U.S. Million Person Study of Low-Level and Low-Dose-Rate Health Effects

Human Health Radiation Risk Assessment in the Nuclear Power and Industrial Radiographer Worker Cohorts

Lawrence T. Dauer

Vanderbilt-Ingram Cancer Center

NCRP — Scientific Authority Since 1929 — Congressionally Chartered

ORISE

Oak Ridge National Laboratory

Memorial Sloan Kettering Cancer Center

Disclosure, L. Dauer

2 y, Indian Point 3 NPP, Radiological Engineer/Supervisor.

20y, Memorial Sloan Kettering Cancer Center.

ational Council on Radiation Protection and Measurements

Council Member

.S. Million Person Study of Low-Level and Low-Dose-Rate Health ffects

The NCRP currently holds several grants/contracts that provide funding for the M
from: DOE, NASA, CDC, US Navy

L. Dauer - Scientific Director – voluntary role assisting John Boice, PI

S: Human Health Radiation Risk Assessment in the lear Power and Industrial Radiographer Worker Cohorts

ics

Boice, et al. A Million Persons, a Mill Dreams… IJRB, 2022

illion Person Study

RC Cohorts

- Nuclear Power Plant Workers
- Industrial Radiographers
- Dosimetry is key.
- Selected Results

John D. Boice, Jr., ScD
MPS Principal Investigator
Vanderbilt University Medical Center,
National Council on Radiation Protection
and Measurements.

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Memorial Sloan Kettering Cancer Center,
National Council on Radiation Protection an
Measurements.

Who? - Million Person Study Population

Oppenheimer, General Leslie
Enrico Fermi, Hans Bethe,
re Hall

Sub-Cohort	Number
Manhattan Project and other DOE Sites	300,000
Atomic Veterans (DOD)	113,806
Nuclear Power Plant Workers (NRC)	135,193
Industrial Radiographers (NRC)	123,401
Medical Radiation Workers (Landauer®)	109,019
Nuclear Submariners and others (US Navy)	210,000
Radium Dial Workers (DOE)	3,200

>25%

Boice et al. *The Million Person Study, Whence it Came and Why*. IJRB April 2022

ow are the NRC Cohorts Different from the other MPS Cohor

e Dosimetry is Exceptional

REIRS Recorded Personal Dose Equivalents

Annual organ doses able to be estimated (NRCP Dosimetry Guidance)

e Follow-up is Exceptional (>99%) for nearly 260,000 Workers

Nuclear Power Plant Workers

ndustrial Radiographers

reer Doses from other work/industries obtained from DOE REMS, Navy, Landauer, and other data sources.

oad Dose Distribution with maximum organ doses ~1 Gy or more.

Up to 30 mSv/quarter, considering 5 x (N-18) limits at the time

Nuclear Power Plant Workers (1957-1985)

efine Study Cohort

opulation Tracing & Vitals

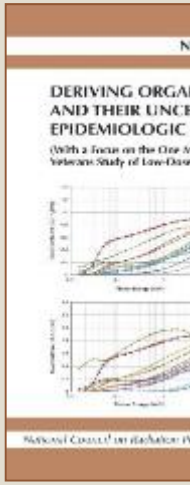
EIRS/Landauer® Dose Data
vailable

adge Result to D_T

xposure Source Term

xposure Conditions

30,000 Nuclear Utility Workers
red prior to 1985



Shippingport Atomic Power Station, 1957

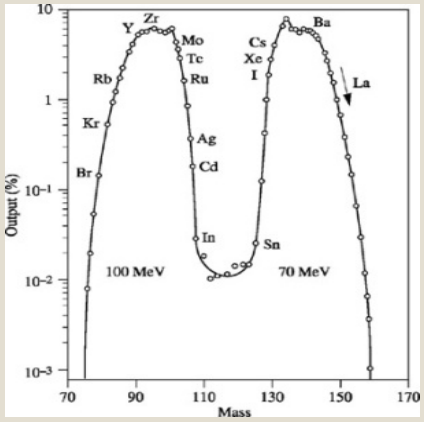
Nuclear Power Plant Exposure Sources

rce Term

eactor Core & System

ission Products

- Cesium
- Iodine
- Krypton/Xenon



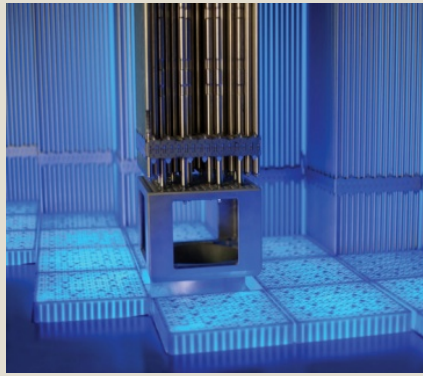
ctivation Products

- Corrosion "Crud"
- Cobalt-60, Cobalt-58
- 80%+ exposures in outage

Source Term Parameters

- System Design
- Operational History
- Operational Mode
- Coolant Chemistry
- Construction Materials
- Fuel Integrity
- ~0.6-1.5MeV
- ~0.7 MeV,

Activity weighted



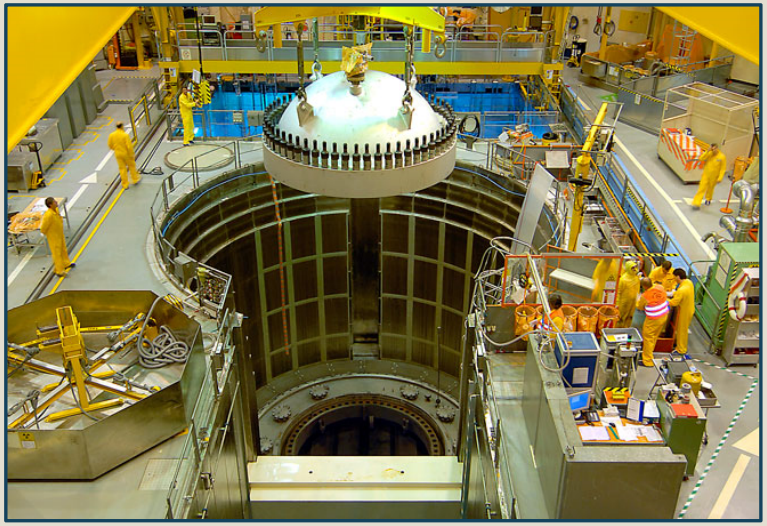
Nuclear Power Plant Exposure Conditions

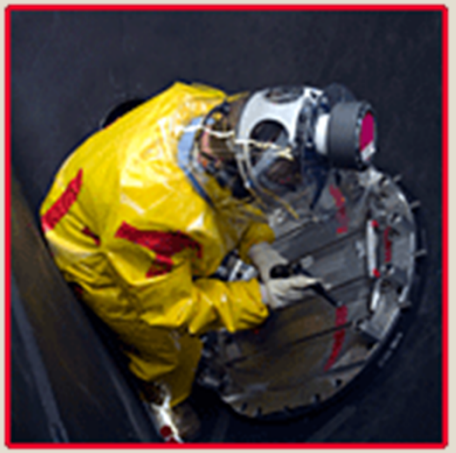
- Mostly external photon
- Neutron and Internal (low)
- Engineering controls & PPE used frequently
  - HEPA
  - Respiratory Protection
  - Gloves/boots
  - Coveralls
  - Eye shields
- Most dose during outages
- Primarily AP
  - With some CC, LAT, PA

Work Function	% Collective Dose (1975-1985)
Reactor Operations and Surveillance	9-13%
Routine Maintenance	27-53%
Inservice Inspection	3-9%
Special Maintenance	19-47%
Waste Processing	3-7%
Refueling	4-8%

NPP Plethora of "Higher Dose" Outage Tasks

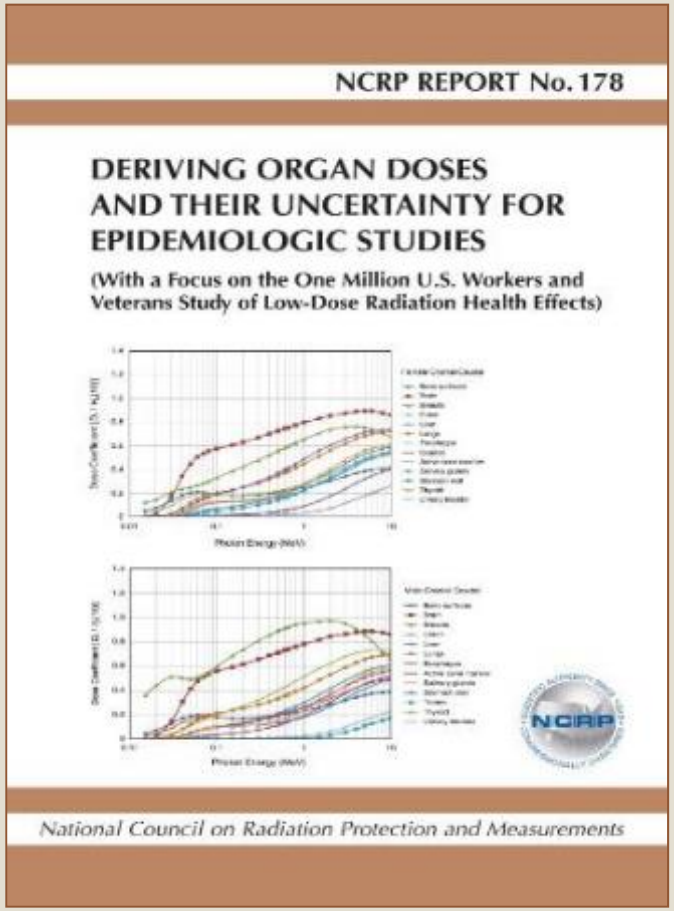
- Inspections
- Decontamination
- Health Physics
- Valve Maintenance
- Insulation
- Control Rod Drives
- Refueling
  - Rx Vessel, Rx Cavity
- Steam Generators
  - Nozzle Dams, eddy current, tube plugging, girth welds
- Drywell work
- Diving
- Scaffolding / Shielding
- Rx Thermocouples
- Transfer Canal Modifications





Industrial Radiographer Exposure Sources

- External gamma
- Typical
  - Ir-192/Co-60 , ~ 200/1
- Much less typical
  - Se-75
  - X-ray tubes
- Neutron (very low)
- AP geometry
  - ~0.3 MeV
- 10 CFR Part 34 (‘65)



Personal Dose Equivalent, $H_p(10)$ Distribution Nuclear Power Plant Workers (1957-1985)

REIRS

Dose Category	N	%
< 10 mSv*	94,454	73.8
10 - <50 mSv*	20,303	15.9
50 - <100 mSv	6,804	5.3
100 - <500 mSv	6,278	4.9
500 - <1000 mSv	141	0.1
>1000 mSv	20	0.02
Study Population	135,193	-

stributions are based on information available in 2018 and
l slightly during the course of the epidemiologic study.

*Sampled < 50 mSv

Personal Dose Equivalent, $H_p(10)$ Distribution Industrial Radiographers (1939-2011)

REIRS
Landauer®

Dose Category	N	%
< 10 mSv*	30,764	20.7
10 - <50 mSv*	77,383	52.0
50 - <100 mSv	21,578	14.5
100 - <500 mSv	18,846	12.7
500 - <1000 mSv	322	0.2
>1000 mSv	22	0.01
Study Population	123, 401	-

stributions are based on information available in 2018 and
l slightly during the course of the epidemiologic study.

*Sampled < 50 mSv

se Estimation in Epidemiology

stimation of Absorbed Doses (**Gy**) for the organ or tissue of interest
RBM, lung, breast, brain, etc.)

External – for the year of exposure.

Internal – for the year of exposure and for each of the following 49 years.

- Using the latest biokinetic models available (in some cases updating the models based o MPS data, e.g. brain, autopsy and science-donated organs, uranium/plutonium USTUR

Addition of External + Internal components of the absorbed dose to the organ or tissue of interest.

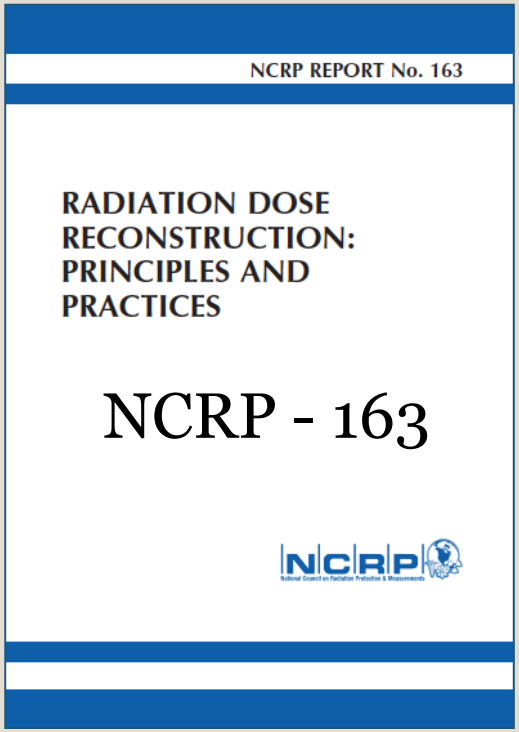
ifferences with regulatory method:

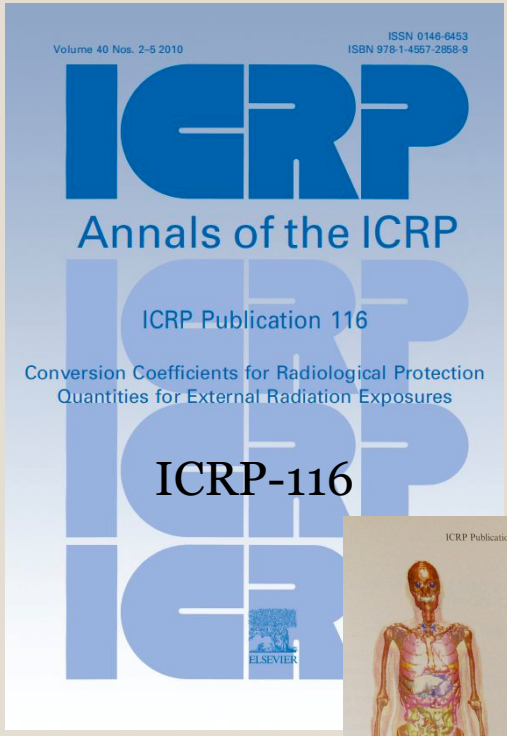
Aim for realistic dose estimates, not 'lower than limits'.

Direct - no use of weighting factors ($\not{W}_R$ and $\not{W}_T$).

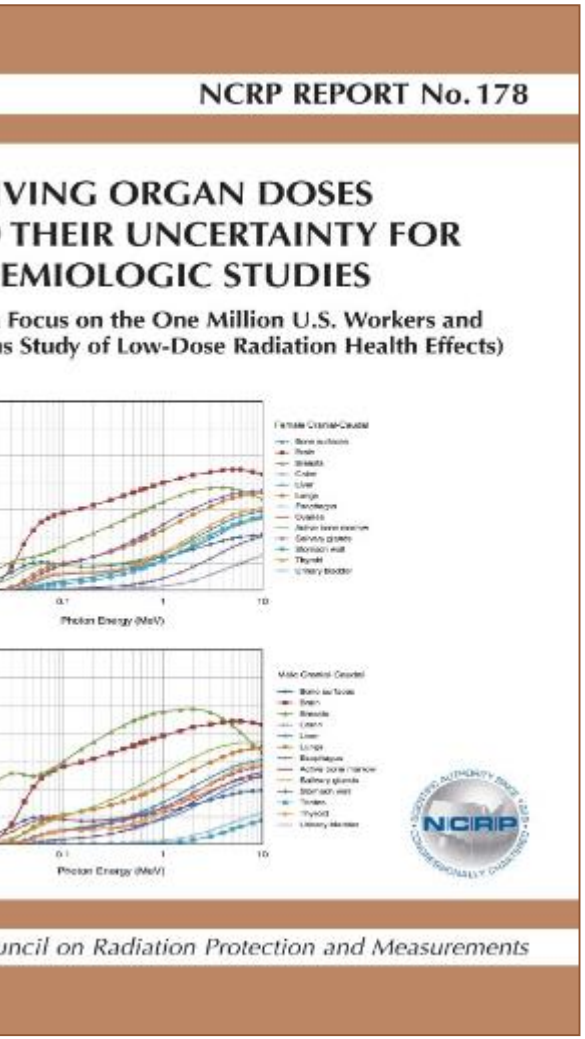
Annual absorbed doses to all organs/tissues.

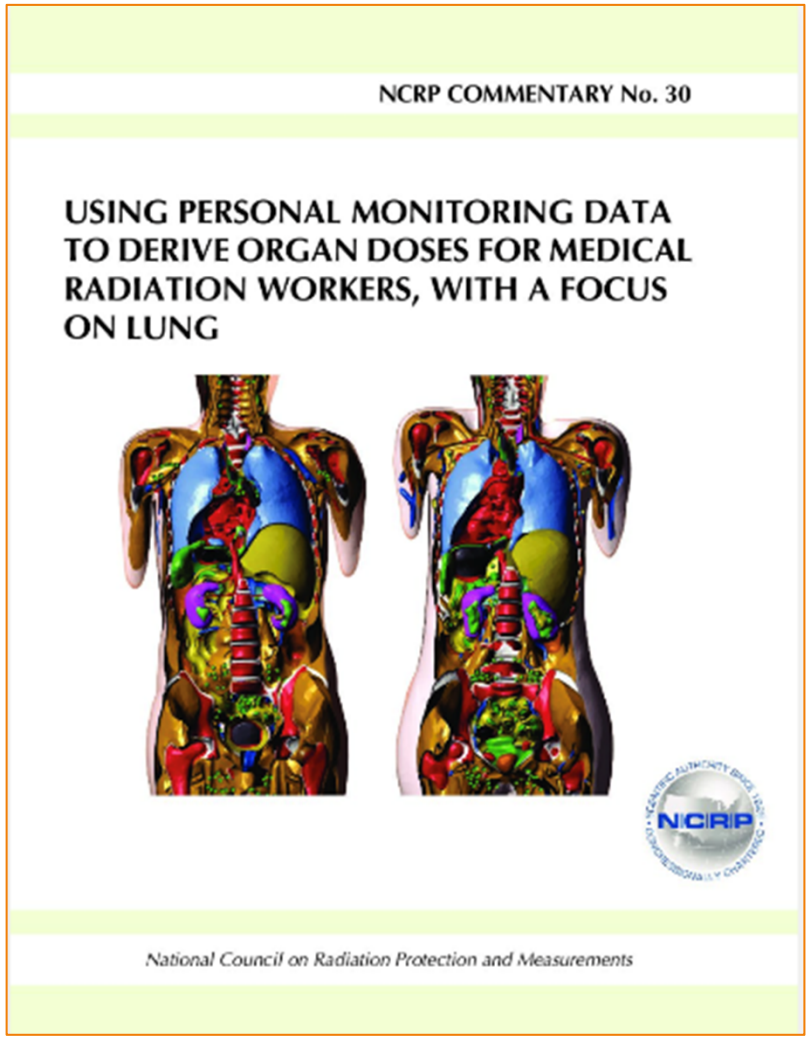
se Reconstruction: Getting to D_T

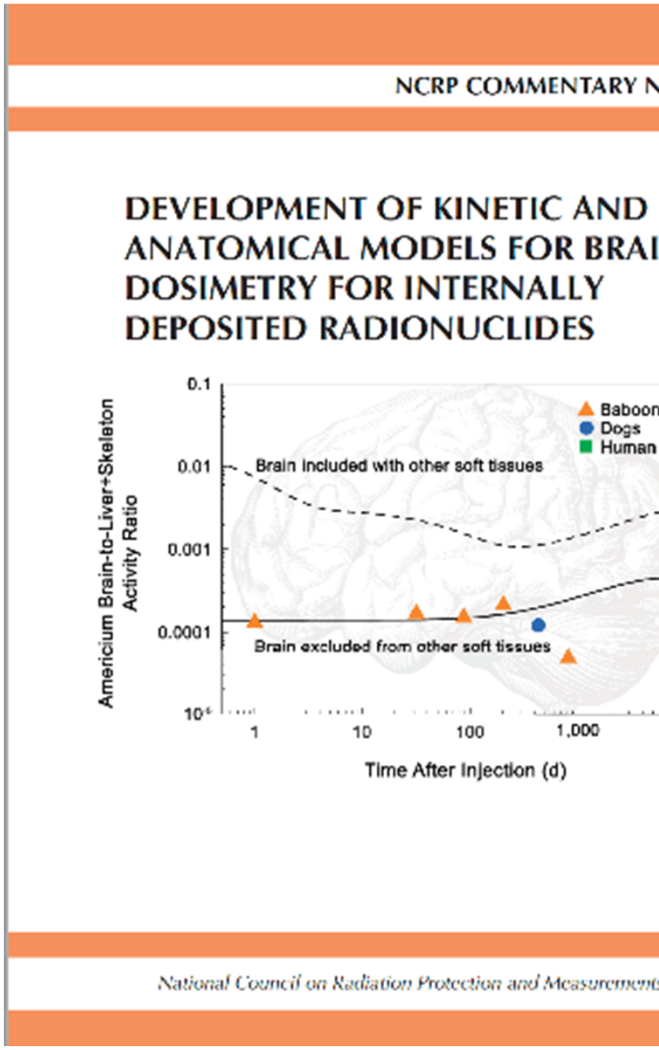




MPS: NCRP Dosimetry Guidance







Dauer LT et al. Int J Rad Biol 2022

Yoder RC et al. J Rad Pro 2022

Leggett RW et al. J Rad

PS: Nuclear Power Plant Cohort – IJRB, April 2022

ONAL JOURNAL OF RADIATION BIOLOGY
98, NO. 4, 657–678
org/10.1080/09553002.2021.1967507

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Taylor & Francis Group

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AL ARTICLE

ality from leukemia, cancer and heart disease among U.S. nuclear power workers, 1957–2011

Boice Jr[a,b], Sarah S. Cohen[c], Michael T. Mumma[d,e], Derek A. Hagemeyer[f], Heidi Chen[e], P. Golden[f], R. Craig Yoder[g], and Lawrence T. Dauer[h]

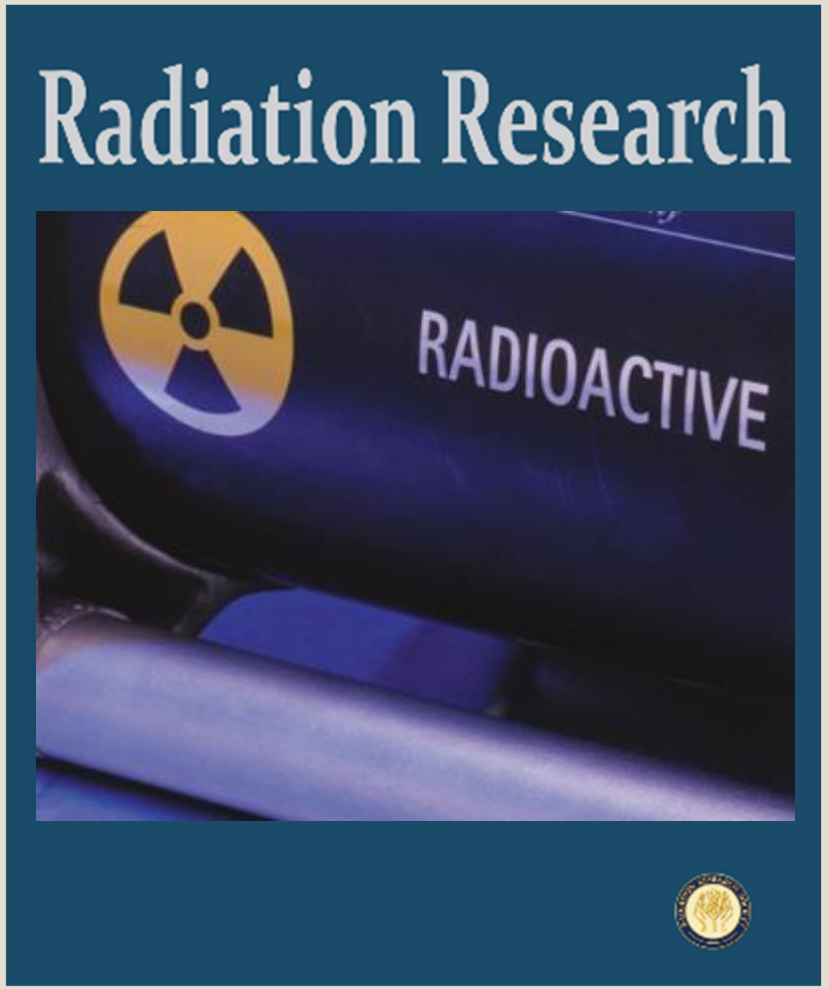
Council on Radiation Protection and Measurements, Bethesda, MD, USA; [b]Division of Epidemiology, Department of Medicine, t Epidemiology Center and Vanderbilt-Ingram Cancer Center, Vanderbilt University, Nashville, TN, USA; [c]EpidStrategies, Cary, NC, ernational Epidemiology Institute, Rockville, MD, USA; [e]Vanderbilt University Medical Center, Nashville, TN, USA; [f]Oak Ridge d Universities, Oak Ridge, TN, USA; [g]Landauer Inc (Retired), Glenwood, IL, USA; [h]Department of Medical Physics, Memorial Sloan Cancer Center, New York, NY, USA

MPS: Industrial Radiographers

oice, Jr., J. D., Cohen, S. S., Mumma, M. T., Walsh, L., agemeyer, D., Yoder, R. C. and Dauer, L. T.

ortality among Industrial Radiographers Exposed o Ionizing Radiation, 1969-2019.

adiat. Res. …to be submitted



Standard Mortality Ratio (SMR) ANALYSES Nuclear Power Plant Workers (N=135,193)

1957-2011 (mean 30.2 y follow-up)

Cause	No. Deaths	SMR	95% CI
All Causes	29,076	0.89*	0.88-0.90
All Cancer	9,329	1.03*	1.01-1.05
All Solid Cancer	8,445	1.04*	1.01-1.06
Leukemia (non-CLL)	296	1.06	0.94-1.19
Lung	3,382	1.10*	1.07-1.14
Ischemic Heart Disease	5,410	0.80*	0.78-0.82
Parkinson's Disease	140	0.90	0.76-1.06
Pleura, Mesothelioma	251	5.66*	4.98-6.40
Asbestosis	87	9.15*	7.33-11.3

Insulat

risons with the General Population can be informative but must be viewed
sly because healthy workers are different from the entire population.

* p<0.05

Mumma MT et al. Int J Radiat Biol 2022

SMR ANALYSES
Industrial Radiographers (N=123,401)
1939-2011 and followed through 2019 (mean 27.7 y follow-up)

Cause	No. Deaths	SMR	95% CI
All Causes	30,537	0.92*	0.91-0.93
All Cancer	8,515	1.00	0.98-1.02
All Solid Cancer	7,734	1.01	0.99-1.03
Leukemia (non-CLL)	241	0.92	0.81-1.04
Lung	2,772	1.04*	1.00-1.08
Ischemic Heart Disease	5,820	0.83*	0.81-0.85
Parkinson's Disease	235	0.96	0.84-1.09
Pleura, Mesothelioma	248	6.08*	5.35-6.89
Asbestosis	134	13.4*	11.2-15.9

Insulat

risons with the General Population can be informative but must be viewed
sly because healthy workers are different from the entire population.

* p<0.05

Mumma MT et al. Int J Radiat Biol 2022

MPS – NRC Cohorts - Select Results

ected Outcomes (ERR per 100 mGy)

on-CLL Leukemia

l Solid Cancers

ung Cancer

chemic Heart Disease

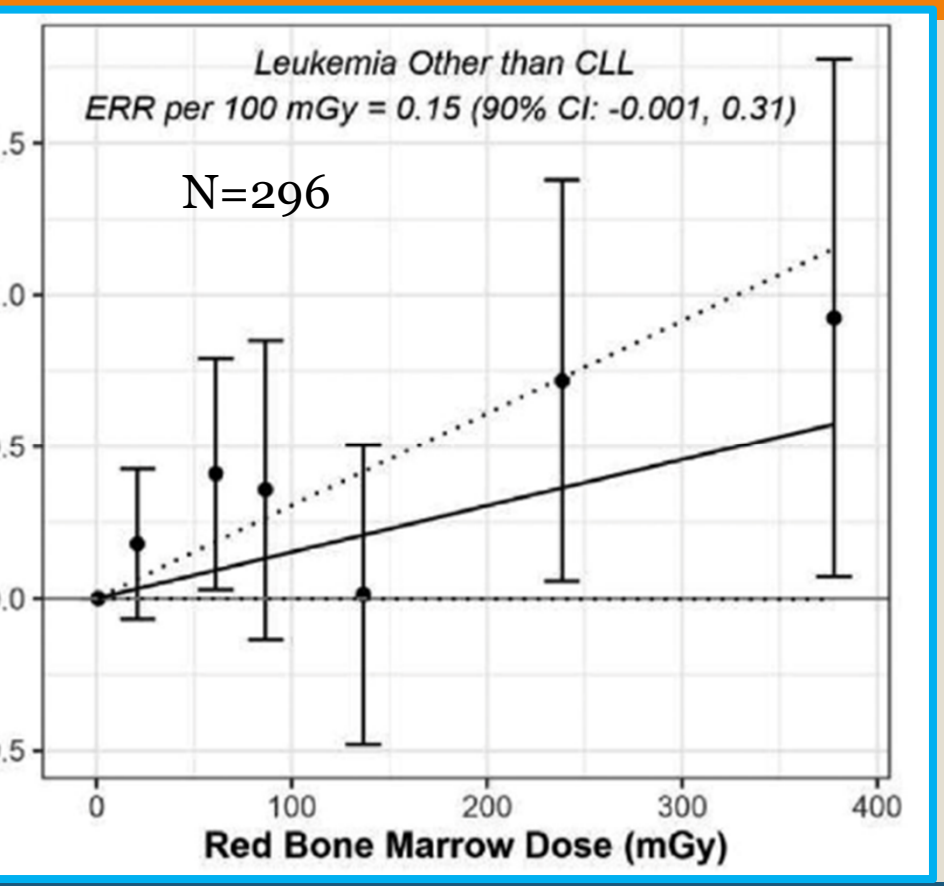
arkinson's Disease

– Excess Relative Risk = Relative Risk-1

S: NRC Cohort Results – Dose-Response for Non-CLL Leukemia

uclear Power Workers

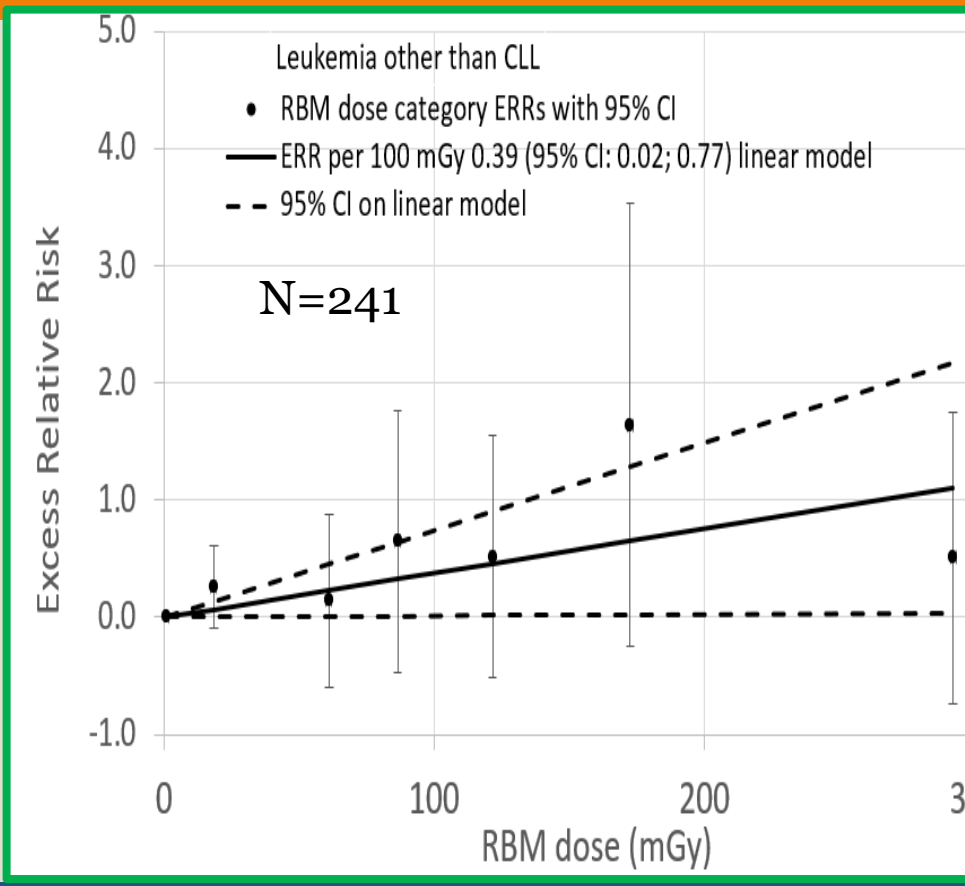
ean 37.9 mGy, Max 953 mGy



e et al. Nuclear Power Plant Workers, IJRB 2022

Industrial Radiographers

Mean 15.2 mGy, Max 1,243 mGy

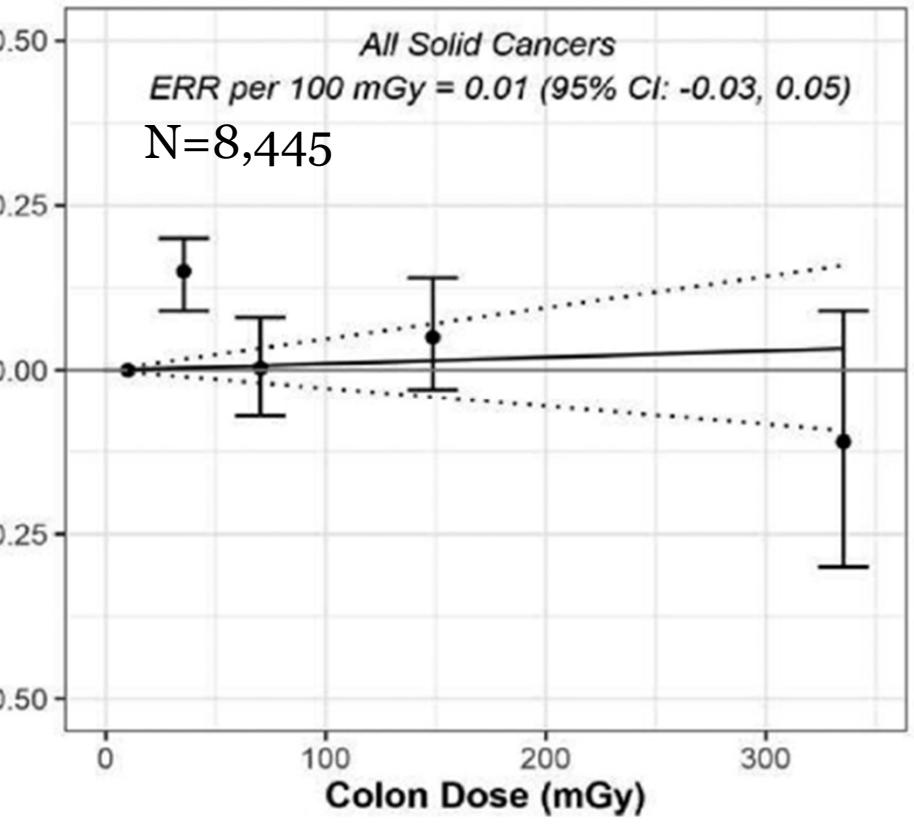


Boice et al. Industrial Rad. Rad Res to be submitted 202

S: NRC Cohort Results – Dose-Response for All Solid Cancers

uclear Power Workers

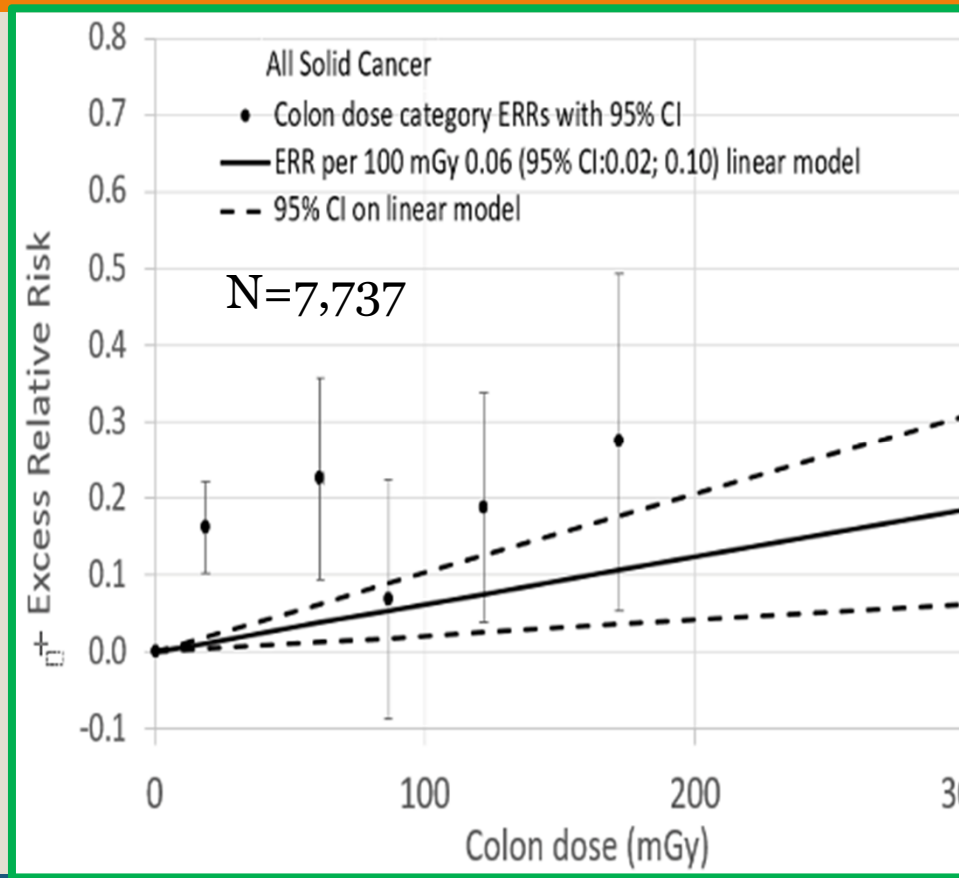
ean 43.7 mGy, Max 1,099 mGy



e et al. Nuclear Power Plant Workers, IJRB 2022

Industrial Radiographers

Mean 18.1 mGy, Max 1,478 mGy



Boice et al. Industrial Rad. Rad Res to be submitted 202

S: NRC Cohort Results – Dose-Response for All Solid Cancers

uclear Power Workers

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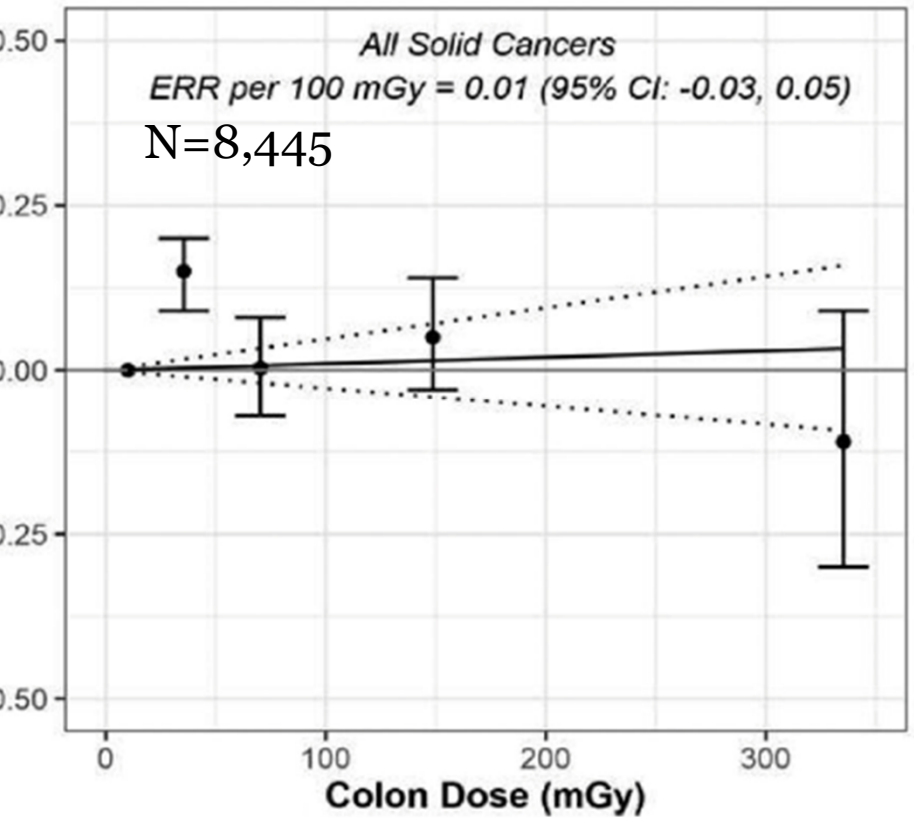
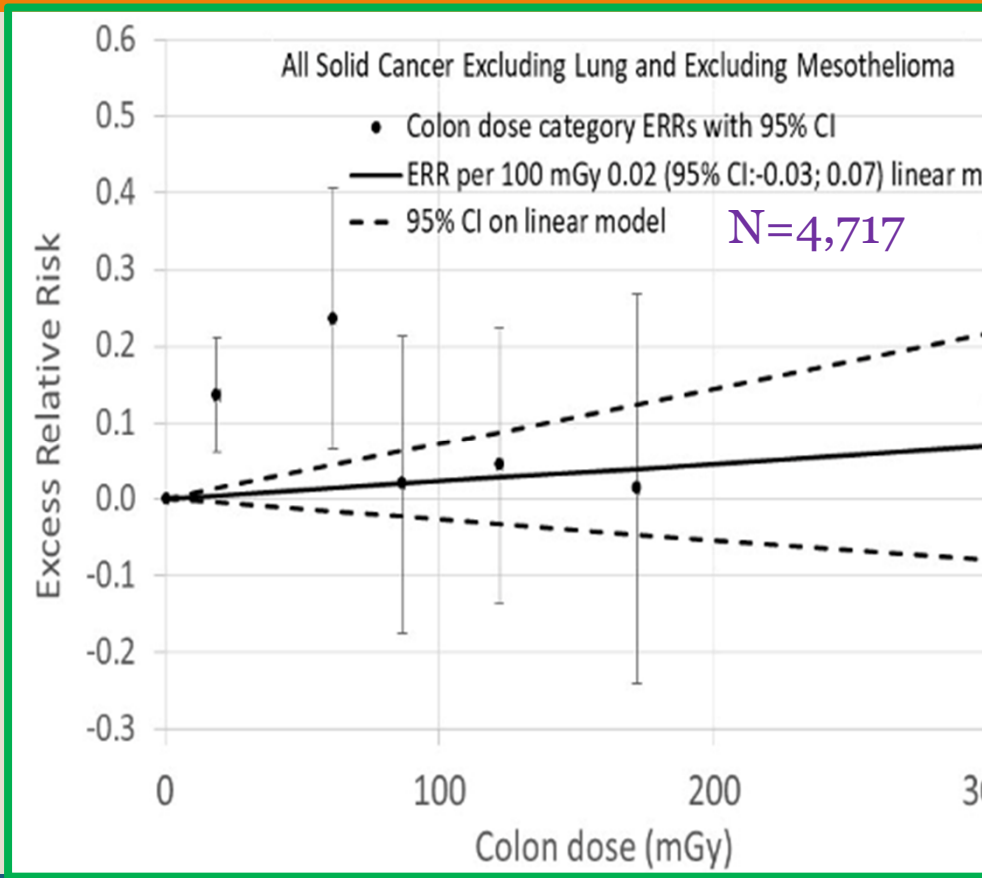


e et al. Nuclear Power Plant Workers, IJRB 2022

Industrial Radiographers

(Excluding Lung and Mesothelioma

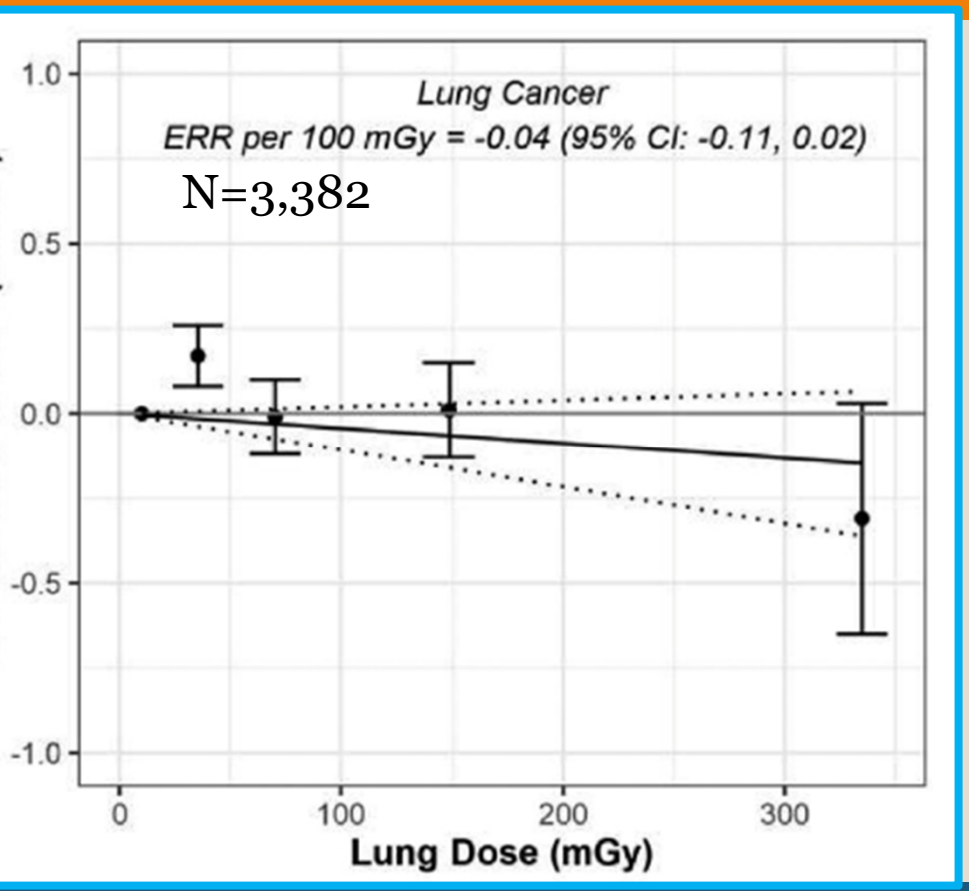


Boice et al. Industrial Rad. Rad Res to be submitted 202

S: NRC Cohort Results – Dose-Response for Lung Cancer

uclear Power Workers

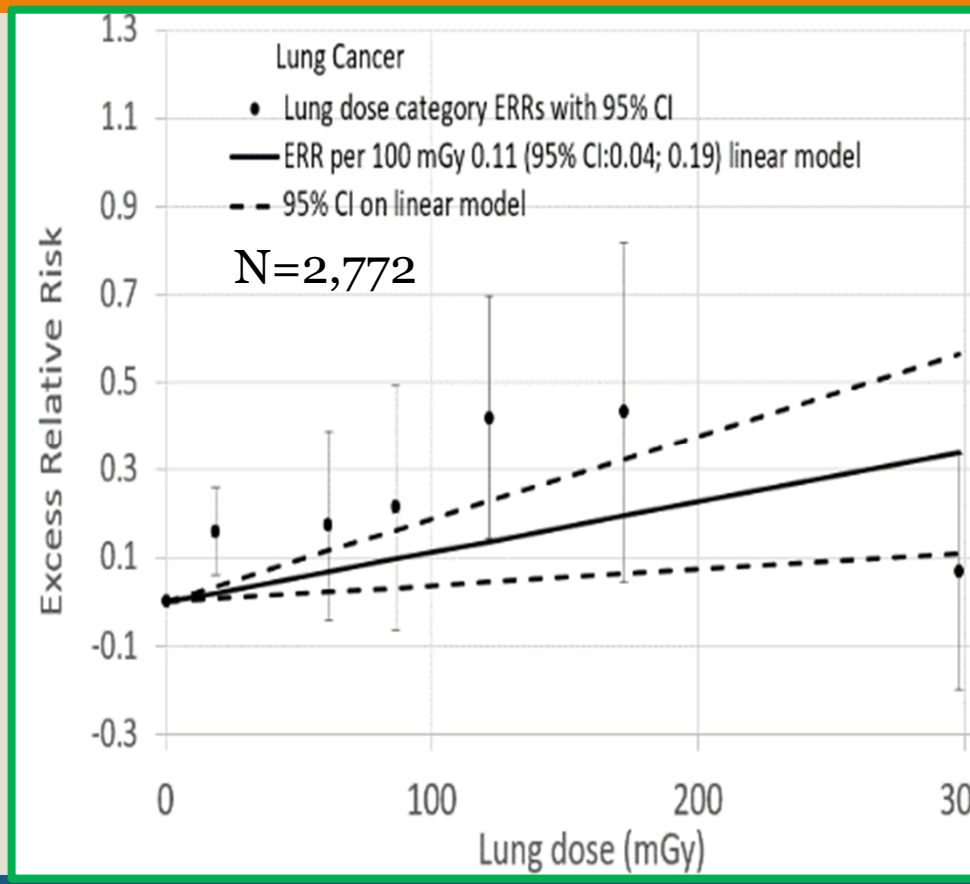
ean 43.2 mGy, Max 1,085 mGy



e et al. Nuclear Power Plant Workers, IJRB 2022

Industrial Radiographers

Mean 17.2 mGy, Max 1,411 mGy



Boice et al. Industrial Rad. Rad Res to be submitted 202

S: NRC Cohort Results – Dose-Response for Lung Cancer

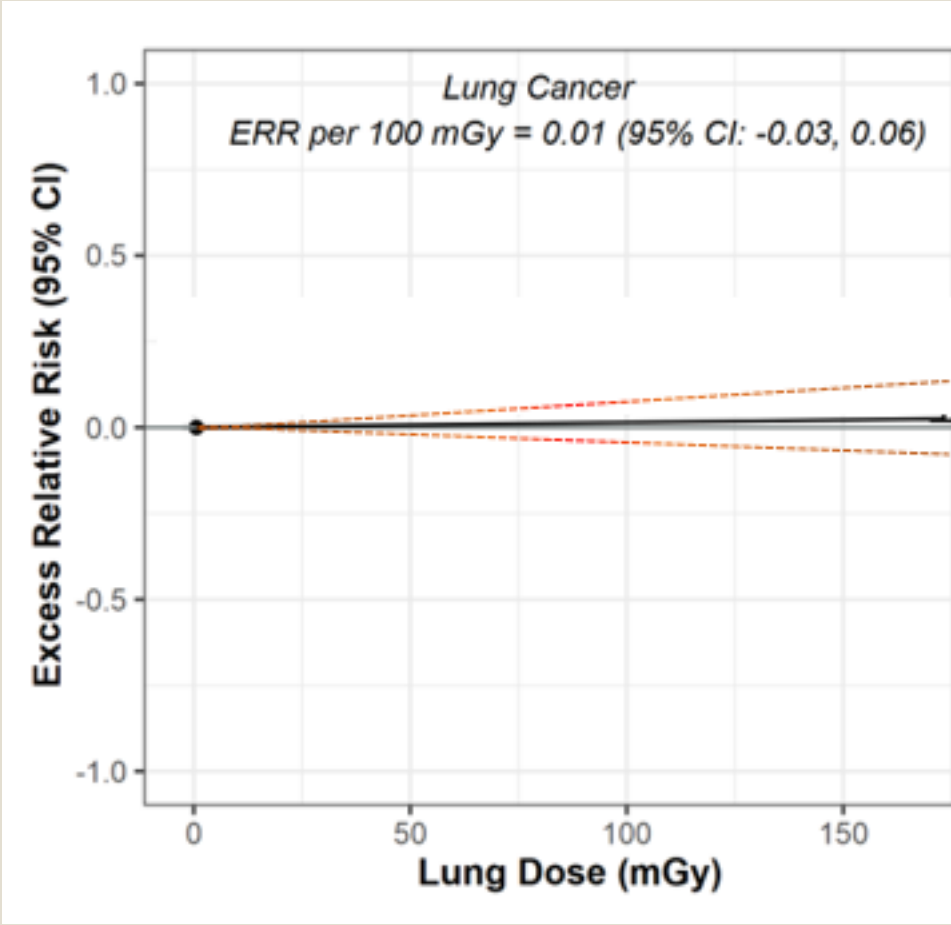
Early Preliminary Pooling

- Nuclear Power Workers + Industrial Radiographers

Mean Lung dose

- ~30 mGy, Max ~1,200 mGy

N >5,500



PS Cohort Results – Dose-Response for Lung Ca

hort	Ref	Workers	Absorbed Dose mGy, Mean (Max)	ERR at 100 mGy (95% CI)
clear Power Plant	Boice et al 2022	135,193	43.2 (1,085)	-0.04 (-0.11, 0.02)
ustrial Radiographers	Boice et al 2023 (to be submitted)	123,401	17.2 (1,411)	0.11 (0.04, 0.19)
S Medical Workers	Boice et al 2022	109,019	13.0 (1,272)	0.15 (0.02, 0.27)
P + IR + MW	Boice et al 2021	367,722	-	0.02 (-0.03, 0.07)
mic Veterans	Boice et al 2022	114,270	6.2 (972)	0.04 (-0.11, 0.19)
und	Boice et al 2014	4,954	98.7 (17,478)	0.00 (-0.03, 0.04)
llinckrodt	Golden et al 2022	2,514	69.9 (885)	-0.06 (-0.18, 0.06)
cketdyne	Boice et al 2011	5,801	19.0 (3,560)	-0.02 (-0.18, 0.17)
Alamos National Lab	Boice et al 2022	26,328	28.6 (16,811)	0.01 (-015, 0.17)
C	Boice et al 2022	26,650	478 (18,500)	-0.09 (-0.19, 0.02)

S - Sex-specific Lung Ca Risks at 100 mGy
ess Relative Risk (ERR at 100 mGy)

Preliminary Evaluations for:	FEMALES	MALES
ort	**ERR at 100 mGy (95% CI)**	**ERR at 100 mGy (95% CI)**
nckrodt (U Processing) (~2.5K)	na	-0.003 (-0.02, 0.02)
ic Veterans (~114K)	na	0.08 (-0.06, 0.22)
nd (polonium - Be) (~5K)	-0.01 (-0.07, 0.07)	0.01 (-0.02, 0.04)
essee Eastman Corp (~27K)	0.01 (-0.10, 0.12)	-0.14 (-0.32, 0.08)
ear Power Plant (NPP) (~135K)	**0.63 (-0.91, 2.17)**	**-0.06 (-0.11, 0.01)**
strial Radiographers (IR) (~123K)	**0.73 (-1.06, 2.52)**	**0.11 (0.04, 0.19)**
cal Worker (~109K)	0.09 (-0.19, 0.36)	0.16 (0.01, 0.32)
bined NPP, IR, Med, and Canadian oscopy cohorts (>400K)	-0.007 (-0.015, 0.002)	0.002 (-0.003, 0.008)

NPP 3% / 97%

IR 10% / 90%

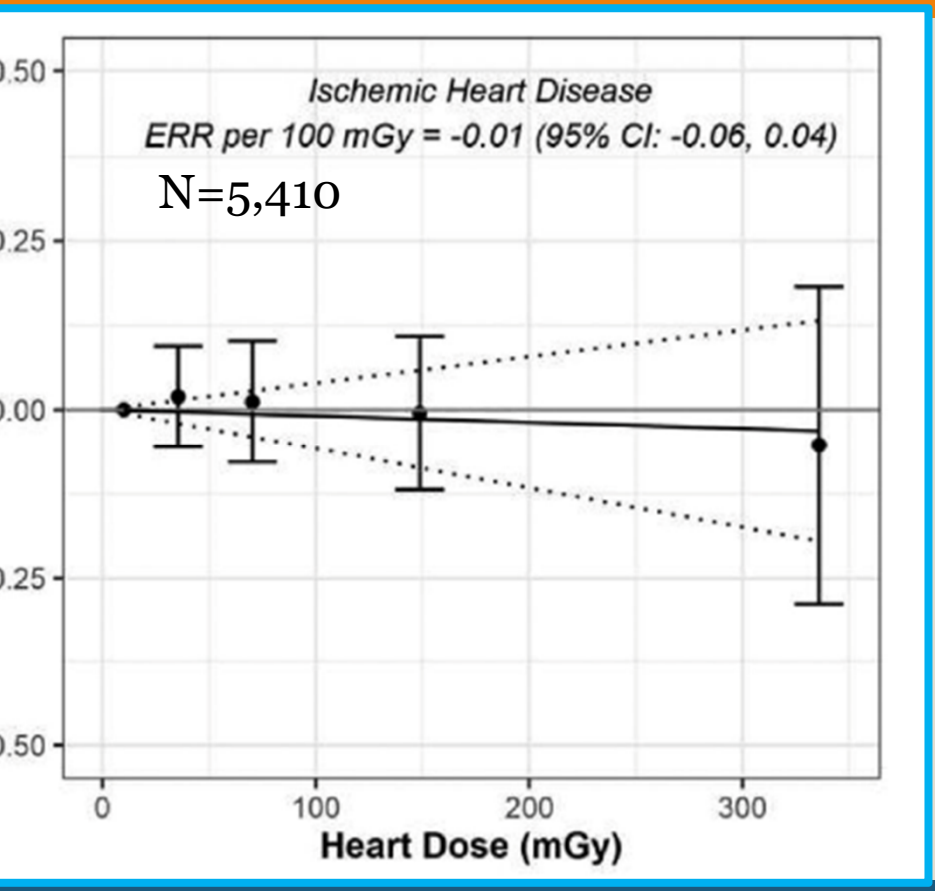
Also see Boice *et al.* Sex-specific lung cancer risk. *IJR*

Little evidence for a significant difference for chronic occupational exposures

S: NRC Cohort Results – Dose-Response for Ischemic Heart Disease

uclear Power Workers

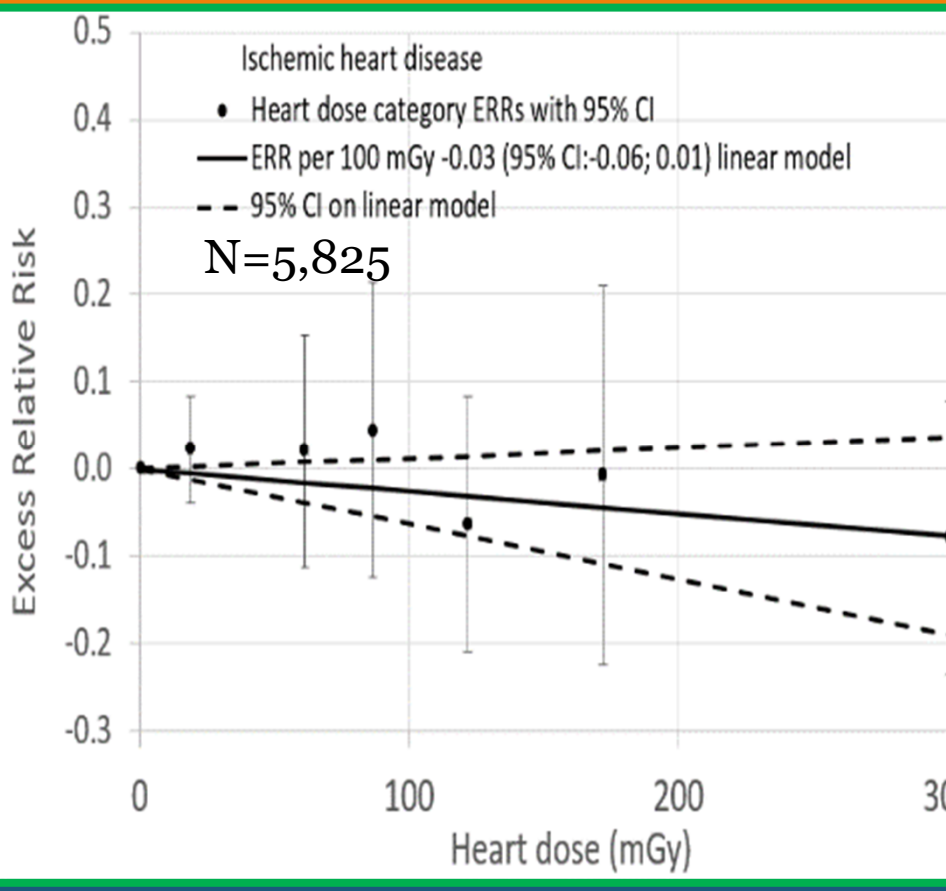
ean 43.9 mGy, Max 1,105 mGy



et al. Nuclear Power Plant Workers, IJRB 2022 Schöllnberger, Dauer et al. IJRB, 2022

Industrial Radiographers

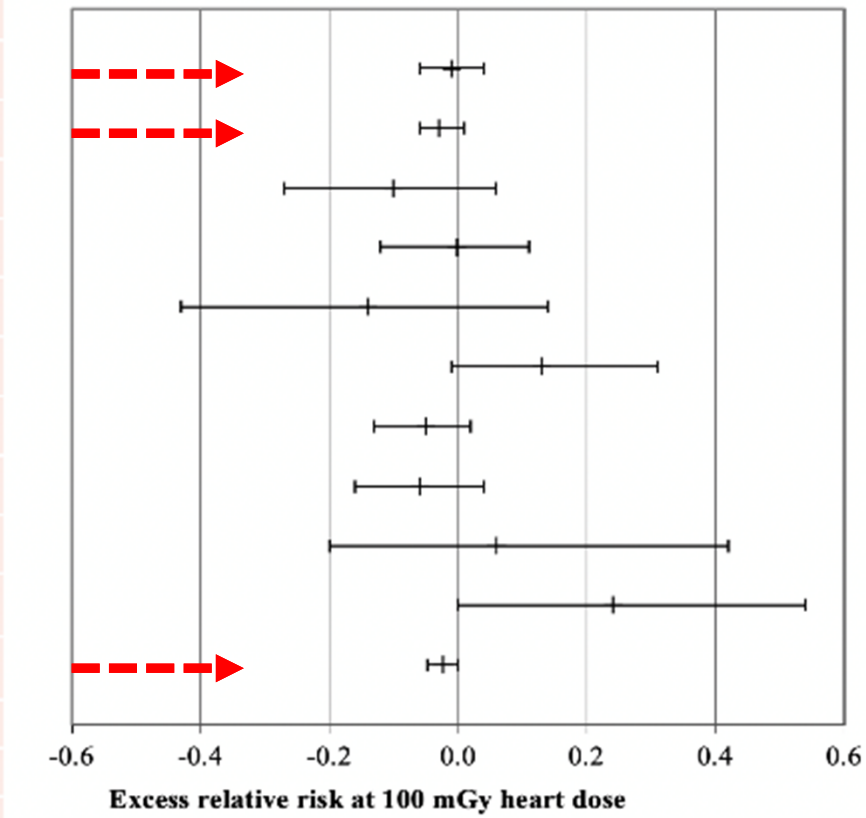
Mean 18.1 mGy, Max 1,480 mGy



Boice et al. Industrial Rad. Rad Res to be submitted 2023

Cohort Results – Dose-Response for Ischemic Heart Disease

from published and *preliminary results soon to be submitted)



	n	ERR at 100 mGy (95% CIs)
wer Plant	5410	-0.01 (-0.06; 0.04)
adiographers *	5825	-0.03 (-0.06; 0.01)
orkers	1654	-0.1 (-0.27; 0.06)
erans	16625	-0.001 (-0.12; 0.11)
	221	-0.14 (-0.43; 0.14)
dt	563	0.13 (-0.01; 0.31)
s *	995	-0.05 (-0.13; 0.02)
s National Lab.	3043	-0.06 (-0.16; 0.04)
*	102	0.06 (-0.2; 0.42)
	948	0.24 (0; 0.54)
IMATE *	**35386**	**-0.02 (-0.05; 0.00)**
		based on data from > 530K

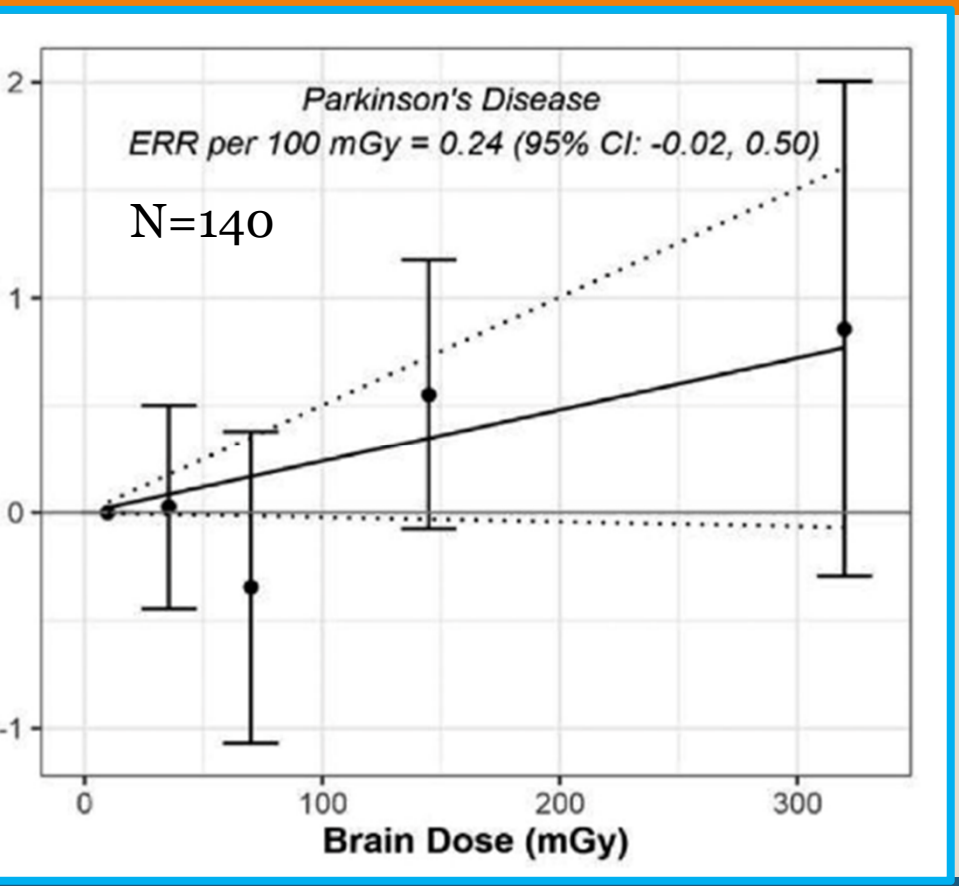
ry results – to be submitted

berger, Dauer et al. IJRB, 2022. Boice et al. Million Dreams...IJRB 2022. Boice et al Ind Radiog 2022 to be submitted

S: NRC Cohort Results – Dose-Response for Parkinson's Disease

uclear Power Workers

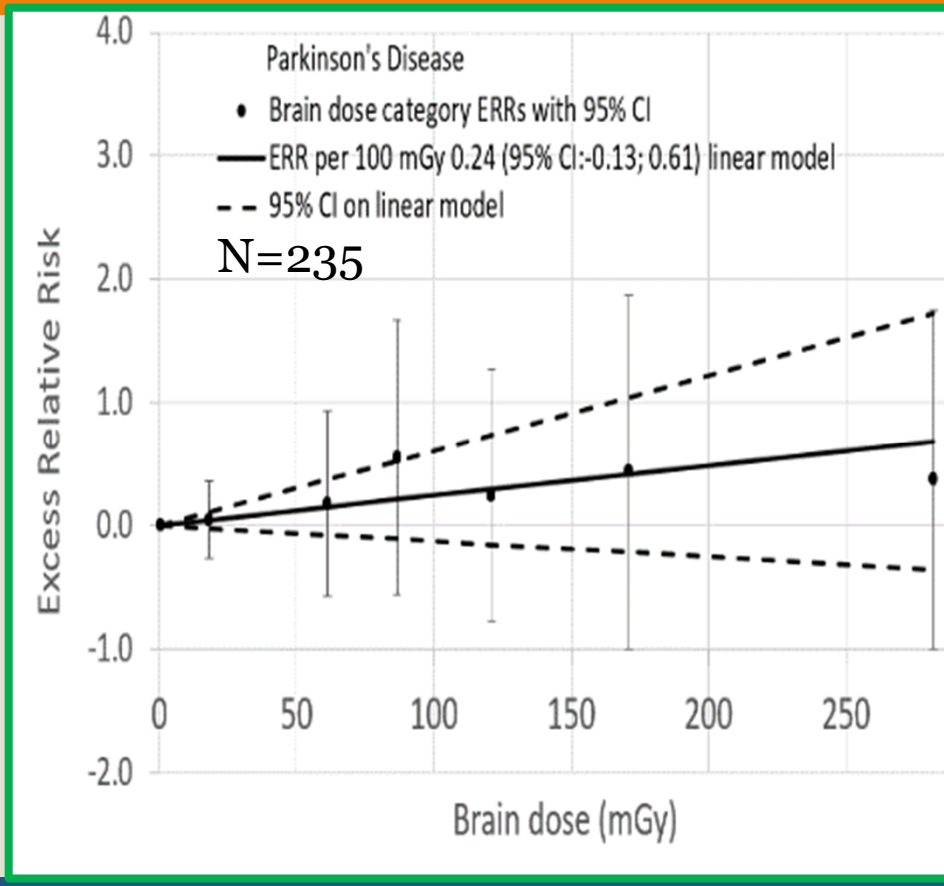
ean 33.2 mGy, Max 834 mGy



et al. Nuclear Power Plant Workers, IJRB 2022

Industrial Radiographers

Mean 11.9 mGy, Max 977 mGy



Boice et al. Industrial Rad. Rad Res to be submitted 2023

PS – Summary of NRC Cohorts to date

- Except for heart (IHD), most risk coefficients are positive
- No significant difference between females and males (Lung Ca)
- Further follow-up & pooling with other low-LET and high-LET MPS cohort studies will provide improved estimates of radiation risk following prolonged exposures
- Parkinson's disease a new finding, warrants additional study
- Cancer incidence, smoking, and chronic conditions information soon to come from MEDICARE linkages

Future - Development of Models for Heart Dosimetry for Internally Deposited Radionuclides and External Exposures ?

oposed - SC 6-14??

intly Sponsored by NCRP PAC 6/1/4

PS and Broad Application

ational and International Interest

ternal/External

gh-LET/Low-LET

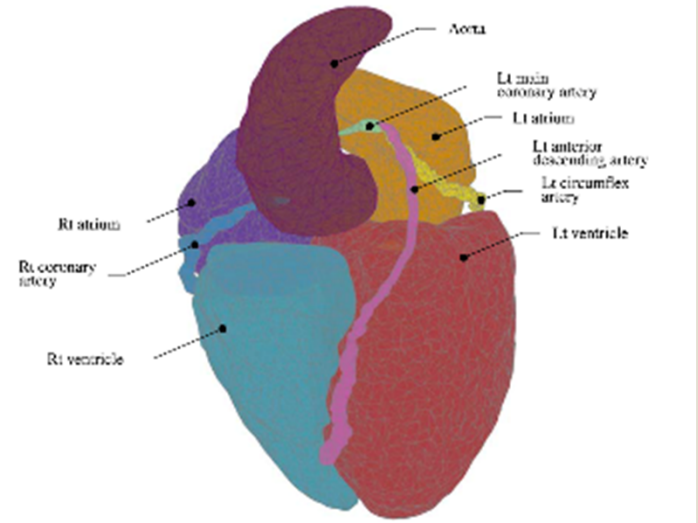
osimetry expertise

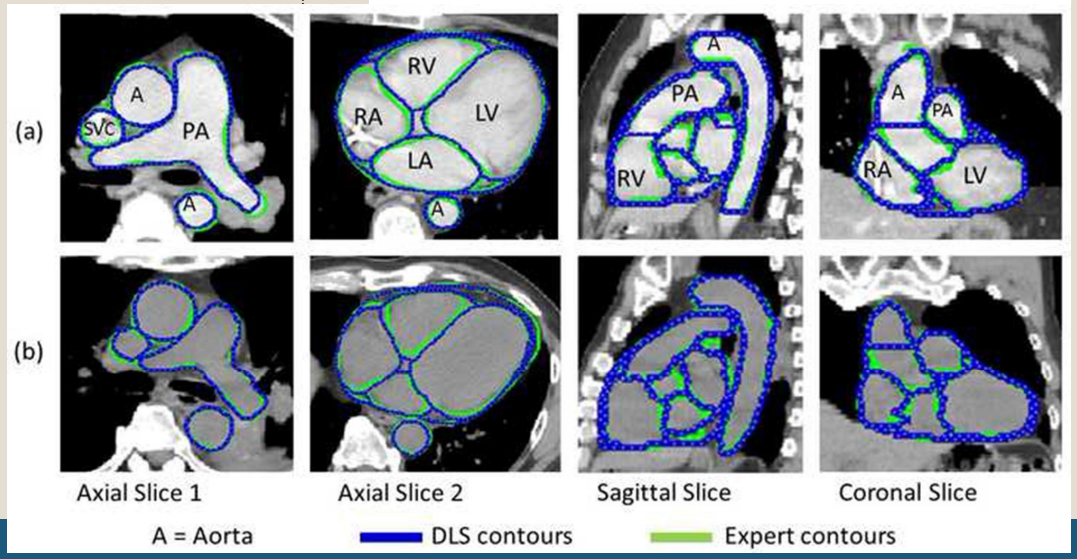
AC-1 – important tissues

AC-4 – clinical input, RT

ntouring…

ub Organ / Flow modeling?





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Alexandra Hotca, A
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THANK YOU!

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The Million Person Study