Estimates of Dose to the Bladder during Direct Radionuclide Cystography: Concise Communication

Panayiotis Dimitriou, Andreas Fretzayas, Polyxeni Nicolaidou, Fotini Gritzali, Angeliki Kasfiki, and Themistokles Karpathios

Department of Pathologic Physiology and First Pediatric Clinic, University of Athens, Athens, Greece

We estimate the absorbed dose to the bladder walls, D_b, due to [^{99m}Tc]pertechnetate direct radionuclide cystography, with due consideration to the dynamic nature of the examination. Our analytical method resulted in D_b values expressed as functions of the bladder filling time. These values are compared with published data based on a static bladder model. It is shown that the D_b value depends strongly on the protocol under which the examination is carried out. It is also shown that the normal saline flow rate and the time of the administration of the radioactive material can be adjusted so that the radiation burden may be greatly reduced.

J Nucl Med 25: 792–795, 1984

Direct radionuclide cystography (DRC) with [^{99m}Tc]pertechnetate has been found useful in studying patients with vesicoureteral reflux (VUR). This method has gained wide acceptance in pediatrics, its main advantage being the low dose to the patient (*1–3*). This dose was estimated by Conway et al. (*3*), who considered the bladder as a static spherical volume. It has been established that the dose to the bladder wall per photon varies by almost an order of magnitude as the bladder fills, being largest for a nearly empty bladder (*4*). Taking into account the dynamic nature of the DRC study, we applied a different method for the evaluation of the bladder dose (D_b). Our method is based on the Diffey and Hilson model (*5*), proposed for the evaluation of the dose to the walls of the bladder from an i.v. injection of Tc-99m DTPA.

METHODS

In the model presented by Diffey and Hilson (*5*), it is assumed that i.v. Tc-99 DTPA is cleared in a single-exponential manner into a spherical bladder by glomerular filtration, and that the urinary flow into the bladder is constant. The volume of the bladder then increases linearly with time until some elapsed time when, it is assumed, the bladder empties instantaneously to zero volume. For the purposes of our study this model was slightly modified in order to correspond to the parameters of DRC. During DRC the urinary flow through the ureters is negligible compared with that of the normal saline entering through the catheter, so we may accept that increase of bladder volume during the bladder-filling phase is due to the saline flow alone. Furthermore, we observe empirically that the flow rate to the bladder from a bottle of 1000 ml normal saline solution placed 100 cm above the bladder (*6*) may be considered as practically constant, ranging from 20–50 ml/min in various runs. After the establishment of the saline flow, it is assumed that the bladder volume starts to increase linearly with time, from zero up to the bladder tolerance volume (V_t). The pertechnetate dose (300–500 μCi Tc-99m) is administered through the catheter as a bolus, at any time T_a after T_0, the time of entrance of the normal saline into the bladder. All the radioactivity remains within the bladder during the filling phase. At micturition, the bladder volume returns back to zero. A brief

Received Nov. 3, 1983; revision accepted Apr. 11, 1984.

For reprints contact: P. Dimitriou, MD, Dept. of Pathologic Physiology, School of Medicine, National University of Athens, Goudi, Athens 11527, Greece.

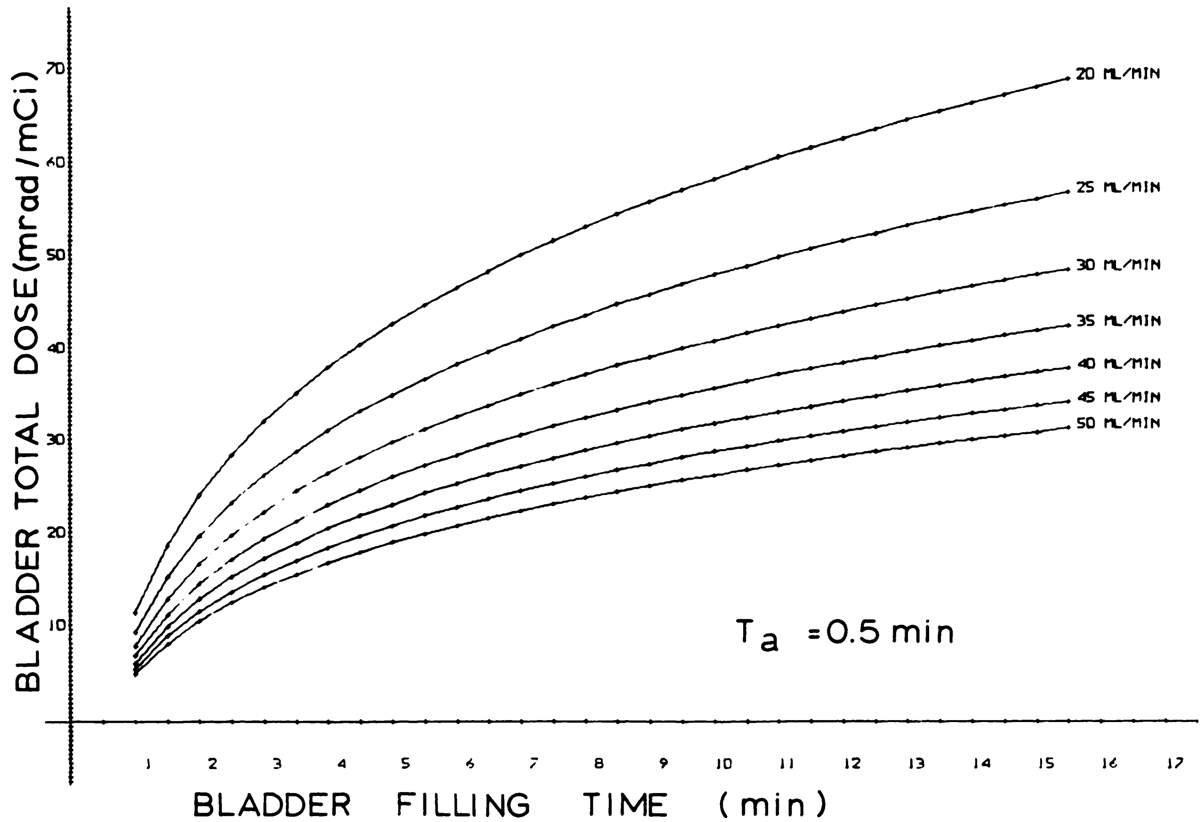

FIG. 1. Variation of total absorbed dose with bladder filling time for different saline flow rates, F_s, and for delay T_a = 0.5 min between start of saline flow and delivery of radiotracer into bladder.

description of Diffey and Hilson model (*5*), along with the modifications made in the present study, is included in the Appendix. The units of the Tc-99m physical constants were converted so that the bladder filling time was expressed in minutes and the bladder dose in mrad/mCi, respectively. Calculations were carried out on a CDC-3300 computer. The total dose to the bladder walls (from photons plus conversion and Auger electrons) was evaluated as a function of the bladder filling time, T_t, for different saline flow rates, F_s, and different administration times, T_a. Between the time T_t and micturition at T_m, there is a small delay, Δt, which is usually less than 1 min. The dose to the bladder walls during the interval Δt may be estimated using Equations (7) and (9) in the Appendix.

Calculations of the dose rate to the gonads were also carried out according to the concept of the absorbed fraction (*7*), using the mathematical phantom of the standard man and the energy-dependent absorbed fractions for the organs of this phantom (*8*). The transformation approach, published by Yamagushi et al. (*9*) was used in order to estimate the gonadal dose for children of various ages.

RESULTS

The calculated radiation doses to the bladder, D_b, are presented graphically in Figs. 1 and 2 as functions of the filling time T_t, for two different administration times, T_a, of the radioactive material. Let us suppose that V_t = 200 ml, F_s = 20 ml/min (T_t = 10 min), and T_a = 0.5 min, then according to Fig. 1 the absorbed dose to the bladder, D_b, is equal to 58 mrad/mCi. According to the same figure, if F_s is increased to 50 ml/min (T_t = 4 min), then the D_b value is reduced to 16 mrad/mCi. In addition, if T_a = 1 min (Fig. 2) when F_s is 50 ml/min, then D_b falls to 12 mrad/mCi. It is obvious that for a given dose A and flow rate F_s, the D_b value is minimized when T_a approaches T_t. Actually if T_a = 3 min, T_t = 4 min, and F_s = 50 ml/min, the estimated D_b becomes 2.7 mrad/mCi. Additionally if there is a difference between T_t and T_m equal to 1 min (Δt = 1 min), then we estimate that the dose to the bladder walls during Δt is equal to 2.4 mrad/mCi.

The estimates of radiation dose rate to the gonads for the standard man and for children of different ages are listed in Table 1. For these calculations it was supposed that T_a is close to T_t, and therefore the distance from the centers of the ovaries or the testes to the center of the bladder is practically constant, since the radius of the spherical bladder does not change significantly with time.

DISCUSSION

The results of the present study clearly demonstrate that the absorbed dose to the bladder walls (D_b) during

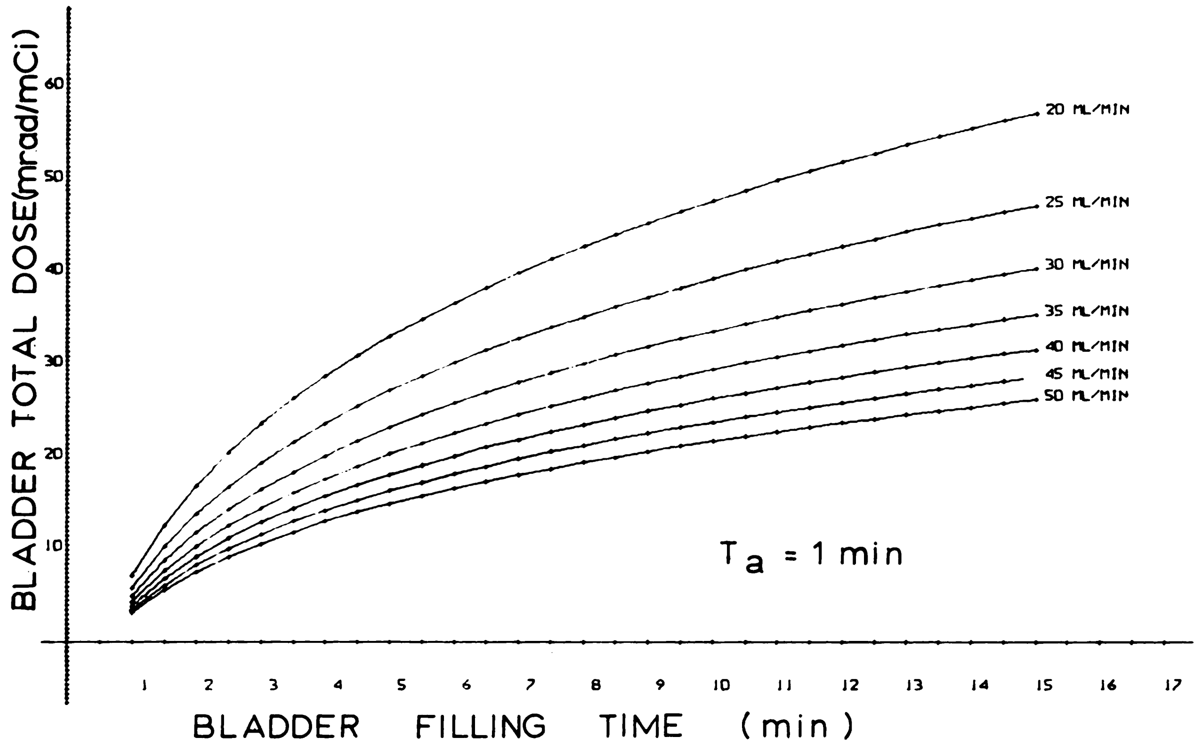

FIG. 2. Variation of total absorbed dose with bladder filling time for different saline flow rates, F_s, and when T_a = 1 min.

DRC, depends strongly on the conditions under which the examination is carried out. It is shown that this dose can be lower or much greater than the average value (28 mrad/mCi-30 min, V_T = 200 ml) estimated by Conway et al. (*3*) on the basis of a static bladder model. Besides a better estimation of the bladder dose, our method of analysis also leads to useful information, relevant to radiation protection of the patient. We may minimize the bladder exposure by increasing the saline flow rate and by delivering the radioactive material through the catheter at a time when a considerable amount of normal saline has already entered the bladder. In our experience (*6*), following these precautions does not degrade the diagnostic value of the examination. We have found when VUR is visualized during the bladder-filling phase it is still visualized during the post-filling, voiding phase, and generally it can still be visualized after the void as well. Moreover, the shortening of the DRC procedure also results in the reduction of the gonadal exposure.

TABLE 1. RADIATION DOSE RATE TO THE GONADS DURING Tc-99m DRC, FOR THE STANDARD MAN AND FOR CHILDREN OF VARIOUS AGES (SOURCE ORGAN: BLADDER CONTENTS)

Target Organ	Dose rate (mrad/mCi-min) 1 yr	5 yr	10 yr	15 yr	Standard man
Ovaries	0.51	0.30	0.20	0.14	0.12
Testes	0.34	0.20	0.14	0.09	0.08

APPENDIX

According to the model of Diffey and Hilson, the exposure rate due to photon radiation at some time t on the surface of the spherical bladder (mR·min^{-1}), including absorption and scattering of radiation within the bladder, is given by

$$X(t) = \Gamma \frac{2\pi A}{\mu F t}(1 - e^{-\lambda_1 t})e^{-\lambda_2 t}\left\{1 - \frac{1 - e^{-2\mu r(t)}}{2\mu r(t)}\right\}, \quad (1)$$

where Γ is the exposure rate constant for Tc-99m (Γ = 12mR·cm^2·min^{-1}·mCi^{-1}), μ is the energy absorption coefficient in water at 141 keV (μ = 0.027 cm^{-1}), A is the injected (i.v.) activity of Tc-99m DTPA (mCi), λ_1 the decay constant of blood clearance, λ_2 the physical decay constant of Tc-99m (min^{-1}), F is the flow rate of the urine into the bladder (ml·min^{-1}) and r(t) is the radius of the bladder, given by

$$r(t) = \left\{\frac{3\,F_s\,t}{4\pi}\right\}^{1/3}. \quad (2)$$

The absorbed dose (mrad) on the surface of the bladder resulting from gamma irradiation is then

$$D_g = \frac{2\pi\Gamma fA}{\mu F}\int_0^T (1 - e^{-\lambda_1 t})e^{-\lambda_2 t}\frac{1}{t}\left\{1 - \frac{1 - e^{-2\mu r(t)}}{2\mu r(t)}\right\}dt, \quad (3)$$

where f is the Roentgen-to-rad conversion factor for soft tissue at 141 keV (f = 0.96).

In the case of dose estimates to the bladder during DRC study, Eqs. (1), (2), and (3) may be modified as follows:

$$X(t) = \Gamma \frac{2\pi A}{\mu F_s t}e^{-\lambda_2 t}\left\{1 - \frac{1 - e^{-2\mu r(t)}}{2\mu r(t)}\right\}, \quad (4)$$

where F_s is the flow rate of saline into the bladder, and r(t) is given by

$$r(t) = \frac{\{3F_s t\}^{1/3}}{4\pi}. \tag{5}$$

The absorbed dose on the surface of the bladder is then given by

$$D_g = \frac{2\pi\Gamma fA}{\mu F_s} \int_{T_a}^{T_t} e^{-\lambda_2 t} \frac{1}{t} \left\{1 - \frac{1 - e^{-2\mu r(t)}}{2\mu r(t)}\right\} dt, \tag{6}$$

where T_a is the time of the Tc-99m administration, after the time T_0 of the start of the saline flow to the bladder, and T_t the time when bladder reaches its tolerance volume V_t.

Regarding the bladder irradiation from conversion and Auger electrons, Diffey and Hilson used the following equations to estimate the dose rate R(t) (mrad·min^{-1}) and the absorbed dose D_e (mrad) to the bladder walls at a time T from the i.v. administration of Tc-99m DTPA:

$$R(t) = 17760\, n\overline{E} \frac{A}{Ft} (1 - e^{-\lambda_1 t}) e^{-\lambda_2 t}, \tag{7}$$

and

$$D_e = 17760\, n\, \overline{E} \frac{A}{F} \int_0^T (1 - e^{-\lambda_1 t}) e^{-\lambda_2 t} \frac{1}{t} dt, \tag{8}$$

where $\overline{E}$ (0.125 MeV) is the average energy released in each internal conversion, and n the number of electrons of energy $\overline{E}$ emitted per disintegration.

In the present work Eqs. (7) and (8) were used in the following forms

$$R(t) = 17760\, n\, \overline{E} \frac{A}{F_s t} e^{-\lambda_2 t}, \tag{9}$$

and

$$D_e = 17760 \frac{n\overline{E}A}{F_s} \int_{T_a}^{T_t} \frac{e^{-\lambda_2 t}}{t} dt. \tag{10}$$

The total radiation dose to the bladder walls may then be given as

$$D_b = D_g + D_e. \tag{11}$$

REFERENCES

1. CONWAY JJ, BELMAN AB, KING LR: Direct and indirect radionuclide cystography. *Semin Nucl Med* 4:197–211, 1974
2. MAJD M, BELMAN AB: Nuclear cystography in infants and children. *Ur Clin Nor Am* 6:395–407, 1979
3. CONWAY JJ, KING LR, BELMAN AB, et al: Detection of vesicoureteral reflux with radionuclide cystography. *Am J Roent Radium Ther Nucl Med* 115: 720–727, 1972
4. UNNIKRISHNAN K: Dose to the urinary bladder from radionuclides. *Ur Phys Med Biol* 19: 329–340, 1974
5. DIFFEY BL, HILSON AJ: Absorbed dose to the bladder from $^{99}Tc^m$ DTPA. *Br J Radiol* 49: 197–198, 1976
6. FRETZAYAS A, KARPATHIOS T, DIMITRIOU P, NICOLAIDOU P, MATSANIOTIS N: Grading of veiscoureteral reflux by radionuclide cystography. *Pediat Radiol:* 14:148–150, 1984
7. SNYDER WS, FISHER HL, FORD MR, WARNER GG: Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom. MIRD Pamphlet No 5, *J Nucl Med* 10: Suppl No 3, 1969
8. SNYDER WS, FORD MR, WARNER GG, WATSON SB: "S" absorbed dose per unit cumulated activity for selected radionuclide and organs. MIRD Pamphlet No 11, *J Nucl Med* 16: Suppl, 1975
9. YAMAGUCHI H, KATO Y, SHIRAGAI A: The transformation method for the MIRD absorbed fraction as applied to various physiques. *Phys Med Biol* 20: 593–601, 1975