Electronic appendix

Risk of lung cancer mortality in nuclear workers from internal exposure to alpha particle-emitting radionuclides

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Table of contents

Supplemental tables..... 2

Supplemental figures..... 14

Supplemental bibliography..... 16

Supplementary tables

eTable 1

Definitions of socioeconomic status (SES), values assigned to original SES variable and binary variable

OPCS[a] definitions of Social Class (OPCS 1980)		**Original SES variable**	**Recoded as binary SES variable**
Category	**Description**		
V	Unskilled occupations	1	1
IV	Partly skilled occupations	2	
III M	Skilled occupations (manual)		
III N	Skilled occupations (non-manual)	3	2
II	Intermediate occupations	4	
I	Professional, etc. occupations		

BNFL[b] definitions of social class	**Original SES variable**	**Recoded as binary SES variable**
Industrial occupations	5	1
Non-industrial occupations	6	2

a OPCS: Office of Population Censuses and Surveys
b BNFL: British Nuclear Fuels Limited

eTable 2

Distribution of internal doses (mGy) and external doses (mSv) cohort and case-control status. P25 and P75 are 25th and 75th percentiles, respectively.

	Cohort	Cases					Controls					Cases & controls				
		n	Median	P25	P75	Max	n	Median	P25	P75	Max	n	Median	P25	P75	Max
Total alpha dose (>0) (mGy)	SCK·CEN[a]	6	0.07	0.04	0.11	0.22	12	1.36	0.03	4.21	6.29	18	0.16	0.04	2.97	6.29
	CEA-COGEMA[b]	17	8.32	1.29	22.62	97.8	33	2.5	0.12	6.05	74.59	50	2.87	0.16	11.24	97.8
	UKAEA[c]	78	1.38	0.38	4.07	304.91	97	1.06	0.3	3.05	83.38	175	1.21	0.34	3.1	304.91
	AWE[d]	86	14.65	5.79	29.87	315.63	146	9.55	3.42	21.1	191.31	232	11.26	3.8	25.14	315.63
	BNFL[e]	314	2.05	0.61	5.91	61.34	932	2.11	0.56	6.39	87.35	1246	2.1	0.56	6.36	87.35
	All cohorts	501	2.43	0.68	9.06	315.63	1220	2.42	0.58	7.77	191.31	1721	2.43	0.6	8.36	315.63
Plutonium alpha dose (>0) (mGy)	SCK·CEN	5	0.09	0.05	0.11	0.22	6	0.15	0.01	0.63	4.74	11	0.09	0.04	0.27	4.74
	CEA-COGEMA	10	6.17	1.29	22.56	97.57	21	3.55	1.9	6.69	24.49	31	3.6	1.36	11.31	97.57
	UKAEA	67	1.05	0.29	2.24	98.67	71	0.95	0.37	2.1	35.35	138	1.01	0.35	2.22	98.67
	AWE	80	6.22	1.5	18	110.43	133	6.06	1.13	15.4	51.87	213	6.16	1.26	16.43	110.43
	BNFL	86	0.69	0.2	1.73	43.15	232	0.85	0.26	1.92	15.79	318	0.75	0.23	1.85	43.15
	All cohorts	248	1.32	0.37	5.78	110.43	463	1.25	0.37	4.14	51.87	711	1.27	0.37	4.66	110.43
Uranium alpha dose (>0) (mGy)	SCK·CEN	--	--	--	--	--	6	3.48	2.1	4.44	6.29	6	3.48	2.1	4.44	6.29
	CEA-COGEMA	15	0.24	0.05	7.24	97.61	29	0.12	0.01	0.34	74.59	44	0.15	0.01	0.46	97.61
	UKAEA	52	0.22	0.07	1.54	301.52	70	0.15	0.03	1.38	81.83	122	0.19	0.04	1.45	301.52
	AWE	72	3.93	1.69	7.68	104.93	125	3.25	1.53	5.93	30.52	197	3.48	1.57	6.13	104.93
	BNFL	259	2.23	0.67	6.56	61.34	781	2.38	0.58	7.04	87.35	1040	2.34	0.6	6.95	87.35
	All cohorts	398	2.08	0.49	6.46	301.52	1011	2.22	0.47	6.4	87.35	1409	2.17	0.48	6.41	301.52
Other radionuclide alpha dose (>0) (mGy)	SCK·CEN	1	0	0	0	0	--	--	--	--	--	1	0	0	0	0
	CEA-COGEMA	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	UKAEA	2	0.55	0.02	1.07	1.07	6	0.35	0.1	0.4	0.6	8	0.35	0.06	0.5	1.07
	AWE	21	1.58	0.29	14.97	308.07	26	0.54	0.07	36.8	186.01	47	1.5	0.15	29.27	308.07
	BNFL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

	Cohort	Cases					Controls					Cases & controls				
		n	Median	P25	P75	Max	n	Median	P25	P75	Max	n	Median	P25	P75	Max
	All cohorts	24	1.29	0.25	14.86	308.07	32	0.4	0.08	28.1	186.01	56	0.54	0.12	21.9	308.07
External photon dose (>0) (mGy)	SCK·CEN	12	1.63	0.76	4.42	708.41	20	10.72	1.32	44	533.97	32	4.12	0.93	29.35	708.41
	CEA-COGEMA	11	2.99	1.45	21.65	143.31	29	5.85	1.5	35.8	121.7	40	5.35	1.48	27.22	143.31
	UKAEA	93	54.66	20.7	126.3	1675.9	104	40.58	14.3	97.9	768.04	197	49.6	17	115	1675.9
	AWE	85	13.73	6.63	27.32	355.78	151	14.18	6.7	38.4	245.54	236	14.01	6.66	35.05	355.78
	BNFL	318	36.59	13	90.79	1352.3	960	38.84	15	98.1	1617.3	1278	38.41	14.6	96.96	1617.3
	All cohorts	519	30.77	10.1	81.34	1675.9	1264	33.86	12	87	1617.3	1783	32.99	11.5	84.55	1675.9

[a] SCK·CEN: Studiecentrum voor Kernenergie·Centre d'Étude de l'énergie Nucléaire (including also Belgoprocess and Belgonucleaire)
[b] CEA-COGEMA: Commissariat à l'énergie atomique – Compagnie générale des matières nucélaires
[c] UKAEA: United Kingdom Atomic Energy Authority
[d] AWE: Atomic Weapons Establishment
[e] BNFL: British Nuclear Fuels Limited

eTable 3

Odds ratios (OR), standard errors (SE) and 90% confidence intervals (CI) for lung cancer mortality with smoking and socioeconomic status (SES) variables

Model	Parameter	Cases	Controls	OR	SE	90% CI[a]	
Smoking	Never (Reference category)	6	48	1	-	-	-
	Ever	457	802	9.2	1.7	4	21
	Unknown	90	483	2.5	1.7	1.1	5.9
Smoking	Never/unknown (Reference category)	83	369	1	-	-	-
	Ever	470	964	3	1.2	2.3	3.9
Smoking	Never (Reference category)	6	48	1	-	-	-
	Ever/unknown	547	1285	6.2	1.6	2.8	14
SES	Unskilled occupations (Reference category)	32	82	1	-	-	-
	Partly skilled and skilled (manual) occupations	12	33	0.91	1.5	0.46	1.8
	Skilled (non-manual) occupations	60	78	2.2	1.4	1.4	3.6
	Intermediate and professional occupations	110	130	2.3	1.3	1.4	3.7
	Industrial occupations	301	805	Aliased	-	-	-
	Non-industrial occupations	38	205	0.46	1.2	0.33	0.65
SES (all centres except BNFL)	Unskilled occupations (Reference category)	32	82	1	-	-	-
	Partly skilled and skilled (manual) occupations	12	33	0.91	1.5	0.46	1.8
	Skilled (non-manual) occupations	60	78	2.2	1.4	1.4	3.6
	Intermediate and professional occupations	110	130	2.3	1.3	1.34	1.4
SES (BNFL only)	Industrial occupations (Reference category)	301	805	1	-	-	-
	Non-industrial occupations	38	205	0.46	1.2	0.33	0.65
Binary SES	Lower (Reference category)	345	920	1	-	-	-
	Higher	208	413	0.91	1.2	0.7	1.1

[a] Based on likelihood profile.

eTable 4

Estimates of excess odds ratio (EOR) per Gy for lung cancer mortality – matched on sex, age and facility, adjusted for external dose and either socioeconomic status or smoking (lag of 10 years)

	EOR/Gy	90% CI[a]	
Not adjusted for either SES or smoking			
Total alpha dose	14	4.9	27
Plutonium alpha dose	43	15	90
Uranium alpha dose	8.7	-0.01	22
Adjusted for SES (not adjusted for smoking)			
Total alpha dose	13	3.8	26
Plutonium alpha dose	49	18	100
Uranium alpha dose	6.6	-1.2	19
Adjusted for smoking (not adjusted for SES)			
Total alpha dose	13	3.7	26
Plutonium alpha dose	42	13	91
Uranium alpha dose	7.5	-0.89	21

[a] Based on likelihood profile

eTable 5

Sensitivity analysis: EOR/Gy (adjusted for external dose, smoking and either original socioeconomic status (SES) or binary SES variable), lag of 10 years.

	EOR/Gy	90% CI[a]		Deviance
Adjustment for original socioeconomic status				
Total alpha dose	11	2.6	24	1153.18
Plutonium alpha dose	50	17	106	1149.05
Uranium alpha dose	5.3	-1.9	18	1157.86
Adjustment for binary-recoded socioeconomic status				
Total alpha dose	13	3.7	26	1176.49
Plutonium alpha dose	42	13	91	1175.28
Uranium alpha dose	7.5	-0.9	21	1181.79

[a] Based on likelihood profile

eTable 7

Excess odds ratio (EOR) per Gy with 90% confidence intervals (CI) for 5- and 15-year lags (adjusted for external dose, socioeconomic status and smoking)

		Lag of 5 years			Lag of 15 years		
	n	EOR/Gy	90% CI[a]		EOR/Gy	90% CI[a]	
Total alpha dose	1886	11	2.7	22	11	2	25
Plutonium alpha dose	1886	39	11	86	56	18	121
Uranium alpha dose	1886	6.6	-1.1	19	5.1	-2.3	18

[a]: Based on likelihood profile

eTable 6

Excess odds ratio (EOR) per Gy of categorical analyses including a zero dose category (adjusted for external dose, socioeconomic status and smoking, 10-year lag)

	Dose category	Cases	Controls	EOR	90% CI[a]	
Total alpha dose	[0][b]	52	113	0	-	-
	(0, 10]	387	968	-0.06	-0.36	0.39
	(10, 25]	61	178	-0.28	-0.55	0.15
	(25, 50]	31	58	0.3	-0.25	1.3
	(50, ∞]	22	16	1.2	0.08	3.6
Plutonium dose	[0][b]	305	870	0	-	-
	(0, 10]	202	401	0.39	-0.01	0.97
	(10, 25]	30	53	0.37	-0.2	1.4
	(25, 50]	10	8	4.5	0.94	15
	(50, ∞]	6	1	32	4.3	428
Uranium dose	[0][b]	155	322	0	-	-
	(0, 10]	336	839	-0.17	-0.41	0.16
	(10, 25]	33	126	-0.43	-0.65	-0.08
	(25, 50]	19	39	0.08	-0.4	0.9
	(50, ∞]	10	7	0.39	-0.45	2.6
Other radionuclide dose	[0][b]	529	1301	0	-	-
	(0, 10]	16	22	0.08	-0.41	0.99
	(10, 25]	4	1	11	1	142
	(25, 50]	1	5	-0.49	-0.95	1.6
	(50, ∞]	3	4	0.47	-0.64	4.9

[a] 90% confidence interval (CI) based on likelihood profile. [b] Reference category.

eTable 8

EOR/Gy to each of 4 lung regions (90% CIs) (adjusted for external dose, socioeconomic status and smoking), 10-year lag (data available for UK cohorts only, n=1805)

	Lung region	EOR/Gy	90% CI[a]		Deviance
Total alpha dose	BBsec	3.8	0.04	9.9	1109.30
	BBbas	28	-1.6	88	1109.99
	bb	7.8	0.36	19	1109.00
	AI	14	4.4	30	1104.12
Plutonium alpha dose	BBsec	25	6.6	57	1105.18
	BBbas	190	49	425	1105.65
	bb	52	14	118	1105.05
	AI	37	11	84	1103.74
Uranium alpha dose	BBsec	1.9	-1.3	8	1111.50
	BBbas	28	-13	102	1111.20
	bb	3.5	-2.2	15	1111.45
	AI	3.6	-0.89	28	1109.94
Alpha dose from other nuclides	BBsec	1.3	-1.5	19	1111.91
	BBbas	3.7	-4.3	54	1111.91
	bb	6.1	-4.1	63	1111.73
	AI	5.8	-1.9	39	1111.19

[a] Based on likelihood profile. BBsec: bronchial secretory cell layer; BBbas: bronchial basal cell layer; bb: bronchiolar region; AI: alveolar-interstitial region.

eTable 9

Excess odds ratio (EOR) per Gy and 90% confidence interval (CI) (adjusted for external dose, socioeconomic status and smoking), 10-year lag – ICRP weighted lung doses vs. average lung doses (energy deposited per unit mass) (data available for UK cohorts only, n=1805)

	ICRP weighted lung dose			Average lung dose		
	EOR/Gy	90% CI[a]		EOR/Gy	90% CI[a]	
Total alpha dose	9.6	1.6	22	14	4.3	30
Plutonium alpha dose	45	12.8	101	36	10.7	83
Uranium alpha dose	5.1	-2.2	18	10	-0.91	28
Plutonium alpha dose	44	12	100	35	9.3	82
Uranium alpha dose	3.9	-2.7	17	8.7	-2.6	28
Plutonium alpha dose	44	12	100	34	5.6	95
Uranium alpha dose	3.9	-2.7	17	8.7	-2.6	28
Other radionuclides alpha dose	3.1	-3.1	39	4.7	-2.5	41

[a] Based on likelihood profile.

eTable 10

Excess odds ratio (EOR) per Gy and 90% confidence interval (CI) for BNFL cohort (adjusted for smoking, socioeconomic status and external dose), 10-year lag

	EOR/Gy	90%CI[a]	
Fully adjusted models[b]			
Total alpha dose	-1.05	<0	13.02
External dose	-0.38	<0	0.25
Plutonium alpha dose	48.83	<0	195.4
External dose	-0.46	<0	0.16
Uranium alpha dose	-3.51	<0	9.72
External dose	-0.38	<0	0.26
External dose	-0.39	<0	0.22

All analyses for 339 cases and 1010 controls; alpha doses and external doses included in linear subterm of all models. [a] 90% confidence interval (CI) based on likelihood profile. [b] Adjusted for smoking and SES (loglinear subterm). <0: lower CI is on boundary of parameter space (1/max dose).

eTable 11

Excess odds ratio (EOR) per Gy and 90% confidence interval (CI) for leave-one-out (cohort) sensitivity analyses (adjusted for smoking, socioeconomic status and external dose), 10-year lag

	n	Cases	Controls	EOR/Gy	90% CI[a]	
Total alpha dose						
All cohorts	*1886*	*553*	*1333*	*11*	*2.6*	*24*
Without SCK·CEN[b]	1858	544	1314	11	2.6	24
Without CEA-COGEMA[c]	1833	536	1297	9.6	1.7	22
Without UKAEA[d]	1681	456	1225	13	3.2	27
Without AWE[e]	1635	462	1173	2.4	-3	14
Without BNFL[f]	537	214	323	28	8.4	68
Plutonium alpha dose						
All cohorts	*1886*	*553*	*1333*	*50*	*17*	*106*
Without SCK·CEN[b]	1858	544	1314	52	18	111
Without CEA-COGEMA[c]	1833	536	1297	43	12	96
Without UKAEA[d]	1681	456	1225	61	21	130
Without AWE[e]	1635	462	1173	37	0.18	121
Without BNFL[f]	537	214	323	50	15	117
Uranium alpha dose						
All cohorts	*1886*	*553*	*1333*	*5.3*	*-1.9*	*18*
Without SCK·CEN[b]	1858	544	1314	5.2	-2	18
Without CEA-COGEMA[c]	1833	536	1297	5.2	-2.1	18
Without UKAEA[d]	1681	456	1225	6.8	-2.6	21
Without AWE[e]	1635	462	1173	-0.1	-3.3	9.3
Without BNFL[f]	537	214	323	26	2.5	80

[a] 90% confidence interval (CI) based on likelihood profile
[b] SCK·CEN: Studiecentrum voor Kernenergie·Centre d'Étude de l'énergie Nucléaire
[c] CEA-COGEMA: Commissariat à l'énergie atomique – Compagnie générale des matières nucélaires
[d] UKAEA: United Kingdom Atomic Energy Authority
[e] AWE: Atomic Weapons Establishment
[f] BNFL: British Nuclear Fuels Limited

Supplementary figures

eFigure 1

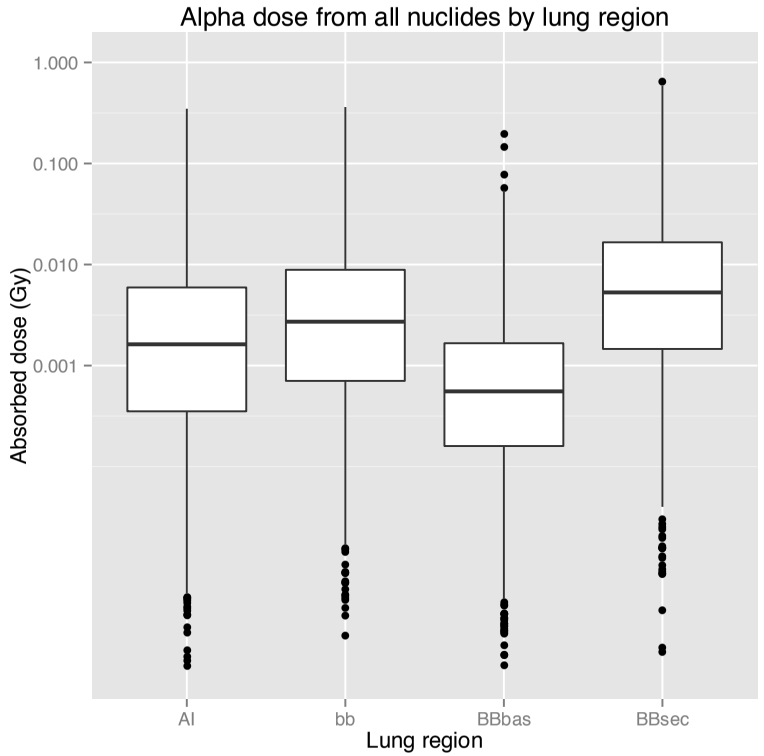
Absorbed doses to individual regions of the lung from all radionuclides, plutonium, uranium and other radionuclides (in Gy), 10-year lag

eFigure 2

Comparison of ICRP weighted lung doses and average lung doses (energy deposited per unit mass), by case and control status, for all UK cohorts pooled

Supplementary bibliography

OPCS. 1980. *Classification of Occupations 1980*. HMSO, London.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BBbas
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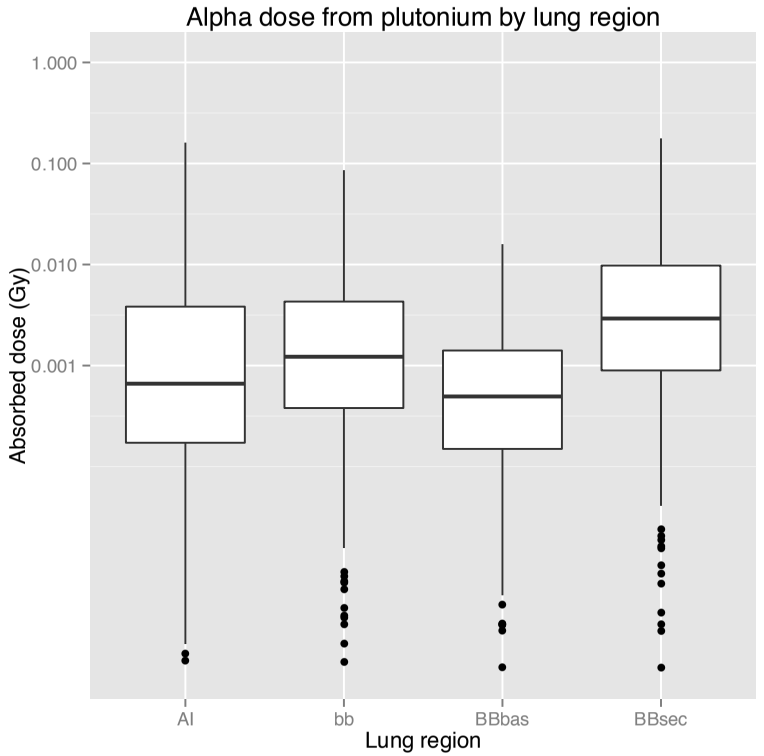
Lung region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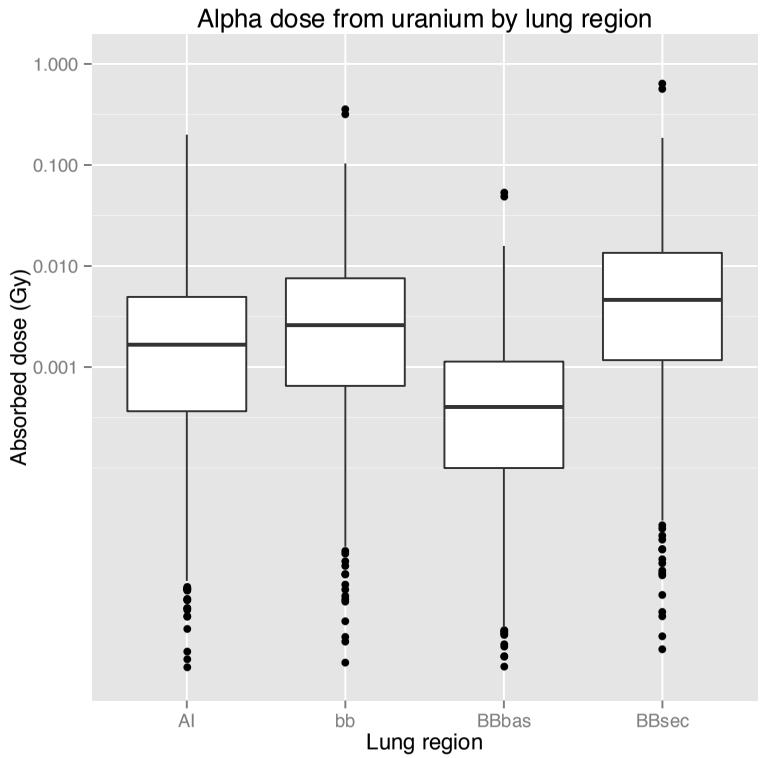
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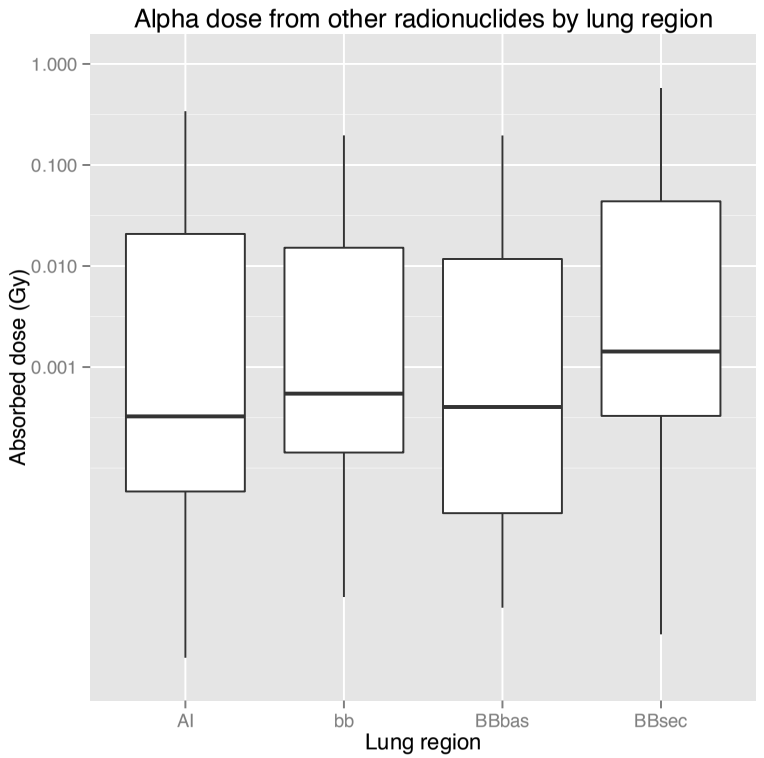
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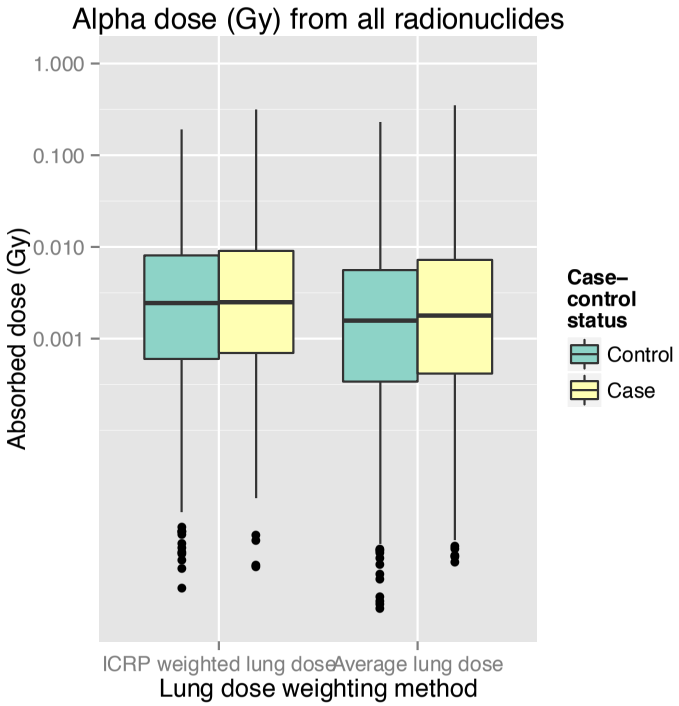
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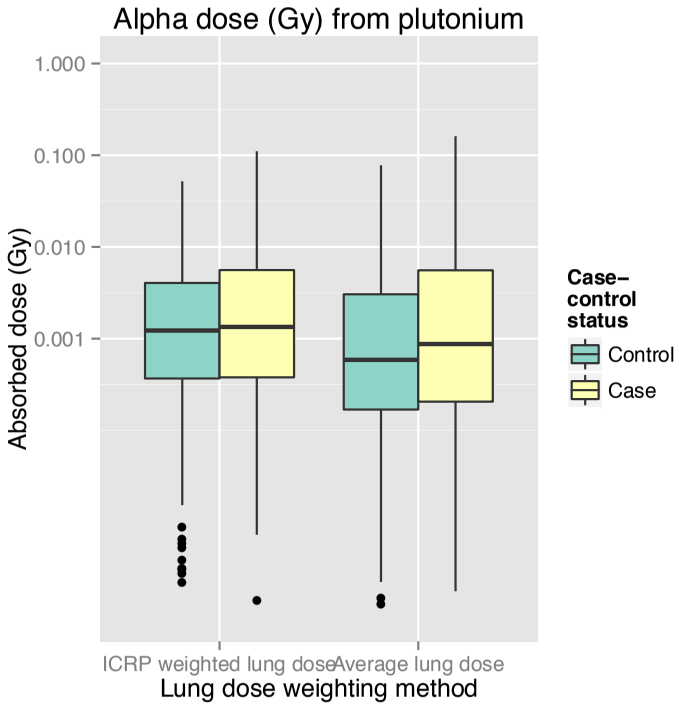
Lung dose weighting method
Case–control status
Control
Case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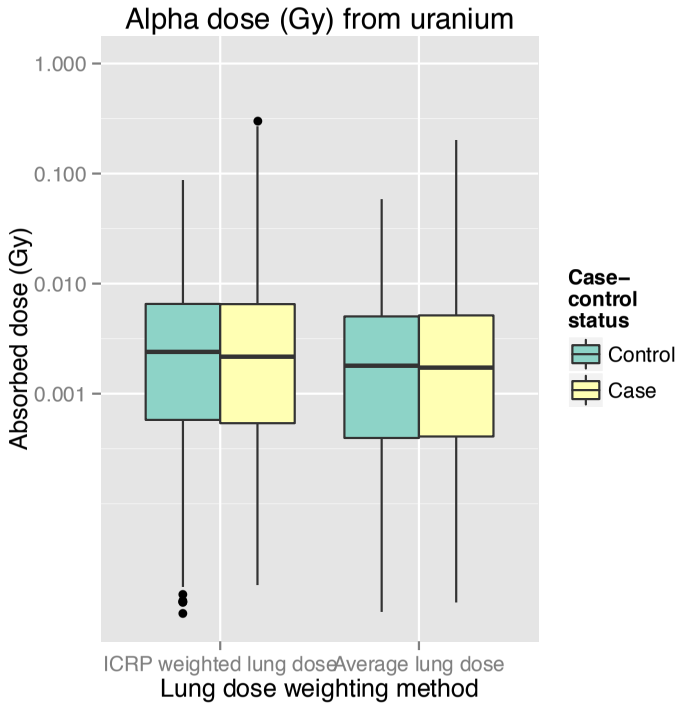
Lung dose weighting method
Case–control status
Control
Case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Control
Case