathrop (1,2)
V0: Initial Bladder Volume (ml)

Dose per administerd activity (mGy/MBq)

First Void Time (min)

V0 (ml)	20	40	60	80	100	120	140	160	180
10	0.0911	0.0853	0.0829	0.0827	0.0839	0.0859	0.0885	0.0913	0.0943
50	0.0845	0.0755	0.0707	0.0687	0.0683	0.0692	0.0707	0.0728	0.0751
100	0.0806	0.0705	0.0644	0.0611	0.0598	0.0597	0.0605	0.0618	0.0636
200	0.0755	0.0649	0.0580	0.0537	0.0512	0.0501	0.0500	0.0505	0.0515
300	0.0718	0.0612	0.0541	0.0494	0.0465	0.0449	0.0443	0.0443	0.0448
400	0.0688	0.0585	0.0513	0.0464	0.0433	0.0414	0.0405	0.0402	0.0404
500	0.0663	0.0562	0.0491	0.0441	0.0409	0.0388	0.0377	0.0372	0.0372

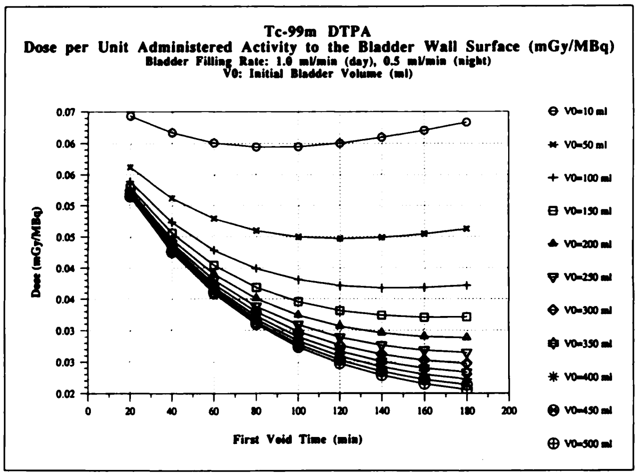

FIGURE A5. New model for ^{99m}Tc-DTPA. Dose per unit administered activity to the urinary bladder wall surface.

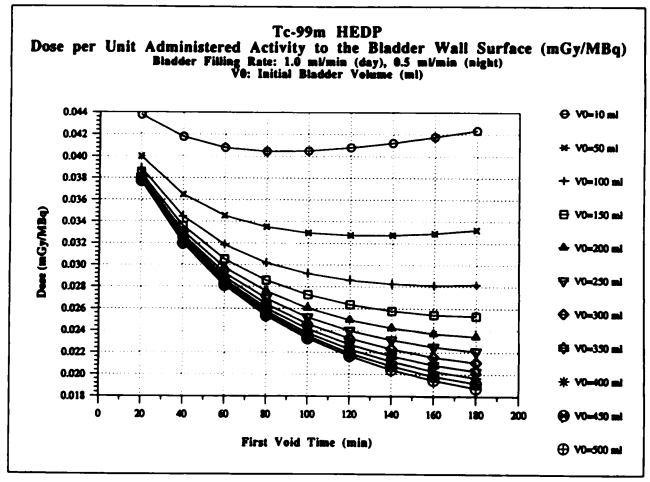

FIGURE A8. New model for ^{99m}Tc-HEDP. Dose per unit administered activity to the urinary bladder wall surface.

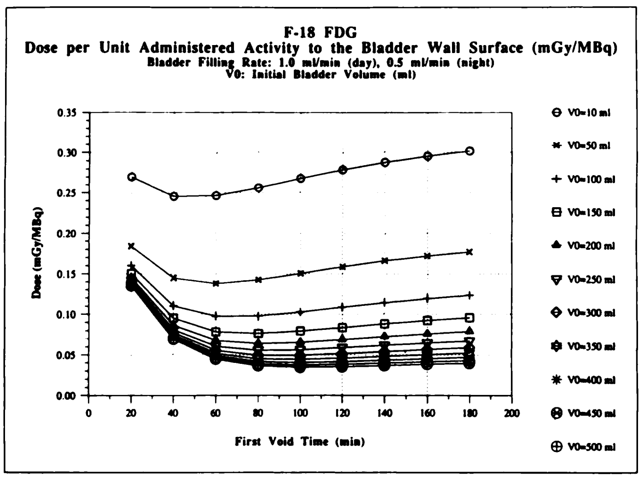

FIGURE A6. New model for [^{18}F]FDG. Dose per unit administered activity to the urinary bladder wall surface.

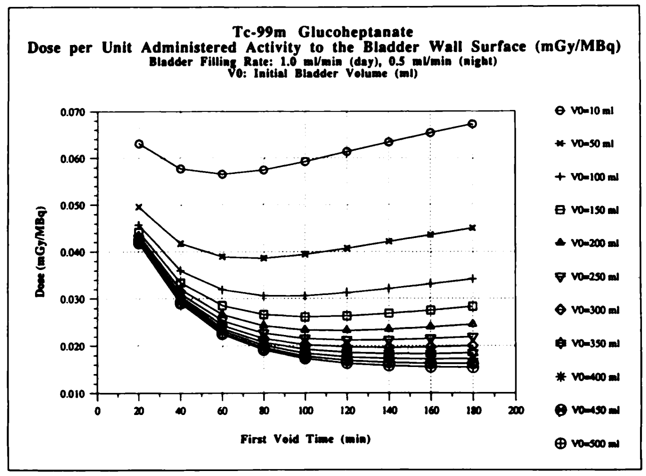

FIGURE A9. New model for ^{99m}Tc-glucoheptonate. Dose per unit administered activity to the urinary bladder wall surface.

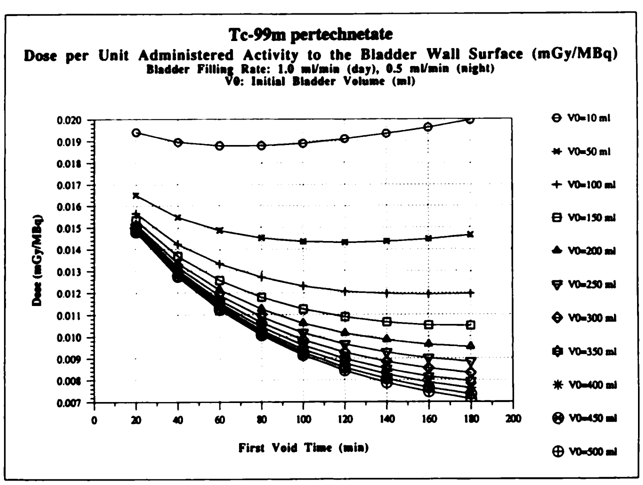

FIGURE A7. New model for [^{99m}Tc]pertechnetate. Dose per unit administered activity to the urinary bladder wall surface.

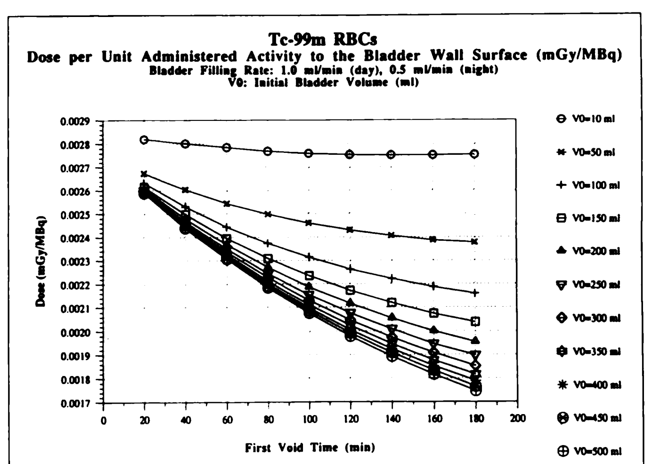

FIGURE A10. New model for ^{99m}Tc-RBCs. Dose per unit administered activity to the urinary bladder wall surface.

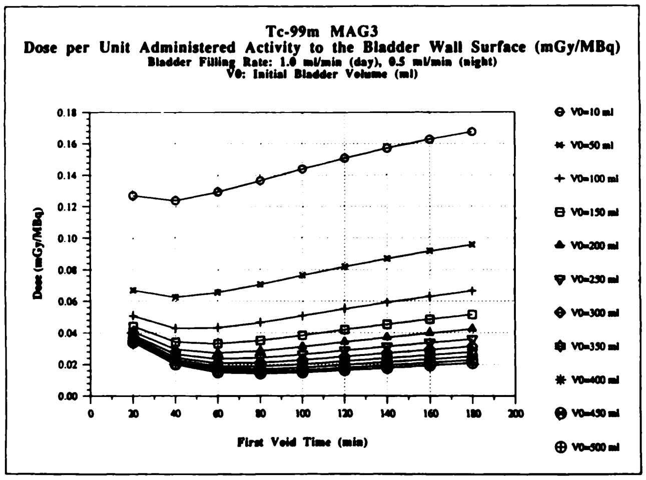

FIGURE A11. New model for ^{99m}Tc-MAG3. Dose per unit administered activity to the urinary bladder wall surface.

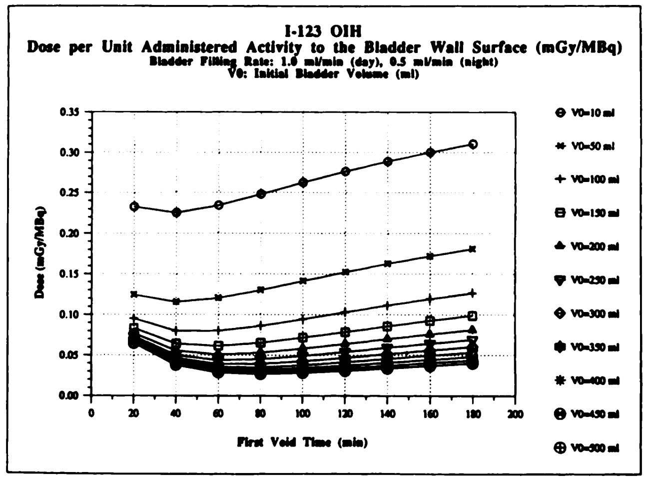

FIGURE A14. New model for [^{123}I]OIH. Dose per unit administered activity to the urinary bladder wall surface.

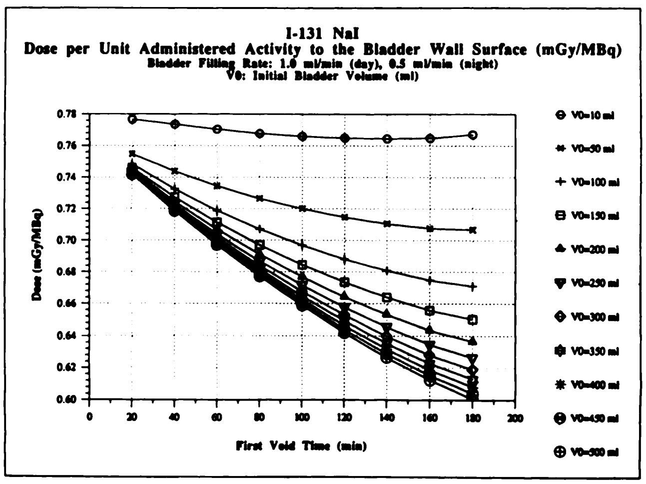

FIGURE A12. New model for ^{131}I(NaI). Dose per unit administered activity to the urinary bladder wall surface.

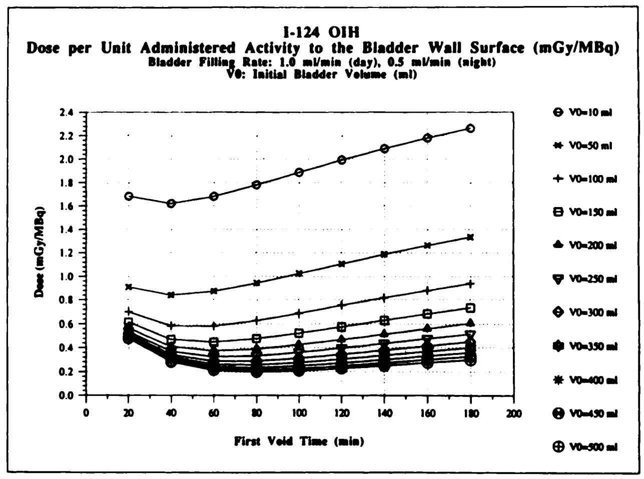

FIGURE A15. New model for [^{124}I]OIH. Dose per unit administered activity to the urinary bladder wall surface.

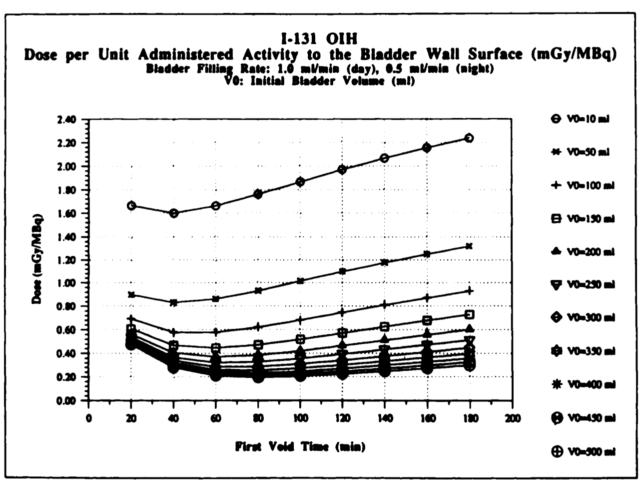

FIGURE A13. New model for [^{131}I]OIH. Dose per unit administered activity to the urinary bladder wall surface.

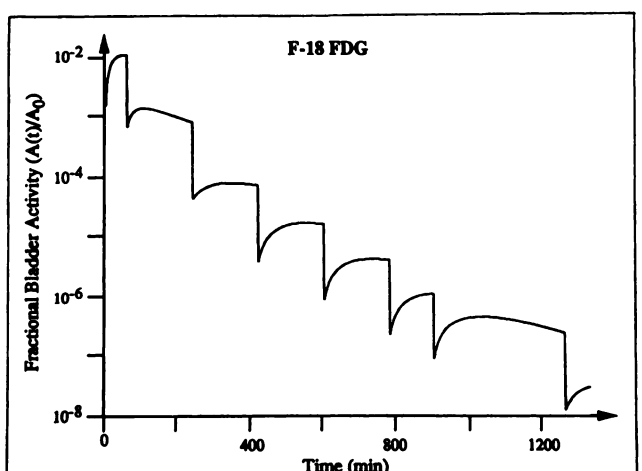

FIGURE A16. Fluorine-18-FDG. Fractional bladder activity ($A(t)/A_0$ from Equation 2) as a function of time. V_0 = 100 ml, T_1 = 60 min, U(t) = 1.0/0.5 ml min^{-1} (day/night).

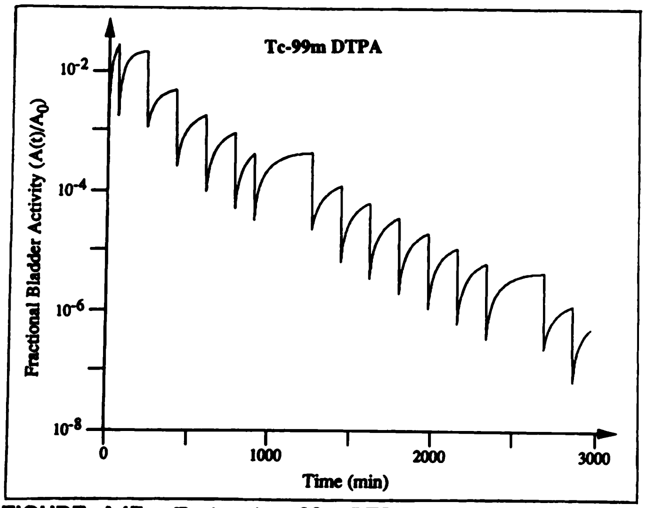

FIGURE A17. Technetium-99m-DTPA. Fractional bladder activity ($A(t)/A_0$ from Equation 2) as a function of time. $V_0 = 100$ ml, $T_1 = 60$ min, $U(t) = 1.0/0.5$ ml min^{-1} (day/night).

TABLE A5

Tc-99m DTPA
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.12	0.064	0.044	0.12	0.060	0.041	0.11	0.060	0.041	0.12	0.063	0.043
50	0.10	0.056	0.039	0.086	0.048	0.034	0.077	0.045	0.032	0.077	0.046	0.034
100	0.100	0.054	0.037	0.077	0.043	0.030	0.062	0.037	0.027	0.059	0.037	0.028
200	0.097	0.052	0.036	0.070	0.039	0.027	0.051	0.031	0.023	0.045	0.029	0.022
500	0.096	0.051	0.035	0.066	0.036	0.025	0.043	0.025	0.018	0.033	0.021	0.016

TABLE A6

F-18 FDG
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.49	0.27	0.19	0.44	0.25	0.17	0.48	0.28	0.20	0.51	0.30	0.22
50	0.30	0.18	0.13	0.21	0.14	0.11	0.23	0.16	0.12	0.25	0.18	0.14
100	0.26	0.16	0.12	0.14	0.097	0.077	0.14	0.11	0.089	0.16	0.12	0.10
200	0.24	0.15	0.11	0.098	0.068	0.054	0.087	0.069	0.059	0.097	0.079	0.068
500	0.23	0.14	0.098	0.068	0.045	0.035	0.044	0.035	0.031	0.046	0.040	0.036

TABLE A7

Tc-99m pertechnetate
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.037	0.019	0.013	0.036	0.019	0.013	0.036	0.019	0.013	0.037	0.020	0.014
50	0.031	0.016	0.011	0.027	0.015	0.010	0.025	0.014	0.010	0.025	0.015	0.011
100	0.029	0.016	0.011	0.024	0.013	0.0094	0.020	0.012	0.0088	0.019	0.012	0.0089
200	0.028	0.015	0.010	0.022	0.012	0.0085	0.017	0.010	0.0074	0.015	0.0095	0.0072
500	0.028	0.015	0.010	0.021	0.011	0.0078	0.015	0.0084	0.0061	0.012	0.0071	0.0054

TABLE A8

Tc-99m HEDP
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.084	0.044	0.030	0.079	0.041	0.028	0.078	0.041	0.028	0.080	0.042	0.029
50	0.075	0.040	0.027	0.063	0.035	0.024	0.058	0.033	0.023	0.057	0.033	0.024
100	0.073	0.039	0.027	0.058	0.032	0.022	0.050	0.029	0.020	0.047	0.028	0.021
200	0.072	0.038	0.026	0.055	0.030	0.021	0.044	0.025	0.018	0.039	0.023	0.017
500	0.071	0.038	0.026	0.052	0.028	0.019	0.039	0.022	0.015	0.032	0.019	0.014

TABLE A9

Tc-99m Glucoheptanate
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.12	0.063	0.043	0.11	0.057	0.039	0.11	0.061	0.043	0.12	0.067	0.047
50	0.089	0.050	0.035	0.067	0.039	0.028	0.066	0.041	0.030	0.071	0.045	0.034
100	0.082	0.046	0.032	0.054	0.032	0.023	0.049	0.031	0.024	0.051	0.034	0.027
200	0.078	0.043	0.030	0.046	0.027	0.019	0.036	0.023	0.018	0.036	0.025	0.020
500	0.076	0.042	0.029	0.040	0.023	0.016	0.026	0.016	0.012	0.023	0.015	0.012

TABLE A10

Tc-99m RBCs
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.0054	0.0028	0.0019	0.0054	0.0028	0.0019	0.0053	0.0028	0.0019	0.0053	0.0028	0.0019
50	0.0051	0.0027	0.0018	0.0048	0.0025	0.0017	0.0045	0.0024	0.0017	0.0043	0.0024	0.0017
100	0.0050	0.0026	0.0018	0.0046	0.0024	0.0017	0.0042	0.0023	0.0016	0.0039	0.0022	0.0015
200	0.0050	0.0026	0.0018	0.0045	0.0024	0.0016	0.0039	0.0021	0.0015	0.0035	0.0020	0.0014
500	0.0049	0.0026	0.0018	0.0044	0.0023	0.0016	0.0037	0.0020	0.0014	0.0032	0.0017	0.0012

TABLE A11

Tc-99m MAG3
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.24	0.13	0.086	0.23	0.13	0.092	0.26	0.15	0.11	0.28	0.17	0.12
50	0.11	0.067	0.049	0.099	0.065	0.051	0.12	0.082	0.064	0.14	0.096	0.075
100	0.083	0.051	0.037	0.062	0.043	0.035	0.074	0.055	0.045	0.090	0.066	0.054
200	0.068	0.041	0.030	0.038	0.027	0.022	0.043	0.034	0.029	0.053	0.042	0.036
500	0.058	0.034	0.025	0.022	0.015	0.012	0.019	0.016	0.015	0.024	0.021	0.019

TABLE A12

I-131 NaI
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	1.5	0.78	0.52	1.5	0.77	0.52	1.5	0.76	0.51	1.5	0.77	0.51
50	1.5	0.75	0.51	1.4	0.73	0.49	1.4	0.71	0.48	1.4	0.71	0.48
100	1.5	0.75	0.50	1.4	0.72	0.48	1.3	0.69	0.47	1.3	0.67	0.46
200	1.5	0.74	0.50	1.4	0.71	0.48	1.3	0.66	0.45	1.2	0.64	0.44
500	1.5	0.74	0.50	1.4	0.70	0.47	1.3	0.64	0.43	1.2	0.60	0.41

TABLE A13

I-131 OIH
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	3.2	1.7	1.1	3.0	1.7	1.2	3.5	2.0	1.4	3.9	2.2	1.6
50	1.5	0.90	0.65	1.4	0.86	0.66	1.7	1.1	0.85	2.0	1.3	1.0
100	1.2	0.69	0.50	0.86	0.58	0.46	1.0	0.75	0.60	1.3	0.93	0.75
200	0.97	0.56	0.41	0.54	0.37	0.30	0.61	0.46	0.39	0.77	0.60	0.51
500	0.84	0.48	0.34	0.31	0.21	0.17	0.28	0.22	0.20	0.35	0.30	0.27

TABLE A14

I-123 OIH
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	0.45	0.23	0.16	0.42	0.23	0.17	0.48	0.28	0.20	0.53	0.31	0.22
50	0.21	0.12	0.091	0.19	0.12	0.092	0.23	0.15	0.12	0.27	0.18	0.14
100	0.16	0.095	0.070	0.12	0.080	0.064	0.14	0.10	0.084	0.17	0.13	0.10
200	0.13	0.077	0.056	0.073	0.051	0.042	0.082	0.064	0.055	0.10	0.081	0.069
500	0.11	0.065	0.046	0.042	0.029	0.023	0.037	0.031	0.027	0.047	0.040	0.036

TABLE A15

I-124 OIH
Dose per Unit Administered Activity to the Bladder Wall Surface
Dose (mGy/MBq)

V0: Initial Bladder Volume (ml)

Bladder Filling Rate (ml/min):
(a) 0.5 / 0.25 (day / night) (b) 1.0 / 0.50 (day / night) (c) 1.5 / 0.75 (day / night)

V0 (ml)	First Void Time (min)											
	20			60			120			180		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
10	3.3	1.7	1.1	3.1	1.7	1.2	3.5	2.0	1.4	3.9	2.3	1.6
50	1.6	0.91	0.66	1.4	0.87	0.66	1.7	1.1	0.86	2.0	1.3	1.0
100	1.2	0.70	0.51	0.87	0.58	0.46	1.1	0.75	0.61	1.3	0.94	0.76
200	0.98	0.57	0.41	0.54	0.37	0.30	0.61	0.47	0.40	0.78	0.61	0.51
500	0.84	0.48	0.34	0.32	0.21	0.17	0.28	0.23	0.20	0.36	0.30	0.27

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