Radiation-Absorbed Dose from ^{201}Tl-Thallous Chloride

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Revised radiation dosimetry estimates for ^{201}Tl-thallous chloride have been developed using new data specifically acquired to address the issue of testicular uptake of this agent and through reevaluation of extant data for biodistribution in other organs. **Methods:** Quantitative testicular scintigraphy data of sequestered testes (body-background shielded) were obtained from 28 patients (56 studies) injected with ^{201}Tl-thallous chloride at peak exercise. Previously published data for 15 patients injected at maximal exercise were reanalyzed to obtain updated biodistribution parameters for designated organs. Radiation dose was calculated according to the MIRD schema. Radiation dose to testes as a function of age was determined. Comparisons are made between organ dose estimates derived in this study and those previously published. The dose contributions of possible contaminants (^{200}Tl, ^{202}Tl, ^{203}Pb) have been included. Estimates are provided of the dose component from these contaminants if injected at the time of the maximum recommended 5-d shelf life (as opposed to at the designated calibration time). **Results:** The radiation dose per unit administered activity to adult testes calculated in this study of 0.21 mGy/MBq (0.77 rad/mCi) is approximately a factor of 2 less than the value of 0.45 mGy/MBq (1.7 rad/mCi) previously accepted. The revised dose estimates for other organs show less variation from published values. The effective dose determined in this work is ~0.16 mSv/MBq (0.60 rem/mCi). Under the assumption of similar biokinetics as for the adult, the testes dose for children increases significantly as age decreases with a value of 7.5 mGy/MBq (28 rad/mCi) for a newborn. Contributions from radiocontaminants that may be encountered in the preparation of ^{201}Tl-thallous chloride are shown to range from a fraction of a percent up to ~20% of the total dose for some organs, with the higher values arising from the long half-life contaminant ^{202}Tl after a 5-d shelf life. **Conclusion:** It is recommended that the dose values determined in this study be used when estimating the radiation dose to the adult testes from intravenous administration of ^{201}Tl-thallous chloride. The potential for increased radiation dose per administered activity to the testes at younger ages should be evaluated before performing procedures on children. The presence of radiocontaminants in the product should be considered when estimating radiation dose and may add a significant contribution to dose dependent on the specific radionuclide and concentration at the time of administration.

Key Words: ^{201}Tl-thallous chloride; ^{201}Tl dosimetry; radiation dosimetry; testes radiation dose; radiocontaminants

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Administered as an intravenous bolus injection, ^{201}Tl-thallous chloride is used primarily for imaging myocardial perfusion (*1–3*). However an extended range of noncardiac applications have been reported, including, for example, detection of malignant neoplasm (*4–7*), differentiation of tumor reoccurrence from therapy-induced tissue changes (*8,9*), and evaluation of parathyroid hyperactivity (*10*). The thallous ion behaves as a potassium analog (*11*), with uptake in tissue being essentially intracellular in nature (*12*). The initial distribution of thallium in organs is directly related to regional blood flow, reflecting the high extraction rate on first pass of the blood through the organs (*13*). Once inside the cell, thallium is released more slowly than is potassium (*11*).

Clinical studies of myocardial perfusion are performed most often during and immediately after physical exercise or administration of a coronary artery vasodilator; however, protocols involving the patient at rest may be used also. Increased myocardial perfusion as a result of exercise or administration of vasodilative agents results in an increase in thallium deposition in myocardium by a variable amount (up to 3–7 times resting levels). Exercise also increases perfusion (and, therefore, thallium uptake) in striated muscle such as in the lower extremities; at the same time, exercise may decrease splanchnic perfusion and thallium uptake in abdominal structures.

After injection of thallium following exercise or administration of a coronary artery vasodilator, redistribution of the tracer from its immediate postexercise distribution may occur over minutes to hours. Human studies have shown that intravenous administration of ^{201}Tl-thallous chloride is characterized by rapid biexponential clearance from the blood, with about 91.5% of blood radioactivity disappearing with a half-time of around 5 min and the remainder having

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a half-time of about 40 h (*14*). Measurements in animals incorporating high sampling rates at early times have identified 4 blood components (*15*); however, some of these components are very rapid or extremely weak and effectively would provide negligible contribution to a dose calculation over and above a 2-component model. Maximal concentration in the normal myocardium occurs at about 10 min after injection with maximum exercise and at approximately 1 h under rest conditions. Uptake of ^{201}Tl has been documented in brain, thyroid, heart, liver, spleen, kidneys, stomach, intestine, and testes (Table 1), with the remainder of the activity distributing fairly uniformly throughout the body. Limited excretion has been demonstrated to take place via the urine (*14*). With regard to fecal excretion of ^{201}Tl, some differences have been noted in the literature (*14,16*); however, no significant component of elimination by this route has been documented.

Radiation dosimetry for ^{201}Tl-thallous chloride has been developed by several authors (*14,17–20*). The International Commission on Radiation Protection (ICRP) dose estimates for ^{201}Tl chloride have incorporated values of testicular uptake published by Gupta et al. (*21*) and Hosain and Hosain (*22*). The values for testicular uptake at 24 h reported by these authors for adults (0.8%–1% of the administered activity) are significantly higher than those reported by Atkins et al. (*14*) or Krahwinkel et al. (*17*) (0.15%–0.3%) and also are above the range presented by Rao et al. (0.38%–0.57%) (*23*). In addition, the ICRP extends their model to children with the prediction of correspondingly higher testes radiation dose at younger ages (*19*). In a recent publication involving injection of ^{201}Tl 24 or 48 h before orchidectomy, the percentage uptake at 24 h was found to be 0.19% (*24*). However, in this population of older patients (>64 y), who had opted to undergo orchidectomy as a means of hormone suppression for the treatment of prostate cancer, the average testes weight (combined) was 24 g in comparison with the normal adult organ value of 35 g. The current study evaluated testicular uptake data of ^{201}Tl in 28 adult human subjects (*25*) and recalculated radiation dose estimates for internal organs using these and other data in the extant literature (*18*). No attempt was made to investigate the small-scale dosimetry considerations described by Rao et al. (*23,26*); rather, the results are provided as whole-organ dose estimates, calculated according to methodology of the MIRD schema (*27,28*). In addition, this work has estimated the possible contribution to radiation dose from several radioactive contaminants that are often present in ^{201}Tl preparations and has evaluated the consequence of administration time relative to preparation (shelf life consideration).

MATERIALS AND METHODS

^{201}Tl (physical half-life, 73.1 h) is cyclotron produced by the reaction ^{203}Tl (p,3n) ^{201}Pb. ^{201}Pb decays with a 9.4 h physical half-life to ^{201}Tl by electron capture and β+ emission (*29*). ^{201}Tl is supplied as thallous chloride in isotonic solution. Possible contam-

TABLE 1
Biologic Parameters of Fractional Distribution Function, $\alpha_h(t)$ ($\alpha_h(t) = \alpha_{h1}\exp(-\lambda_{h1}t) + \alpha_{h2}\exp(-\lambda_{h2}t)$), for Intravenous Administration of ^{201}Tl as Thallous Chloride

Source organ*	α_{h1}†	λ_{h1} (h^{-1})‡	α_{h2}†	λ_{h2} (h^{-1})‡	τ_h (h)§
Brain	0.0176	0			1.85
Lower large intestine	0.036	0.00363			2.74
Small intestine	0.144	0.00363			10.96
Stomach	0.028	0.00338			2.17
Upper large intestine	0.047	0.00363			3.58
Heart wall	0.034	0.00387			2.54
Kidneys	0.045	0.00267	0.0097	0.0257	3.97
Liver	0.046	0.00318			3.63
Spleen	0.0074	0.00108	0.0028	0.0187	0.798
Testes‖	0.00568	0.00445	−0.00614	0.298	0.255
Thyroid	0.0029	0.00198	0.0024	0.00417	0.428
Urinary bladder¶	0.062	0.00475	0.138	0.00138	0.0913
Remainder					52.2

*For organs other than testes, data used were from Table 1 in Krahwinkel et al. (*17*), which gives mean and SD of kinetic data for their 15 patients. Following the revision of Castronovo (*18*), these pooled data were reanalyzed in this report.

†α_{hj} values are fractional distribution functions for source organ, h.

‡λ_{hj} values are biologic rate constants for source organ, h.

§Residence time τ_h (h) includes physical decay and, with exception of urinary bladder (see ¶ below), is calculated using the relationship: $\tau_h = \Sigma\ \alpha_{hj}/(\lambda + \lambda_{hj})$, where λ is physical decay constant given in reciprocal hours (for ^{201}Tl, $\lambda = 0.009482\ h^{-1}$).

‖For testes, the results were derived from quantitative scintigraphy of 28 patients (56 studies) (*25*). Values shown for testes parameters are averages of individual results obtained for each patient. As testes residence time shown is average of individual patient τ values, it differs from value that would be derived from average α and λ values given in table. Residence time for testes: range = 0.095–0.46 h; SD = 0.087 h.

¶For urinary bladder, residence time was determined using model of Cloutier et al. (*33*) with a 4.8-h voiding interval.

inants (with the physical half-lives in parentheses) are ^{200}Tl (26.1 h), ^{202}Tl (12.23 d), and ^{203}Pb (51.87 h). The physical half-life of ^{200}Tl is considerably shorter than that of ^{201}Tl so that its contribution decreases with increased shelf life. On the other hand, the physical half-life of ^{202}Tl is considerably longer than that of ^{201}Tl, so that its contribution to absorbed dose increases with increasing shelf life. Levels of the contaminants were taken from internal records of the Radiation Internal Dose Information Center in Oak Ridge, TN, derived from industry-reported values. The biokinetic model for lead was taken from ICRP Publication 30 (*30*).

The biologic data used in this dose estimate report are derived from (a) total-body pharmacokinetics, as determined through conjugate view imaging out to 216 h after injection in 14 male and 1 female patient undergoing diagnostic exercise myocardial scintigraphy and ranging in age from 41 to 62 y (*17*), and (b) quantitative testicular scintigraphy in 28 patients (56 studies) injected after peak exercise (*25*). The testes evaluation was a component of a clinical trial that had the primary objective of comparing bolus injection of an experimental pharmaceutical clearance agent with that of a placebo on the identification of thallium redistribution in the myocardium. Patients participated in a randomized crossover protocol with the second injection occurring at 1–2 wk after the first. No statistical difference was observed in the testes residence times for the paired (crossover) patient data; therefore, all 56 studies were combined for the analysis in this report. For this dedicated testicular study on 28 subjects, a lead vinyl shield (1 mm lead equivalent) was placed over the pelvis and upper thighs. The testes were pulled through an opening and placed on the lead vinyl such that they were sequestered and shielded from the body background during imaging. Anterior image data were acquired at 5–7 time points (nominally, 1, 2, 4, 8, 24, 48, and 168 h after administration) with a ^{201}Tl standard (vial with saline configured to approximate the size of one testis) imaged simultaneously within the field of view at each session. A 20% energy window centered over the 68- to 80-keV x-ray emissions for ^{201}Tl was used. The biokinetic data were fit to 2 exponential terms of the form $\alpha_{h1}\exp(-\lambda_{h1}t) - \alpha_{h2}\exp(-\lambda_{h2}t)$ (Table 1) to accommodate the uptake component using standard regression software (*31*). For organs other than the testes, the metabolic model was based on the data of Krahwinkel et al. (15 patients) (*17*) as revised by Castronovo (*18*) (to achieve better correlation with then current estimates of ^{202}Tl dosimetry through model incorporation of intravenous administration of tracer). The resultant residence times were used with the MIRD methodology to provide the dose estimates (*27,28,32,33*). The effective dose was calculated according to ICRP Publication 80 (*20*).

RESULTS

Table 1 presents the biologic parameters derived in this study for the source organs considered. As indicated, both mono- and biexponential functions have been fitted to the data as appropriate for the purpose of dosimetry calculations. A comparison of uptake in the human testes as determined by various investigators is presented in Table 2. The distribution data provided in Table 1, coupled with appropriate dose conversion factors (*32*), were used according to the MIRD schema (*27,28,32,33*) in the calculation of absorbed dose estimates for the various organs, with inclusion of contributions from contaminants (Tables 3 and 4). The effective dose is 0.155 mSv/MBq (0.57 rem/mCi) for the contaminant levels in Table 3 and 0.162 mSv/MBq (0.60 rem/mCi) for the contaminant levels in Table 4. Radiation dose estimates to the testes of children were determined by applying the new adult activity–time integrals generated in this work to the mathematical phantoms representing children of various ages (*34*) and using the MIRDOSE software (*32*). The results are presented in Table 5.

DISCUSSION

As shown in Table 2, the 24-h percentage uptake of ^{201}Tl in the testes reported in the literature covers an extended

TABLE 2
Human Testes (Adult) Uptake and Dosimetry of ^{201}Tl-Thallous Chloride: Comparison of Results from Various Investigators

Reference	No. of subjects	Exercise vs. rest	Testicular uptake (% at 24 h)	Testicular biologic $t_{1/2}$	Data acquisition method	Estimated radiation dose to testes	
						rad/mCi	mGy/MBq
Rao et al. (*23*)	4	Rest	0.43 ± 0.10	280 h	Anterior imaging, shielded	1.3	0.35
Atkins et al. (*14*)	3		~0.15	Long	Imaging, geometric mean	0.59	0.16
Hosain and Hosain (*22*)			0.8		Extrapolation from animals	1.4	0.4
Gupta et al. (*21*)	4		~1.1		Imaging		
Krahwinkel et al. (*17*)	14	Exercise	0.30 ± 0.10	Long	Imaging, geometric mean	0.34 ± 0.21	0.09 ± 0.06
Castronovo (*18*)	14	Exercise	0.30 ± 0.10	Long	Imaging, geometric mean	0.91	0.25
Nettleton et al. (*24*)	4		0.19		Orchidectomy	0.41–0.52	0.11–0.14
This study and Stabin et al. (*25*)	28*	Exercise	0.29 ± 0.09	429 h†	Anterior imaging, shielded	0.77	0.21
ICRP 80 (*20*)						1.7	0.45

*Fifty-six studies done in 28 patients.
†Obtained from average of biologic half-time (biologic $t_{1/2}$) for long biologic component for all patients. Range = 34–5,139 h; SD = 810 h.

TABLE 3
Estimated Absorbed Dose at Time of Calibration from ^{201}Tl as Thallous Chloride Plus Contaminants After Intravenous Administration (Assumed Percentages of ^{201}Tl, ^{200}Tl, ^{202}Tl, and ^{203}Pb: 0.983, 0.003, 0.012, 0.002) and Percent Contribution of Each Radionuclide to Absorbed Dose

	Estimated radiation dose									
	rad/mCi					mGy/MBq,	% contribution			
Organ	^{201}Tl	^{200}Tl	^{202}Tl	^{203}Pb	Total	Total	^{201}Tl	^{200}Tl	^{202}Tl	^{203}Pb
Adrenals	2.10E−01	2.18E−03	2.14E−02	8.34E−04	2.34E−01	6.33E−02	89.58	0.93	9.14	0.36
Brain	1.91E−01	1.08E−03	1.77E−02	3.35E−04	2.10E−01	5.68E−02	90.88	0.51	8.45	0.16
Breasts	1.15E−01	9.42E−04	9.64E−03	2.35E−04	1.25E−01	3.39E−02	91.38	0.75	7.68	0.19
GB wall	2.75E−01	2.95E−03	2.80E−02	1.01E−03	3.07E−01	8.31E−02	89.60	0.96	9.11	0.33
LLI wall	1.04E+00	4.88E−03	4.53E−02	3.19E−04	1.09E+00	2.96E−01	95.39	0.45	4.13	0.03
Small intestine	1.34E+00	5.73E−03	5.32E−02	3.67E−04	1.40E+00	3.79E−01	95.77	0.41	3.80	0.03
Stomach wall	5.95E−01	3.69E−03	3.47E−02	3.59E−04	6.34E−01	1.71E−01	93.89	0.58	5.47	0.06
ULI wall	1.03E+00	6.35E−03	5.61E−02	4.08E−04	1.10E+00	2.97E−01	94.27	0.58	5.11	0.04
Heart wall	8.74E−01	3.82E−03	3.49E−02	4.31E−04	9.14E−01	2.47E−01	95.71	0.42	3.82	0.05
Kidneys	1.45E+00	6.37E−03	6.05E−02	1.68E−03	1.52E+00	4.10E−01	95.49	0.42	3.98	0.11
Liver	3.19E−01	2.51E−03	2.29E−02	3.02E−03	3.47E−01	9.39E−02	91.80	0.72	6.61	0.87
Lungs	1.59E−01	1.33E−03	1.40E−02	4.64E−04	1.75E−01	4.73E−02	90.98	0.76	8.00	0.27
Muscle	1.53E−01	1.42E−03	1.44E−02	3.71E−04	1.70E−01	4.59E−02	90.46	0.83	8.49	0.22
Ovaries	3.38E−01	3.72E−03	3.40E−02	3.43E−04	3.76E−01	1.02E−01	89.90	0.99	9.02	0.09
Pancreas	2.49E−01	2.61E−03	2.57E−02	6.62E−04	2.78E−01	7.53E−02	89.59	0.94	9.23	0.24
Red marrow	1.44E−01	1.68E−03	1.68E−02	1.31E−03	1.64E−01	4.44E−02	87.93	1.02	10.25	0.80
Bone surface	3.18E−01	1.65E−03	2.06E−02	6.78E−03	3.47E−01	9.37E−02	91.62	0.48	5.95	1.96
Skin	1.07E−01	8.42E−04	8.79E−03	2.45E−04	1.17E−01	3.16E−02	91.55	0.72	7.52	0.21
Spleen	5.74E−01	3.39E−03	3.61E−02	3.18E−04	6.14E−01	1.66E−01	93.51	0.55	5.88	0.05
Testes	7.38E−01	2.59E−03	3.15E−02	2.20E−04	7.73E−01	2.09E−01	95.56	0.34	4.08	0.03
Thymus	1.54E−01	1.37E−03	1.42E−02	2.96E−04	1.70E−01	4.60E−02	90.69	0.81	8.33	0.17
Thyroid	1.94E+00	5.31E−03	5.75E−02	2.84E−04	2.00E+00	5.42E−01	96.85	0.27	2.87	0.01
UB wall	2.09E−01	1.94E−03	1.98E−02	2.56E−04	2.31E−01	6.25E−02	90.50	0.84	8.55	0.11
Uterus	2.87E−01	3.03E−03	2.87E−02	3.05E−04	3.19E−01	8.64E−02	89.98	0.95	8.98	0.10
Total body	1.96E−01	1.54E−03	1.59E−02	6.11E−04	2.14E−01	5.77E−02	91.56	0.72	7.43	0.29
	Effective dose									
	rem/mCi					mSv/MBq,	% contribution			
	5.42E−01	2.64E−03	2.70E−02	6.26E−04	5.73E−01	1.55E−01	94.70	0.46	4.72	0.11

GB = gallbladder; LLI = lower large intestine; ULI = upper large intestine; UB = urinary bladder.
Effective dose and percent contribution to effective dose for each radioisotope are provided at bottom of table.

range (0.15%–1.1%). The values determined in the current study (0.3%) fall toward the lower end of this range in basic agreement with estimates by Atkins et al. (*14*), Krahwinkel et al. (*17*), Rao et al. (*23*), and Nettleton et al. (*24*). This suggests that the values given by Gupta et al. (*21*) and Hosain and Hosain (*22*) that are used in the ICRP dosimetry (*19,20*) overestimate testicular uptake and consequently lead to an overestimation of dose. The radiation dose per unit administered activity to adult testes calculated in this study of 0.21 mGy/MBq is approximately a factor of 2 less than the value of 0.45 mGy/MBq currently quoted within ICRP Publication 80 (*20*). In addition, as shown in Table 5, when testicular radiation dose is extrapolated to children, the ICRP values are about 2.5 times higher than the estimates provided in this report. However, of importance is the fact that the testes dose per administered activity for children increases significantly as age decreases, with a value of 7.5 mGy/MBq for a newborn. This potential for increased radiation dose at younger ages should be taken into consideration before performing procedures on children.

It is recognized that the calculated testicular dose in the current study may represent an overestimate, since the image-based data acquisition cannot differentiate testicular uptake alone from uptake in the surrounding tissues (scrotum and epididymis). Data by Hosain and Hosain in animals (*22*) indicate that the uptake in the testes becomes greater than that in the surrounding tissues within hours, with the activity accumulating predominately in the testes. The data of Nettleton et al. (*24*) for the excised testes show a lower uptake (0.19% vs. 0.30%) that might be indicative of the lack of contribution from surrounding tissues in vivo (Table 2); however, as the testes mass involved was below the normal standard, the lower percentage uptake would be due in part to this factor. Thus, if there is any

TABLE 4
Estimated Absorbed Dose from ^{201}Tl as Thallous Chloride Plus Contaminants After Intravenous Administration, Allowing for Shelf Life of 5 Days After Calibration (Assumed Percentages of ^{201}Tl, ^{202}Tl, and ^{203}Pb: 0.9707, 0.0280, 0.0013; Contribution of ^{200}Tl Is Effectively Zero and Is Not Included) and Percent Contribution of Each Radioisotope to Absorbed Dose

	Estimated radiation dose							
	rad/mCi				mGy/MBq,	% contribution		
Organ	^{201}Tl	^{202}Tl	^{203}Pb	Total	Total	^{201}Tl	^{202}Tl	^{203}Pb
Adrenals	2.07E−01	4.99E−02	5.42E−04	2.58E−01	6.96E−02	80.41	19.38	0.21
Brain	1.88E−01	4.14E−02	2.18E−04	2.30E−01	6.22E−02	81.91	17.99	0.09
Breasts	1.13E−01	2.25E−02	1.53E−04	1.36E−01	3.67E−02	83.34	16.55	0.11
GB wall	2.72E−01	6.53E−02	6.56E−04	3.38E−01	9.13E−02	80.47	19.33	0.19
LLI wall	1.03E+00	1.06E−01	2.08E−04	1.14E+00	3.07E−01	90.70	9.28	0.02
Small intestine	1.32E+00	1.24E−01	2.39E−04	1.45E+00	3.92E−01	91.41	8.57	0.02
Stomach wall	5.88E−01	8.09E−02	2.34E−04	6.69E−01	1.81E−01	87.87	12.09	0.03
ULI wall	1.02E+00	1.31E−01	2.65E−04	1.15E+00	3.12E−01	88.62	11.36	0.02
Heart wall	8.64E−01	8.15E−02	2.80E−04	9.45E−01	2.55E−01	91.35	8.62	0.03
Kidneys	1.43E+00	1.41E−01	1.09E−03	1.57E+00	4.25E−01	90.97	8.97	0.07
Liver	3.15E−01	5.35E−02	1.96E−03	3.70E−01	1.00E−01	85.01	14.46	0.53
Lungs	1.57E−01	3.27E−02	3.02E−04	1.90E−01	5.14E−02	82.67	17.17	0.16
Muscle	1.52E−01	3.36E−02	2.41E−04	1.85E−01	5.01E−02	81.74	18.13	0.13
Ovaries	3.34E−01	7.92E−02	2.23E−04	4.13E−01	1.12E−01	80.78	19.16	0.05
Pancreas	2.46E−01	6.00E−02	4.30E−04	3.07E−01	8.29E−02	80.30	19.56	0.14
Red marrow	1.43E−01	3.93E−02	8.49E−04	1.83E−01	4.94E−02	78.03	21.51	0.46
Bone surface	3.14E−01	4.82E−02	4.41E−03	3.66E−01	9.90E−02	85.65	13.15	1.20
Skin	1.06E−01	2.05E−02	1.59E−04	1.26E−01	3.41E−02	83.64	16.23	0.13
Spleen	5.67E−01	8.43E−02	2.07E−04	6.51E−01	1.76E−01	87.03	12.94	0.03
Testes	7.29E−01	7.35E−02	1.43E−04	8.03E−01	2.17E−01	90.82	9.16	0.02
Thymus	1.52E−01	3.31E−02	1.92E−04	1.86E−01	5.02E−02	82.08	17.82	0.10
Thyroid	1.92E+00	1.34E−01	1.85E−04	2.05E+00	5.54E−01	93.45	6.54	0.01
UB wall	2.07E−01	4.61E−02	1.66E−04	2.53E−01	6.84E−02	81.70	19.23	0.07
Uterus	2.84E−01	6.70E−02	1.98E−04	3.52E−01	9.49E−02	80.87	19.07	0.06
Total body	1.93E−01	3.70E−02	3.97E−04	2.31E−01	6.23E−02	83.76	16.07	0.17
	Effective dose							
	rem/mCi				mSv/MBq,	% contribution		
	5.36E−01	6.31E−02	4.07E−04	5.99E−01	1.62E−01	89.40	10.50	0.068

GB = gallbladder; LLI = lower large intestine; ULI = upper large intestine; UB = urinary bladder.
Effective dose and percent contribution to effective dose for each radioisotope are provided at bottom of table.

overestimate in the testicular dose in this report, it is considered to be <30%.

The dose estimates provided here and in most publications are based on standard physical considerations (emission energy, geometry) and biologic clearance without taking into account possible effects of nonuniform energy distribution within the testes by low-energy electrons or enhancement factors such as relative biological effectiveness (RBE). An RBE constituting a 2- to 4-fold enhancement associated with the effect of Auger electron emission on spermatogonia has been found in mice administered ^{202}Tl chloride via intratesticular injection (*26*). As noted, neither small-scale dosimetry considerations nor RBE effects are considered in this study. However, RBE effects as they ultimately may influence the interpretation and application of physical dose estimates represent an important area worthy of continuing investigation.

As shown by comparison of Tables 3 and 4, with increasing shelf life there is a progressive increase in radiation dose from the ^{202}Tl contaminant due to its longer half-life. This contaminant is shown to contribute up to 20% of the total radiation dose to some organs under the delayed administration scenario. However, these conditions result in only about a 10% contribution to the effective dose. Dose estimates at intermediate times between calibration and 5 d may be obtained by interpolation.

The radiation-absorbed doses for an extended list of organs have been recalculated from the published biologic data and are in reasonable agreement with those of most authors (Table 6). The differences relative to those provided by Krahwinkel et al. (*17*) may be attributed to a modeling error in their analysis for the dosimetry, although the biokinetic data presented are considered sound. The current estimates differ from those in ICRP

TABLE 5
Radiation Dose to Testes as Function of Age Using Data From This Study in Comparison with Values Provided by ICRP Publication 80 (*20*)

	Radiation dose to testes		
	This study		ICRP 80 (*20*),
Age	rad/mCi	mGy/MBq	mGy/MBq
Newborn	27.8	7.5	
1 y	19.0	5.1	13
5 y	14.3	3.9	9.6
10 y	12.1	3.3	8.3
15 y	1.6	0.43	1.1
Adult	0.77	0.21	0.45

Publications 53 and 80 (*19,20*) for bone and marrow due to the fact that activity was not assigned directly to marrow as done by the ICRP task group. In addition, it is noted that the dose estimates here are nearly identical to those in NUREG/CR-6345 (*35*) as they were also based on the Krahwinkel biokinetic data and the testicular uptake data reported here and were calculated using standard techniques equivalent to those described in this report.

CONCLUSION

The radiation dosimetry of ^{201}Tl-thallous chloride has been revised introducing new data specifically acquired to address the issue of testicular uptake of this agent and reevaluating the extant data on biodistribution in other organs. It is recommended that the dose value determined through this study be used when estimating the radiation dose to the adult testes from intravenous administration of ^{201}Tl-thallous chloride (0.21 mGy/MBq) as opposed to the higher values currently quoted (0.45 mGy/MBq; ICRP Publication 80 (*20*)). The potential for increased radiation dose per administered activity to the testes at younger ages should be evaluated before performing procedures on children. The presence of radiocontaminants in the product should be considered when estimating radiation dose and may add a significant contribution to dose dependent on the specific radionuclide and concentration at the time of administration.

TABLE 6
Comparison of Organ Dose Estimates Between This Study and Other Previous Publications

	Estimated radiation dose (mGy/MBq)					
Organ	This study*	Atkins et al. (*14*)	Castronovo (*18*)	Krahwinkel et al. (*17*)	ICRP 53† (*19*)	ICRP 80 (*20*)
Adrenals	6.33E−02		4.97E−02	1.05E−02	5.1E−02	5.7E−02
Brain	5.68E−02		4.62E−02			2.2E−02
Breasts	3.39E−02		1.33E−02		2.8E−02	2.4E−02
GB wall	8.31E−02		6.57E−02			6.5E−02
LLI wall	2.96E−01	2.4E−01	1.19E−01	1.45E−01	3.6E−01	3.2E−01
Small intestine	3.79E−01		1.26E−01	1.64E−02	1.6E−01	1.6E−01
Stomach wall	1.71E−01		1.69E−01	4.62E−02	1.2E−01	1.4E−01
ULI wall	2.97E−01	2.4E−01	4.23E−01	7.02E−02	1.9E−01	3.2E−01
Heart wall	2.47E−01		3.01E−01	8.89E−03	2.3E−01	2.0E−01
Kidneys	4.10E−01	3.16E−01	5.68E−01	6.38E−02	5.4E−01	4.8E−01
Liver	9.39E−02		9.49E−02	1.45E−02	1.8E−01	1.5E−01
Lungs	4.73E−02		3.29E−02	9.20E−03	1.2E−01	1.1E−01
Muscle	4.59E−02		7.75E−02	9.24E−03		5.2E−02
Ovaries	1.02E−01		1.01E−01		1.2E−01	7.3E−01
Pancreas	7.53E−02		6.10E−02	1.33E−02	5.4E−02	5.7E−02
Red marrow	4.44E−02		3.34E−02	1.71E−02	1.8E−01	1.6E−01
Bone surface	9.37E−02		8.31E−02		3.4E−01	3.4E−01
Skin	3.16E−02			6.76E−03		2.2E−02
Spleen	1.66E−01		1.86E−01	2.68E−02	1.4E−01	1.2E−01
Testes	2.09E−01	1.59E−01	2.45E−01	9.08E−02	5.6E−01	4.5E−01
Thymus	4.60E−02		3.41E−02			3.6E−02
Thyroid	5.42E−01	2.78E−01	5.64E−01	9.22E−02	2.5E−01	2.2E−01
UB wall	6.25E−02		5.44E−02	1.20E−02	3.6E−02	4.0E−02
Uterus	8.64E−02		6.35E−02	1.35E−02	5.0E−02	5.1E−02
Total body	5.77E−02	5.67E−02	7.68E−02			

*Total, from Table 3. Essentially identical dose estimates may be found in NUREG/CR-6345 (*35*) as they were based on nearly all of the same input data and equivalent model assumptions.

†Includes ^{200}Tl and ^{202}Tl impurity contributions.

GB = gallbladder; LLI = lower large intestine; ULI = upper large intestine; UB = urinary bladder.

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