Modeling Plutonium Decorporation in Female Nuclear Worker Treated with Ca-DTPA after Inhalation Intake

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Abstract

The present work models plutonium (Pu) biokinetics in a female former nuclear worker. Her bioassay measurements are available at the U.S. Transuranium and Uranium Registries. The worker was internally exposed to a plutonium-americium mixture via acute inhalation at a nuclear weapons facility. She was medically treated with injections of 1 g Ca-DTPA on days 0, 5, and 14 after the intake. Between days 0 and 20, 13 fecal and 24 urine samples were collected and analyzed for ^{239}Pu and americium (^{241}Am). Subsequently, she was followed-up for bioassay monitoring over 14 years, with 13 additional post-treatment urine samples collected and analyzed for Pu. The uniqueness of this dataset is due to the availability of: (i) both early and long-term bioassay data from a female with Pu intake; (ii) data on chelation therapy for a female; and (iii) fecal measurement results. Chelation therapy with DTPA is known to aid in reducing the internal radiation dose by enhancing the excretion of Pu from the body. Such enhancement affects Pu biokinetics in the human body, posing a challenge to the internal dose assessment. The current dose assessment practice is to exclude the data affected by DTPA from the analysis. Using this standard approach, i.e., only using data obtained 100 days after the last DTPA administration, the worksite's Radiation Protection personnel estimated the ^{239}Pu intake to be 73 Bq, with a committed effective dose equivalent to the whole-body of 16 mSv and a committed organ dose equivalent to the bone surfaces of 340 mSv. The present analysis is the first attempt to model explicitly the combined biokinetics of Pu and DTPA by using a newly developed chelation model. The bioassay data collected during and after the DTPA administrations were used for biokinetic modeling and dose assessment. The Markov Chain Monte Carlo method was used to investigate model parameter uncertainty, given the bioassay data and assumed prior probability distributions. Preliminary results of this study show that the worker's Pu intake was 21 Bq, with a committed effective dose to the whole-body of 2.31 mSv and a committed equivalent dose to the bone surfaces of 66.7 mSv. Differences in results are expected not only because of the different dosimetric systems used, but also because this analysis includes chelation-affected bioassay data and uses a biokinetic model that accounts for the effect of chelation therapy in removing Pu from the body.

Historical Case Study

Nuclear Weapons Facility

➢ **Female worker was about 4.5 meters away from a glovebox**
- A can containing a Pu-Am mixture and enriched U exploded
- A fire was ignited in the glove box, and breached the glovebox containment
- The worker was wearing a respirator
- The chemical form of the inhaled material was suspected to be Pu oxide

USTUR: Unique Dataset

➢ **A female with Pu intake treated with Ca-DTPA**
➢ **Both early and late urine bioassay data**
➢ **Fecal measurements**

Plutonium Decorporation

Ca-DTPA

➢ **DTPA - Diethylenetriaminepentaacetic acid (1950s):**
- Used to treat internal contamination with Pu, Am, and Cm
- Administration of Ca-DTPA chelating agent accelerates Pu removal from the body (vs 'free' Pu)

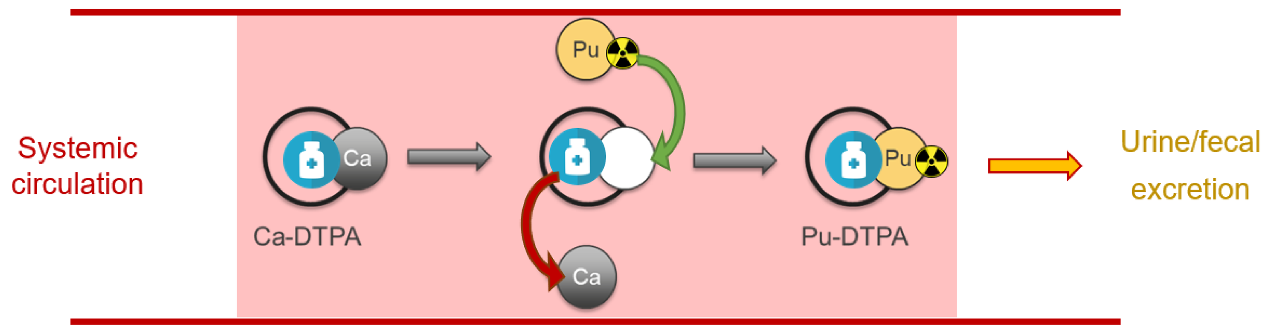


Figure 1. DTPA Mechanism of Action

Chelation Treatment

➢ **Chelation with 1 g Ca-DTPA**
- One intramuscular injection: day 0
- Two intravenous injections: days 5 and 14

Data and Methods

Bioassay Data

➢ **Urinalysis:** 10 measurements: days 1–20 (early) and 13 measurements: days 264–4,869 (late)

➢ **Fecal Analyses:** 11 measurements: days 2–19

➢ **Lung Count:** 1 measurement: day 7

Models

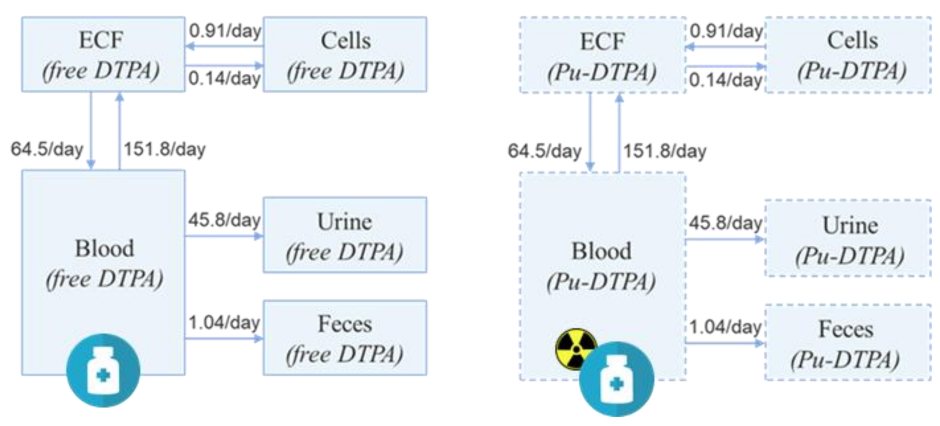
Model type	Reference	Model identification	Varied parameters during fit
Biokinetic	ICRP 1979	ICRP 30 gastrointestinal (GI) tract model	Default: all fixed, $f_1 = 10^{-4}$
	ICRP 1994	ICRP 66 human respiratory tract model	Selected: Intake, AMAD, and blood absorption parameters
	Leggett et al. (2005)	Plutonium systemic model	Default: all fixed
	Dumit et al. (2020b, 2023a)	Chelation model	Default: all fixed
Dosimetric	ICRP 1991	ICRP 60 dosimetric system	N/A

Statistical Analysis

➢ **IDode software (Miller et al. 2012) was used**
- Minimization of χ^2 was performed
- Starting from some given point in parameter space, the unknown parameters are varied to find a minimum χ^2 point

➢ **Markov Chain Monte Carlo (MCMC)**
- Yields a chain of model parameter values
- Results are reported as posterior mean (chain-average), standard deviation, and 2.5%, 50%, 97.5% percentiles

Chelation Modeling Approach



- Biokinetic models for the Ca-DTPA drug and the Pu-DTPA chelate are coupled and, via 2nd-order kinetics
- This "system of models" describes the in vivo chelation process: transfer of material to the various compartments
- Allows interpretation of bioassay data affected by Ca-DTPA

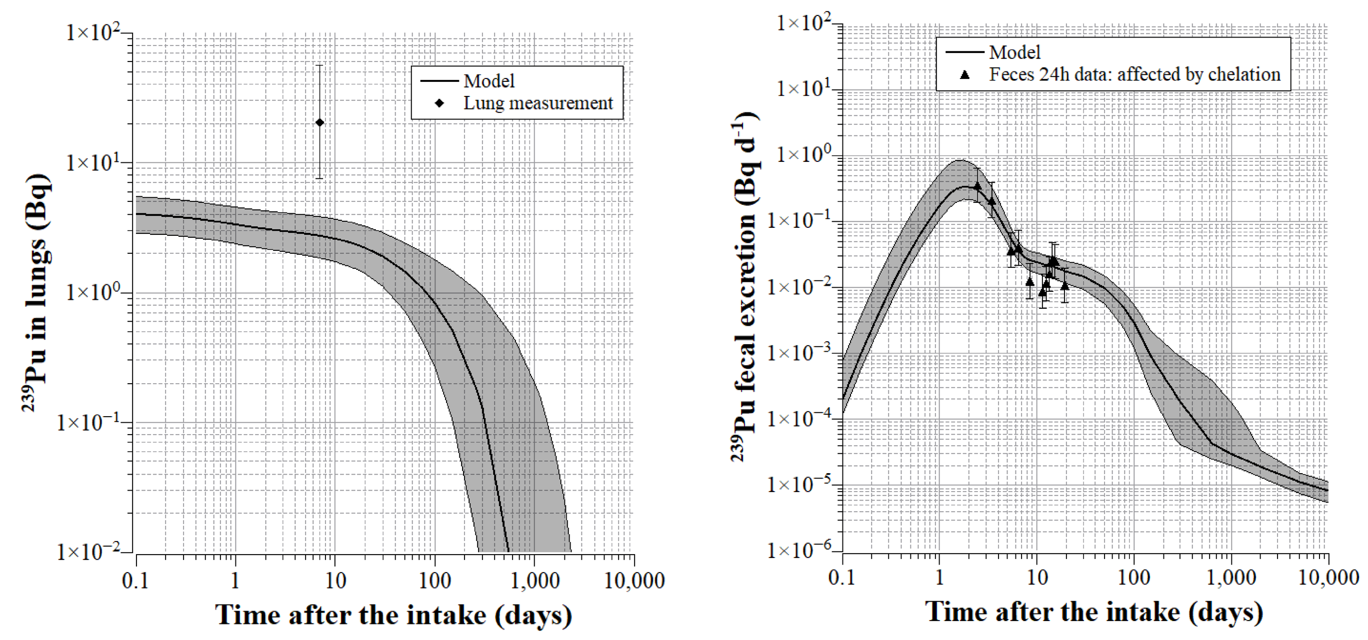
Results

MCMC Calculations

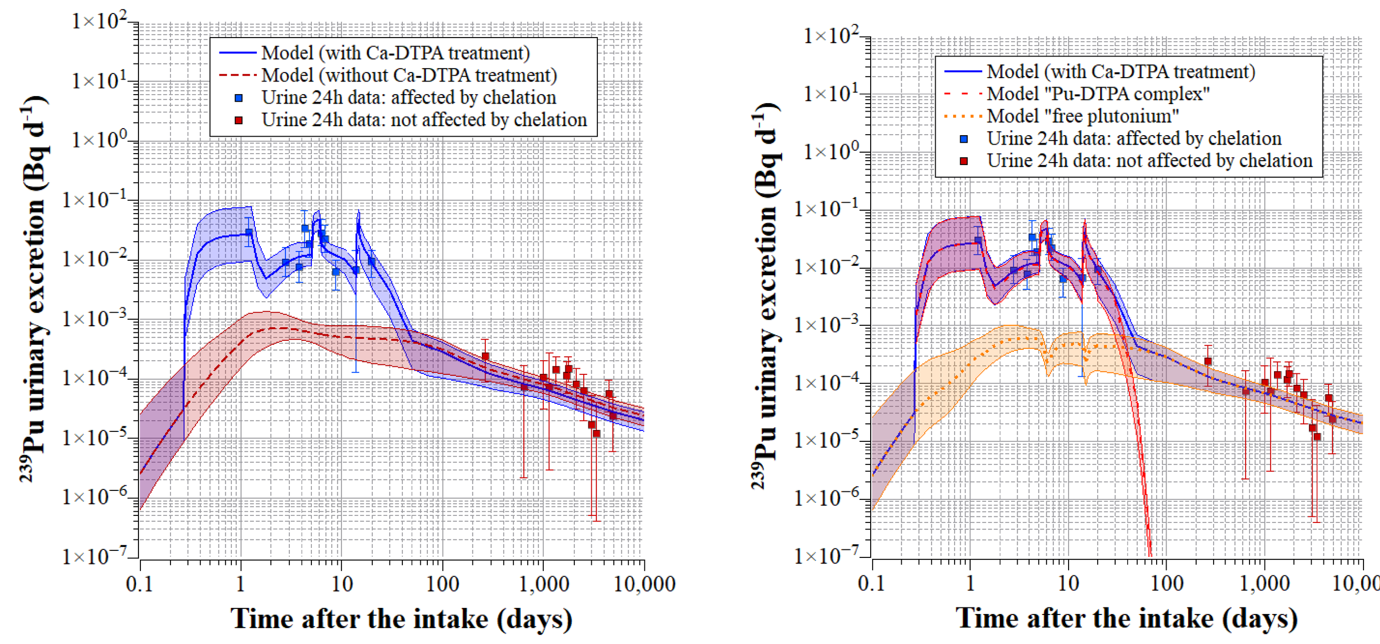
Parameter (unit)	Prior[a] (range)	Minimum χ^2 value	Average	Standard Deviation (SD)	Percentiles[b] 2.50%	50.00%	97.50%
Intake (Bq)	Log-uniform (0.161–1606)	16.1	12.0	5.2	4.6	11.6	22.4
AMAD (μm)	Log-uniform (0.002–22)	0.22	0.16	0.11	0.02	0.13	0.41
Absorption, s_p (d^{-1})	Log-uniform (0.0004–4)	0.04	0.11	0.23	0.01	0.05	0.83
Absorption, s_{pt} (d^{-1})	Log-uniform (0.0064–64)	0.64	5.99	12.16	0.02	0.97	48.83
Absorption, s_t (d^{-1})	Log-uniform (0.00007–0.7)	0.007	0.008	0.005	0.001	0.008	0.017
Calculated Quantities (unit)		**Minimum χ^2 value**	**Average**	**Standard Deviation (SD)**	**Percentiles[b] 2.50%**	**50.00%**	**97.50%**
Committed effective dose, $E(50)$ (Sv)		1.3	1.2	0.2	0.163	0.194	0.024
Committed equivalent dose, Bone Surfaces, $H_{BS}(50)$ (Sv)		38.7	37.8	6.8	0.192	0.219	0.249
Committed equivalent dose, Lung, $H_{LU}(50)$ (Sv)		9.3	9.1	1.6	0.063	0.079	0.101
Committed equivalent dose, Liver, $H_{LI}(50)$ (Sv)		0.8	0.8	0.2	0.066	0.077	0.090
χ^2/nData		**0.71**	**0.88**	**0.10**	**0.74**	**0.86**	**1.11**

Goodness-of-fit for Lungs and Feces

➢ **Simultaneous 5-parameter fit to the entire bioassay data**
- χ^2 /nData = 0.88 for nData = 35



Goodness-of-fit for Urine



Radiation Dose Reduction

➢ **Committed effective dose, E(50)**
➢ **Committed equivalent dose to the bone surfaces (H_{BS}), liver (H_{LI}), and lungs (H_{LU})**

Scenario	Committed dose (mSv) $E(50)$	$H_{BS}(50)$	$H_{LI}(50)$	$H_{LU}(50)$
With Ca-DTPA treatment	1.2 ± 0.2	37.8 ± 6.8	9.1 ± 1.6	0.8 ± 0.2
Without Ca-DTPA treatment	1.5 ± 0.2	44.5 ± 7.3	11.0 ± 1.8	0.8 ± 0.2
Reduction of dose	**20%**	**15%**	**17%**	**0%**

References

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