LNT와 역학

(LNT & epidemiology)

한국원자력학회

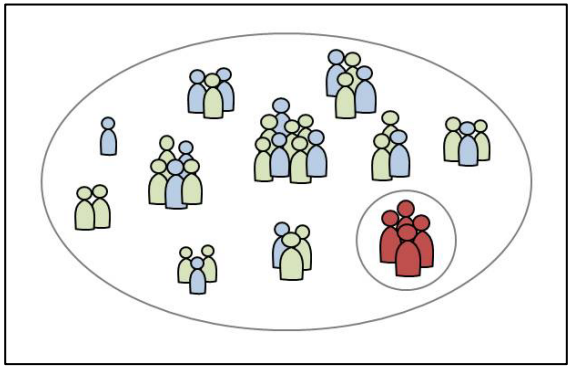
(2025. 5. 21)

이 원 진

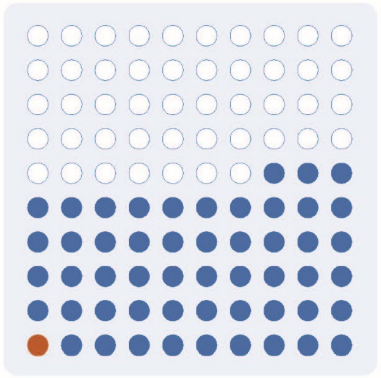
고려대학교 의과대학 예방의학교실

발표 내용

- **역학 연구의 의미와 한계**



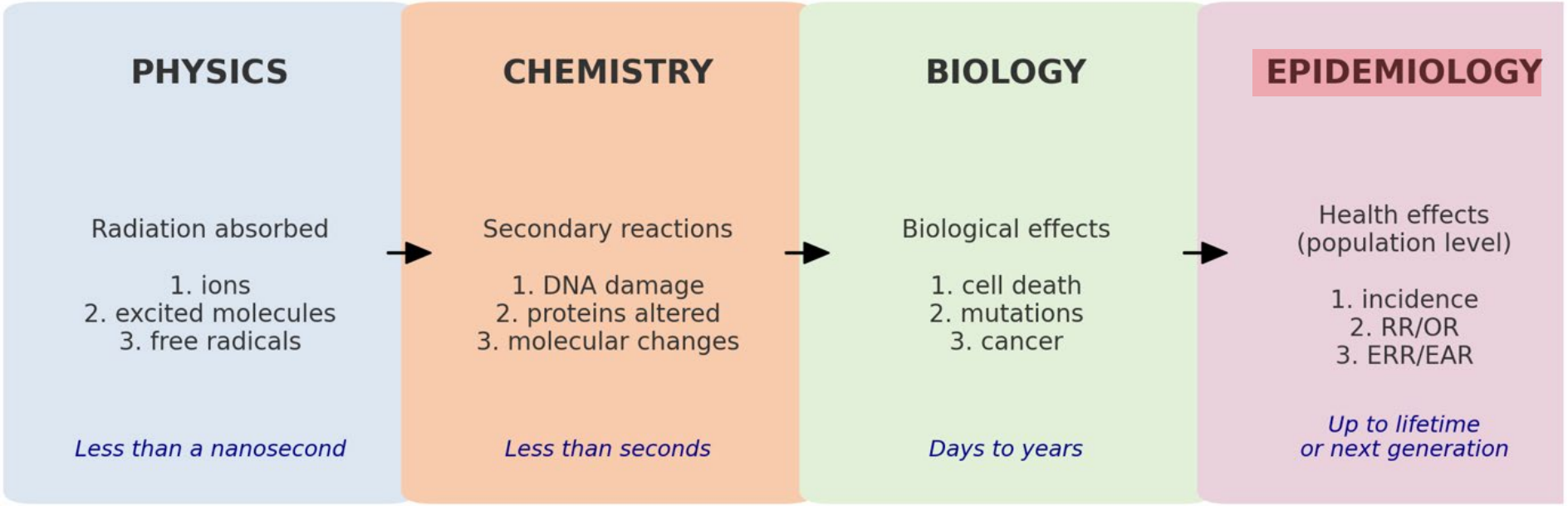
- **선량-반응에 대한 역학적 근거**
  - UNSCEAR 보고서
  - 원폭 생존자 연구
  - 직업노출 연구
  - 의료노출 연구
  - 환경노출 연구
  - 통합분석 연구



- **방사선 위험도의 크기**

본 발표와 이해충돌 없음

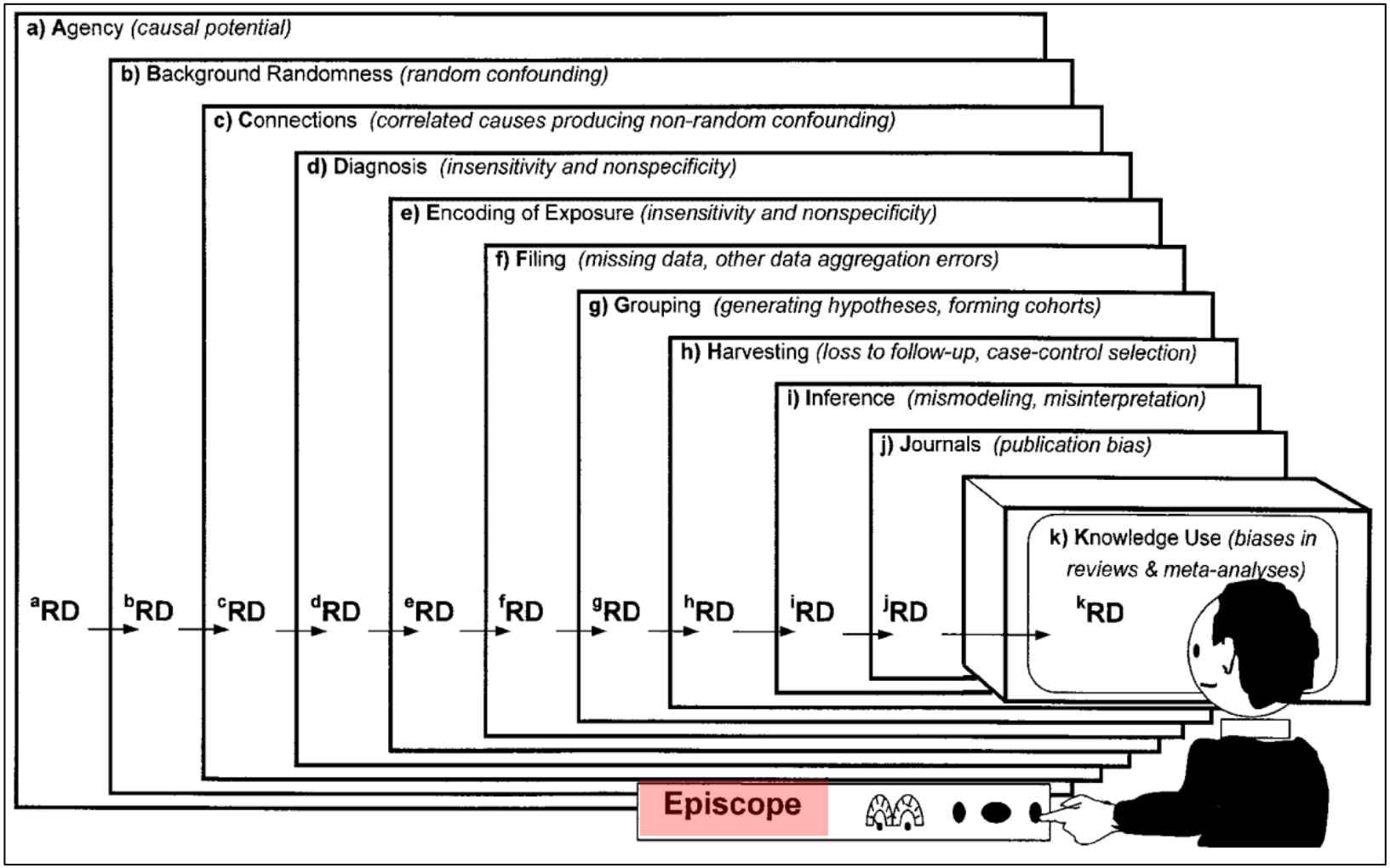
학문간 건강영향의 종류와 특성



- **인구집단 차원의 비교**
- 인구집단간 특성 및 기저율 차이
- 노출 형태 및 양의 차이
- 다른 요인들에 의한 방사선의 효과변경
- 여러 바이어스 영향 (선택바이어스, 정보바이어스, 교란작용 등)

- 다양한 지표: Incidence, Prevalence, Rate ratio, Odds ratio, ERR/EAR, Attributable risk, LAR 등
- 다양한 연구방법 : Cohort study, (nested) Case-control study, Cross-sectional study, Ecological study, Systematic review 등

역학적 접근과 결과 해석



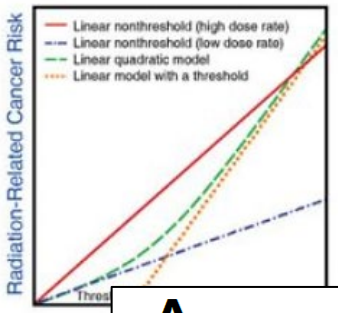
- 연관성(association) vs. 인과성(causation)

Maclure & Schneeweiss. Epidemiology. 2001

선량-반응 관련성에 대한 역학적 고찰

NCRP COMMENTARY No. 27

IMPLICATIONS OF RECENT EPIDEMIOLOGIC STUDIES FOR THE LINEAR-NONTHRESHOLD MODEL AND RADIATION PROTECTION



J. Radiol. Prot. 43 (2023) 024003 https://doi.org/10.1088/1361-6498/acdfd7

Journal of Radiological Protection

OPINION ARTICLE

The scientific basis for the use of the linear no-threshold (LNT) model at low doses and dose rates in radiological protection

Dominique Laurie
Institute for Radiologic

Cancer risk
epidemiolog

W. Rühm [a,*], D

[a] Helmholtz Center Munich
[b] Institut de Radioprotectio
[c] Centre for Occupational

Annals of the ICR

ICRP PUBLICATION XXX

Scientific Evidence Relevant to the
Assessment of Solid Cancer Radiation R
Low Dose and Low Dose Rate

United Nations
General Assembly

A/AC.82/R.767
Distr.: Restricted

7 April 2025
Original: English only

United Nations Scientific Committee
on the Effects of Atomic Radiation

Seventy-second session
Vienna, 16–20 June 2025

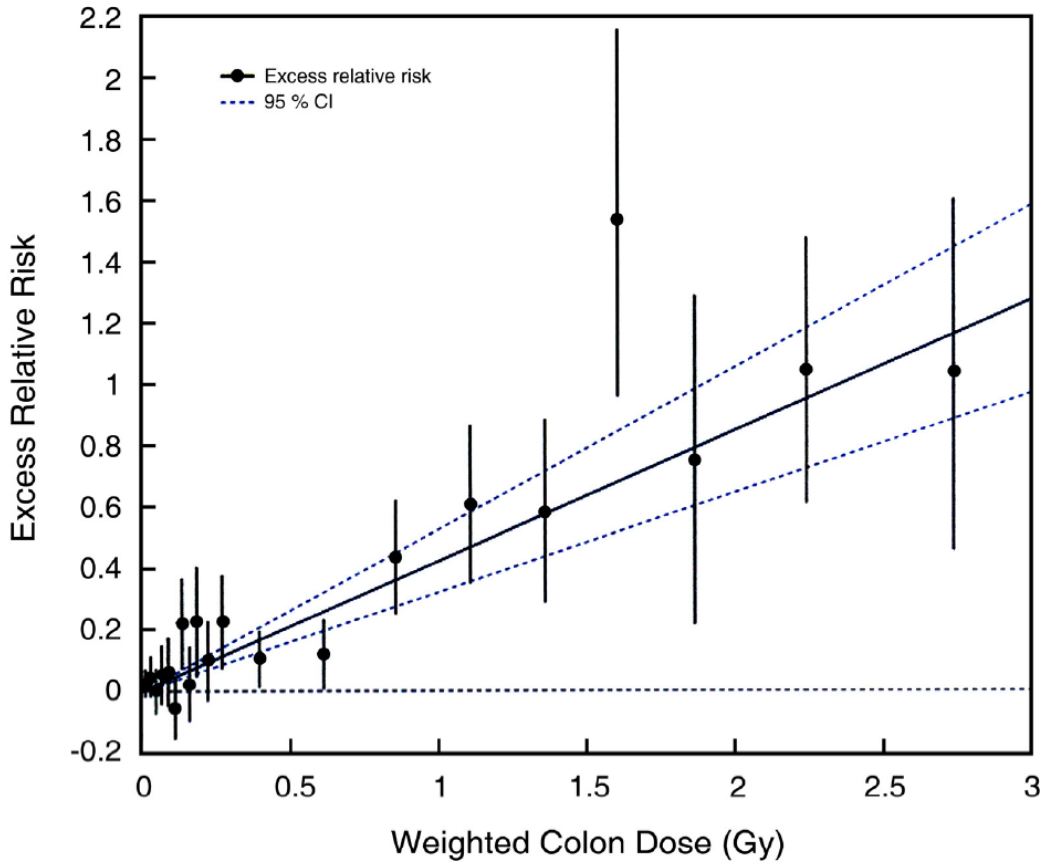
Agenda item 5(a)
Technical discussions

EPIDEMIOLOGICAL STUDIES OF IONIZING RADIATION AND CANCER

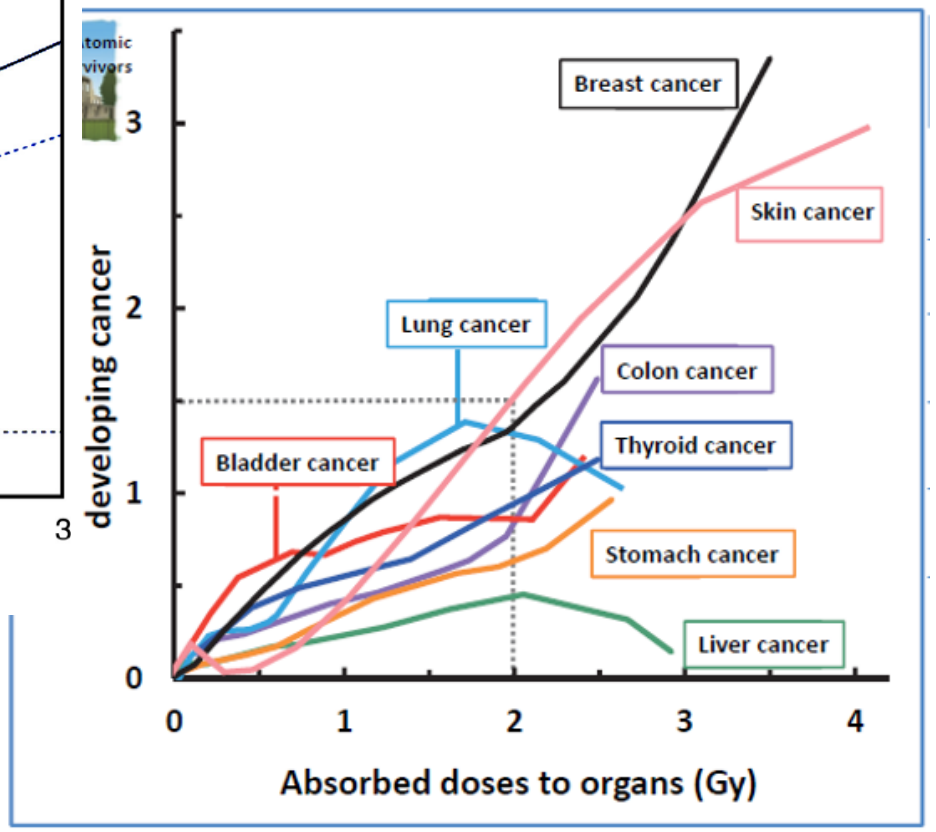
악성 종양과 역학 결과 종합 (UNSCEAR)

Cancer site	Weight of evidence	Dose-response
Esophagus	Sufficient	Non-linearity
Stomach	Sufficient	Linearity
Colon	Sufficient	Linearity
Thyroid	Sufficient	Linearity
Ovary	Sufficient	-
Pancreas	Limited	Linearity
Lung	Sufficient	Linearity
Non-melanoma skin	Sufficient	Upward curvature
Leukemia	Sufficient	Upward curvature
Cutaneous melanoma	Inadequate	-
Uterus (cervical)	Inadequate	-
Hodgkin lymphoma	Inadequate	-
Sufficient (15), Limited (9), Inadequate (3)		

원폭 생존자 연구 (암사망, 1950-2003)

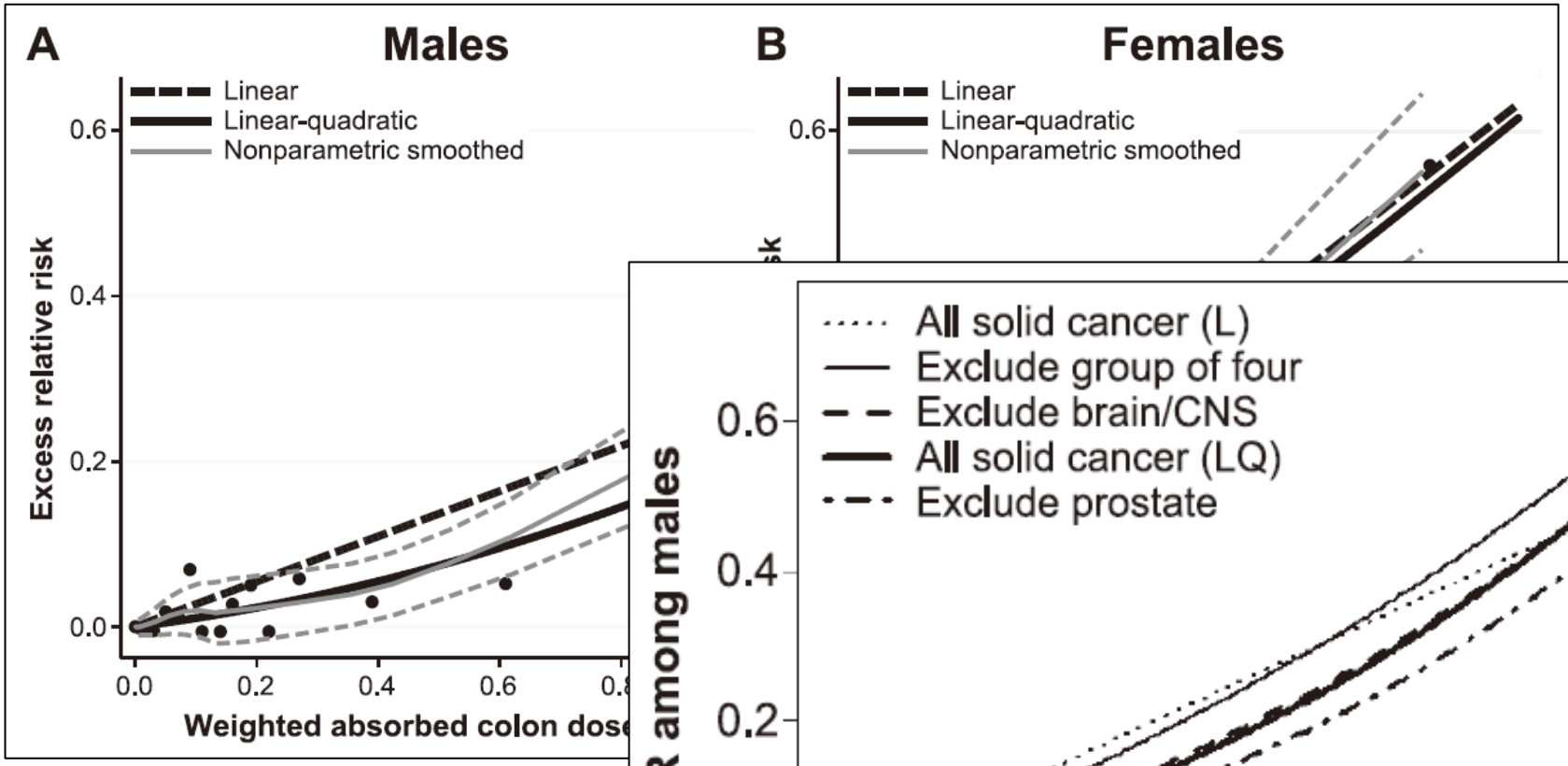


Ozasa et al. Radiat Res. 2012

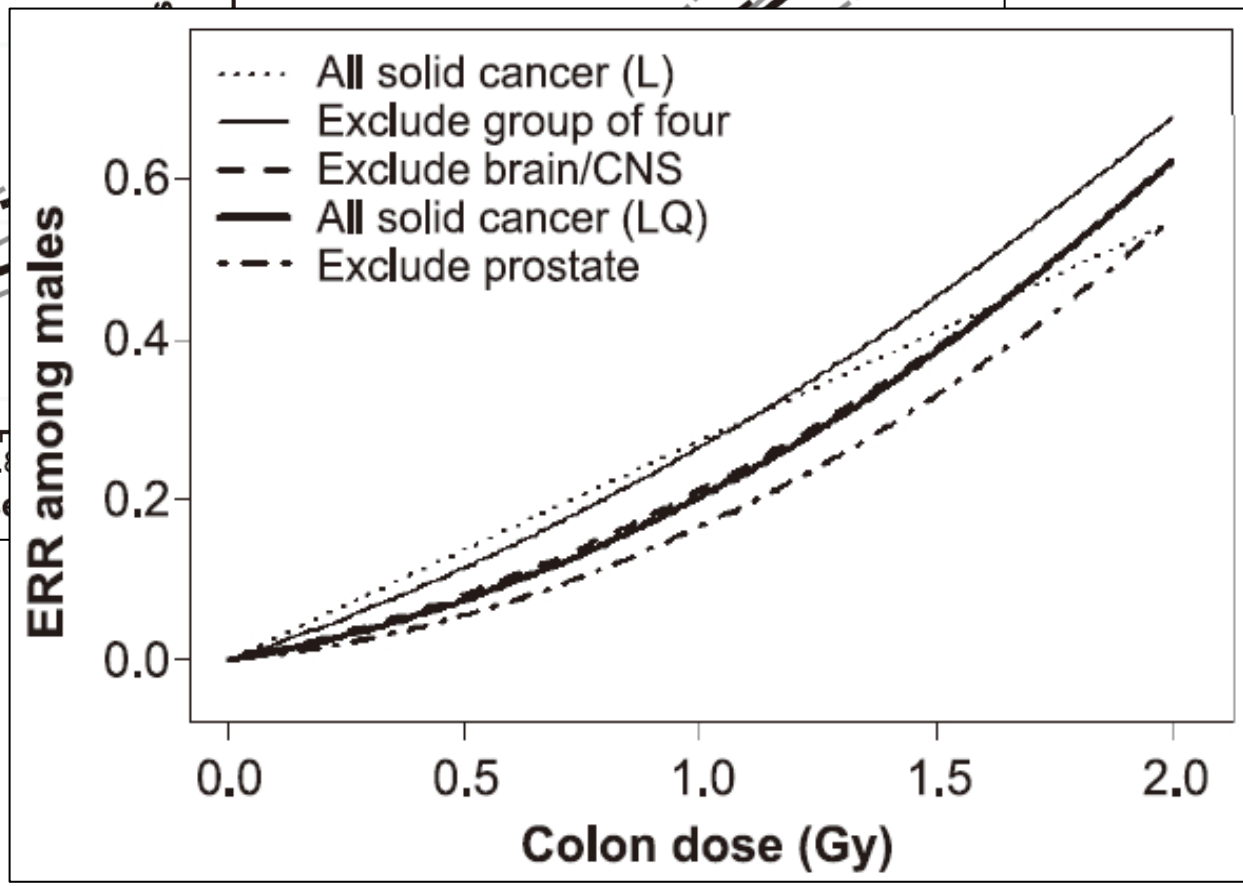


Source: Prepared based on Preston et al., Radiat Res., 168, 1, 2007

원폭 생존자 연구 (암발생, 1958-2009)

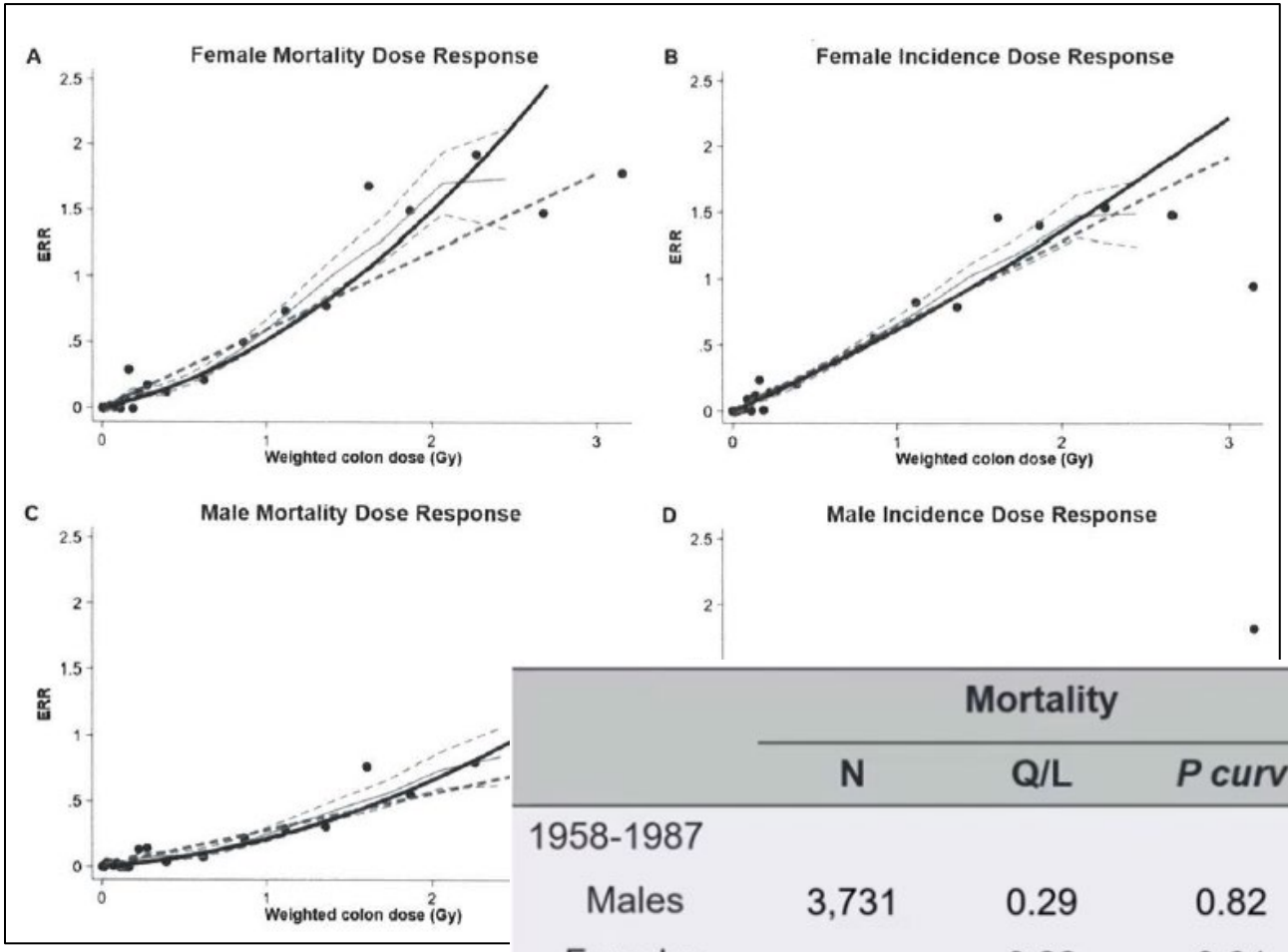


Grant et al., Radiat Res. 2017



Cologne et al., Radiat Res. 2019

원폭 생존자 연구 (암발생 및 사망, -2009)



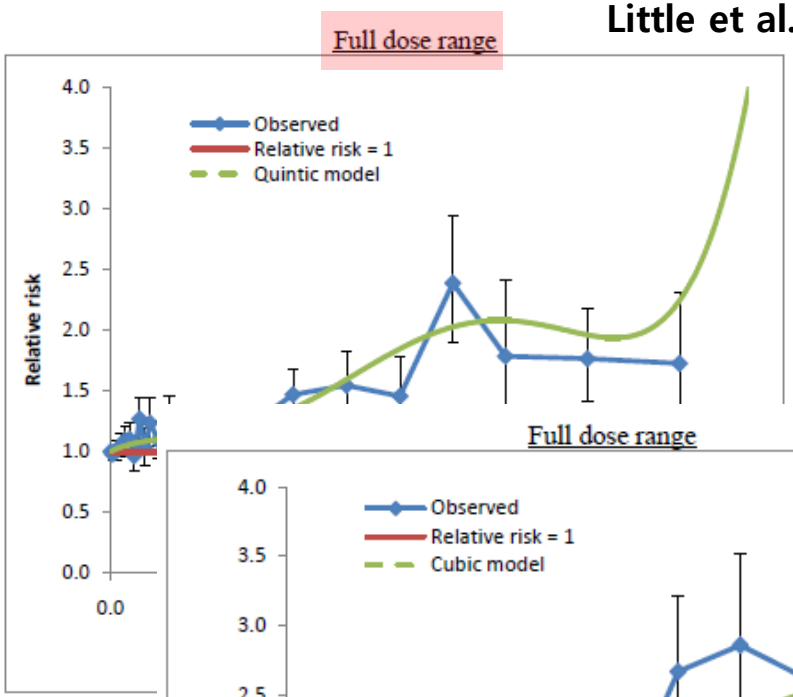
Brenner et al. Rad Res 2022

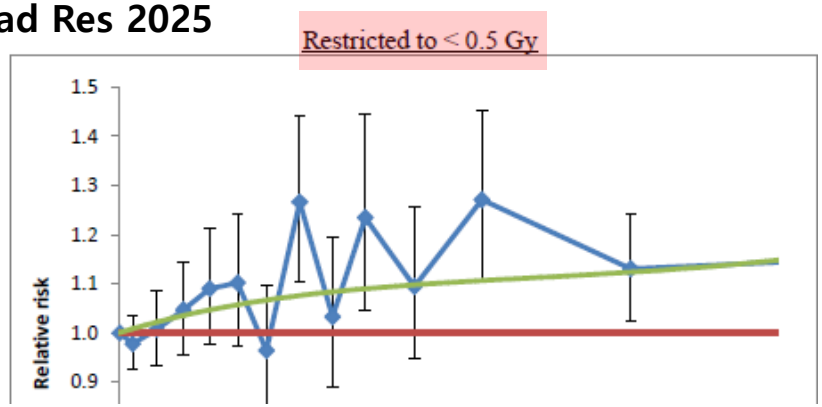
- **암종별 구성 차이**
  - 성별
  - 발생과 사망
  - 개별 암종 구성
- **최근 추가된 암종의 영향** (어린 나이 노출자)

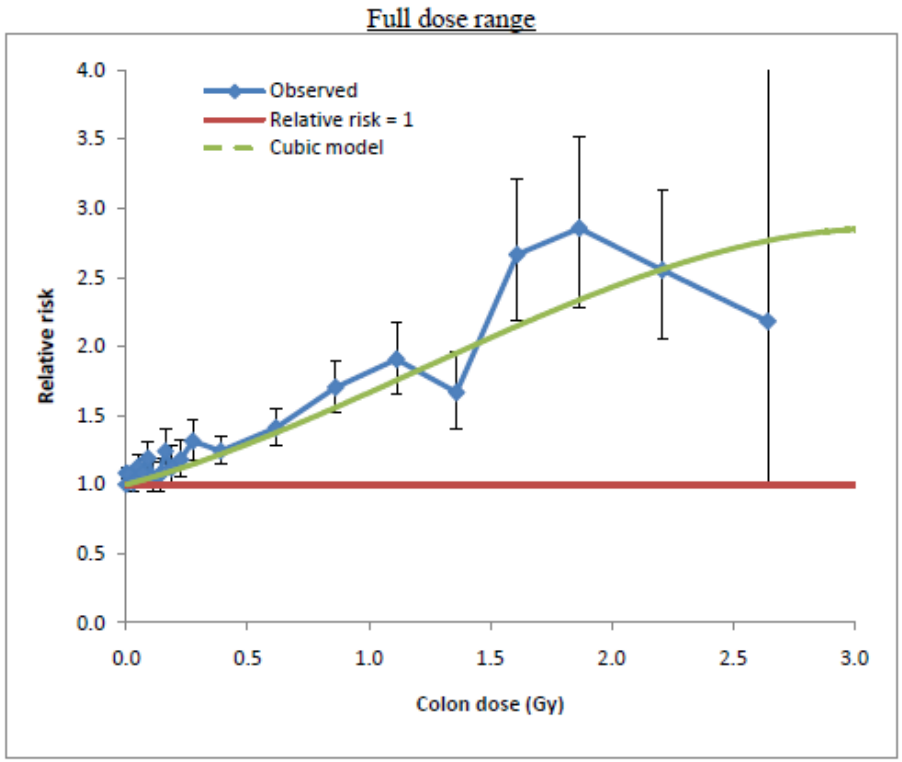
	Mortality			Incidence		
	N	Q/L	*P curv*	N	Q/L	*P curv*
1958-1987						
Males	3,731	0.29	0.82	4,878	**2.34**	**0.03**
Females	3,885	0.22	0.64	6,053	0.04	0.85
1988-2009						
Males	3,793	**5.99**	**0.02**	5,595	**1.52**	**0.02**
Females	4,010	**4.97**	**0.003**	6,012	0.23	0.37

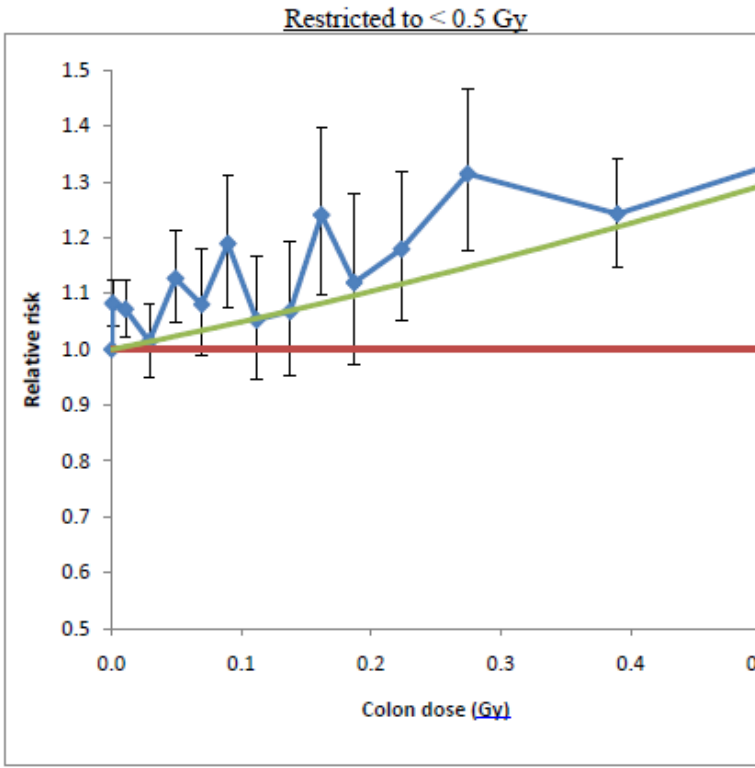
원폭 생존자 연구 (다항식 모델)

Little et al. Rad Res 2025









직업노출 (INWORKS, 고형암/백혈병)

IRSN

National cohort

n = 59 003

Public Health England

UK NRRW

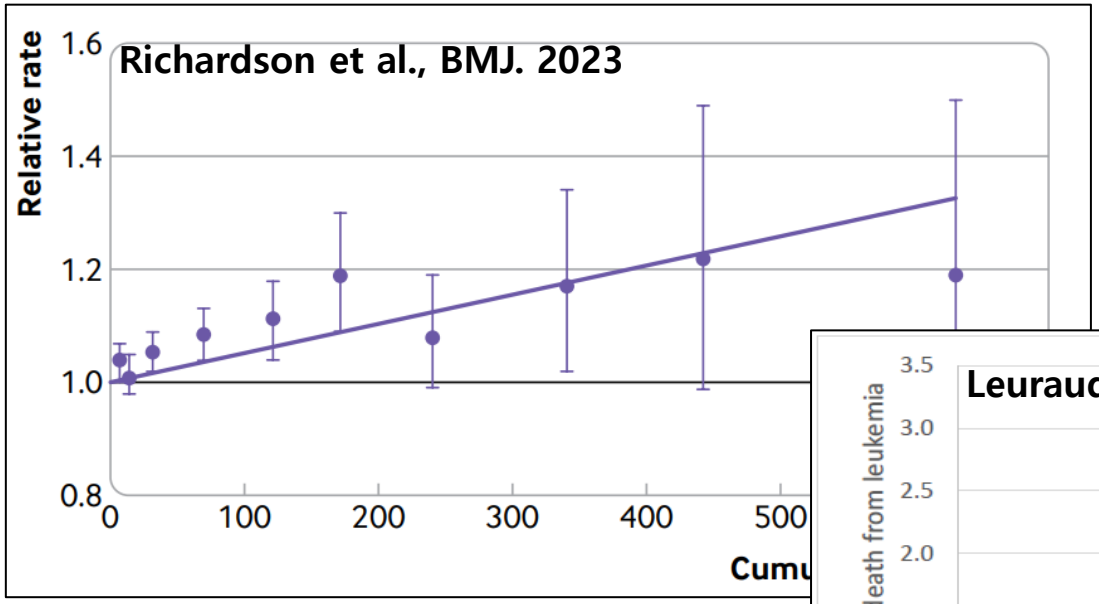
n = 147 866

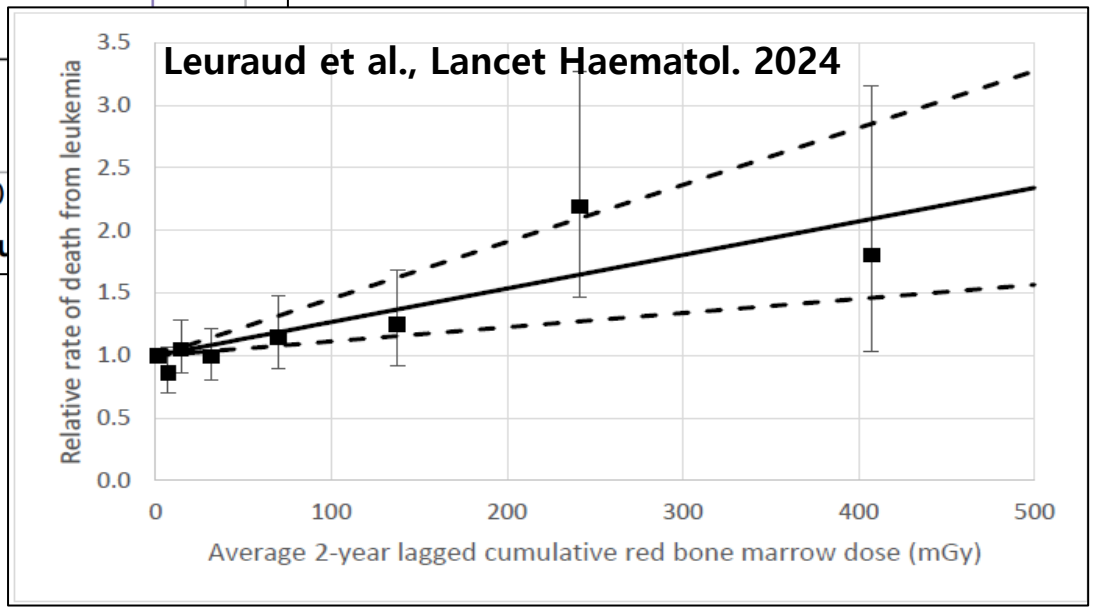
NIOSH

US combined cohort

n = 101 428

- IARC 주관 후향적 코호트
- 원전종사자 약 30만명
- 평균 대장 및 골수선량: 20.9mGy/15.9mGy
- **선량-반응 관련성 (선형)**





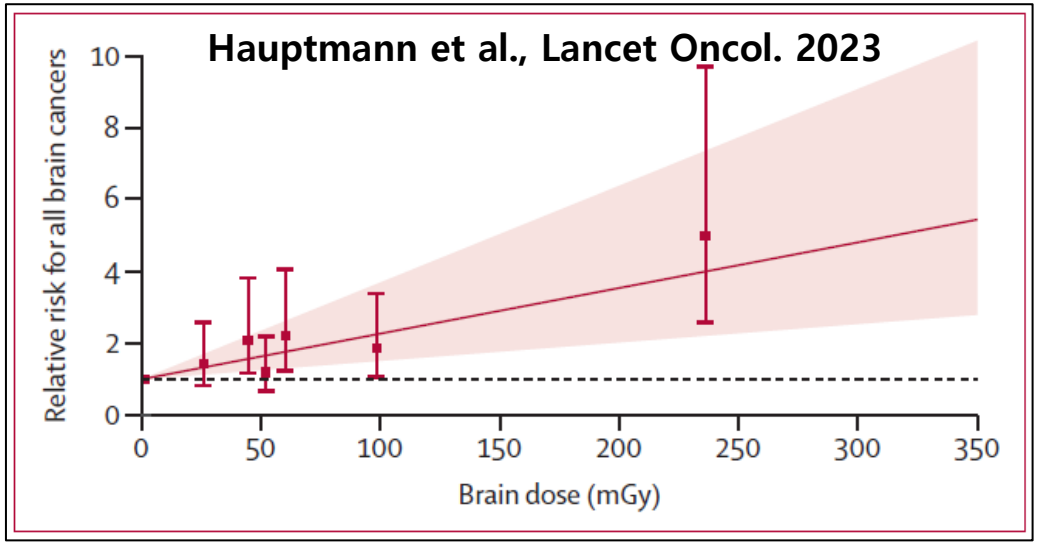
Cohort Profile: The International Nuclear Workers Study (INWORKS)

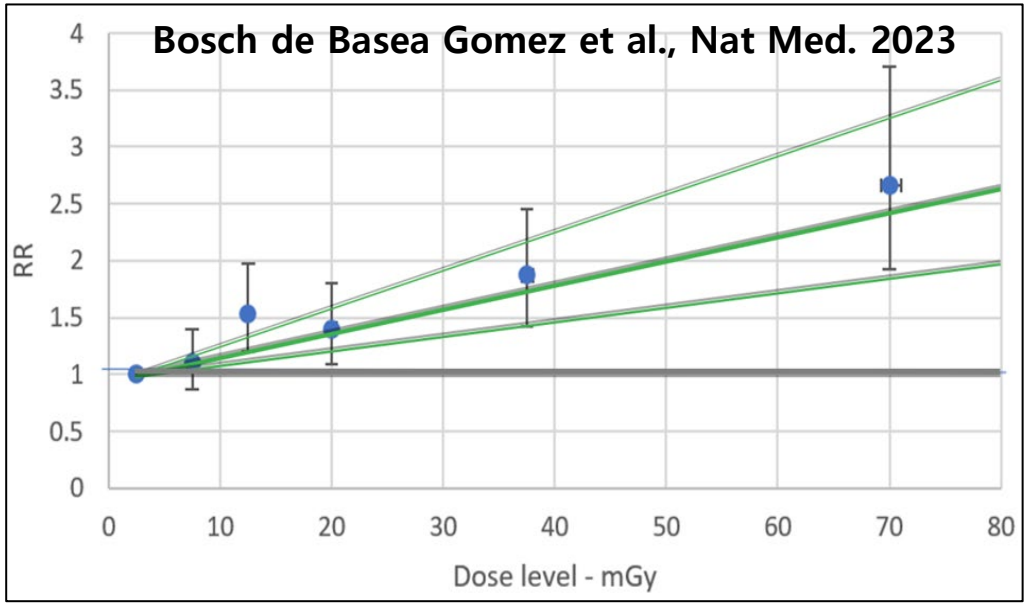
Ghassan B Hamra,[1]* David B Richardson,[2] Elisabeth Cardis,[3,4,5] Robert D Daniels,[6] Michael Gillies,[7] Jacqueline A O'Hagan,[7] Richard Haylock,[7] Dominique Laurier,[8] Klervi Leuraud,[8] Monika Moissonnier,[9] Mary Schubauer-Berigan,[6] Isabelle Thierry-Chef[9] and Ausrele Kesminiene[9]

International Journal of Epidemiology, 2016,

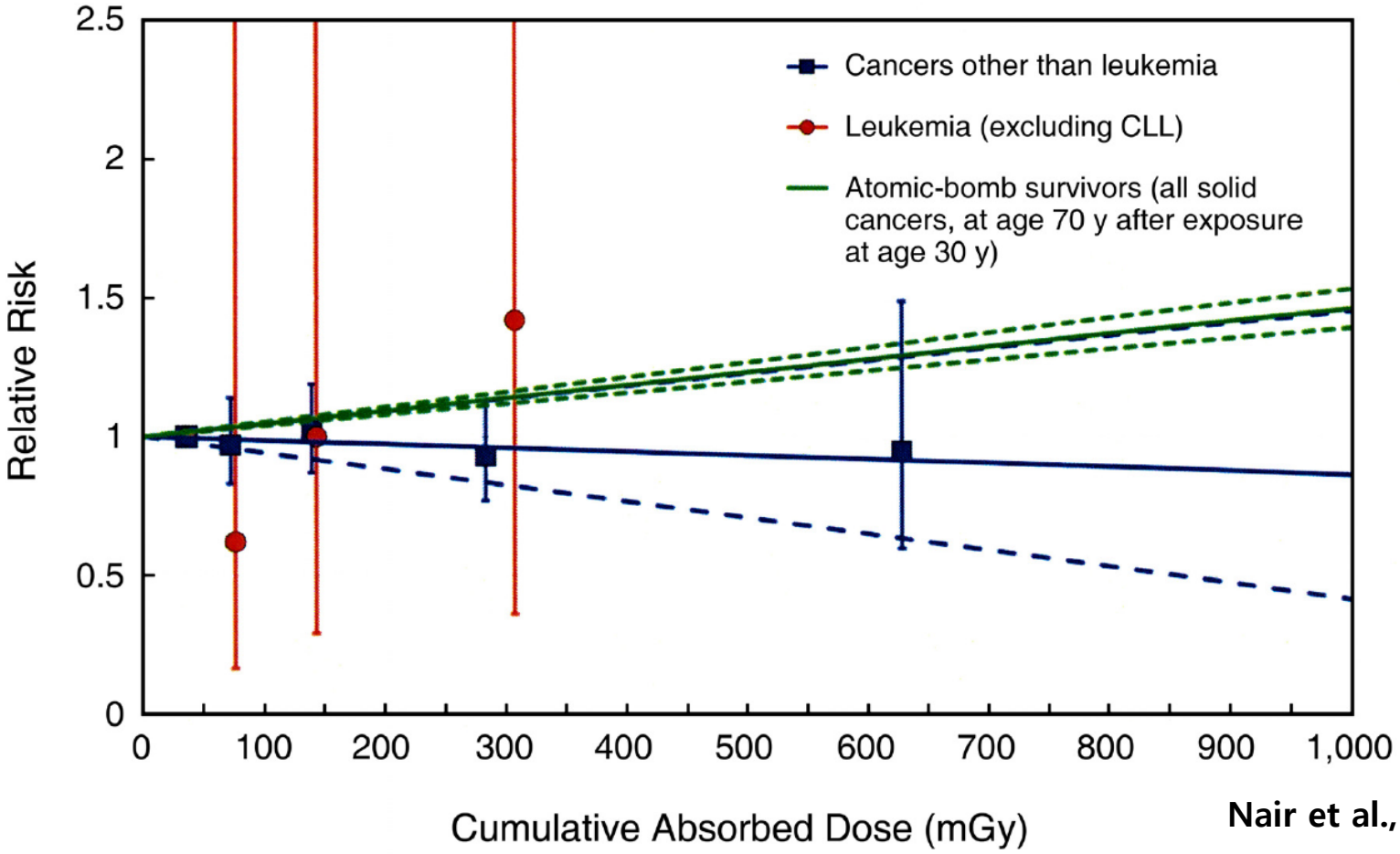
의료노출 (EPI-CT, 소아암)

- IARC 주관 국제공동연구 (9개국)
- 약 90만명의 어린이(CT exposure)
- 코호트(병원자료+등록자료)
- 뇌선량/골수선량: 47.4/15.6mGy





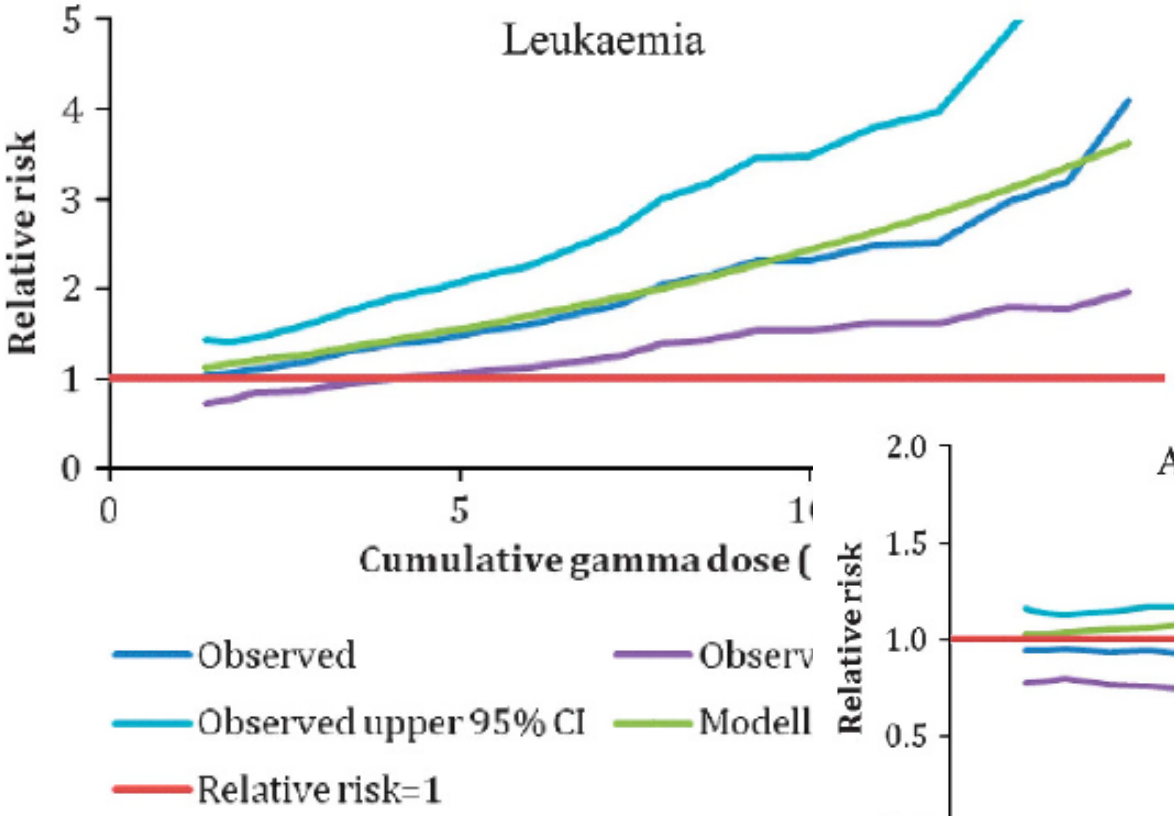
환경 노출 (자연 방사선, 성인)



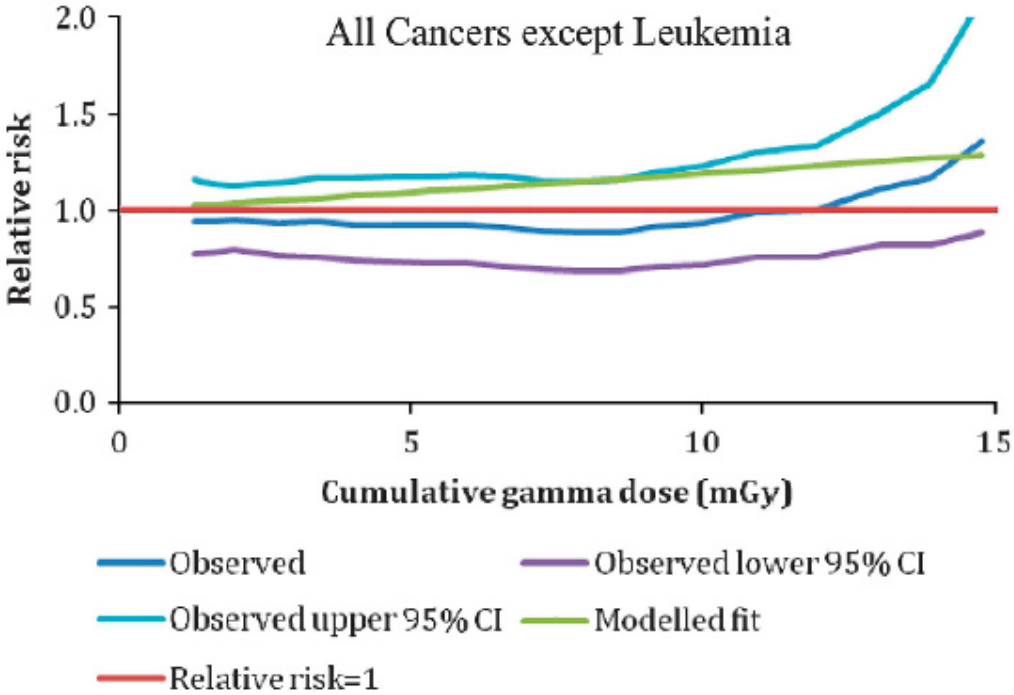
Nair et al., Health Phys. 2009

- 인도 Kerala 고준위 방사선 지역 (연간 자연방사선 농도 4-70mSv)
- 전체암(백혈병 제외) (ERR -0.13/Gy, 95% CI: -0.58-0.46)

환경 노출 (자연방사선, 소아)



- 영국 연구 (1980-2006)
- 27,447 어린이 암환자
- 지각 감마선
- 백혈병: mSv당 12% 증가
- 다른 소아암: 증가 않음

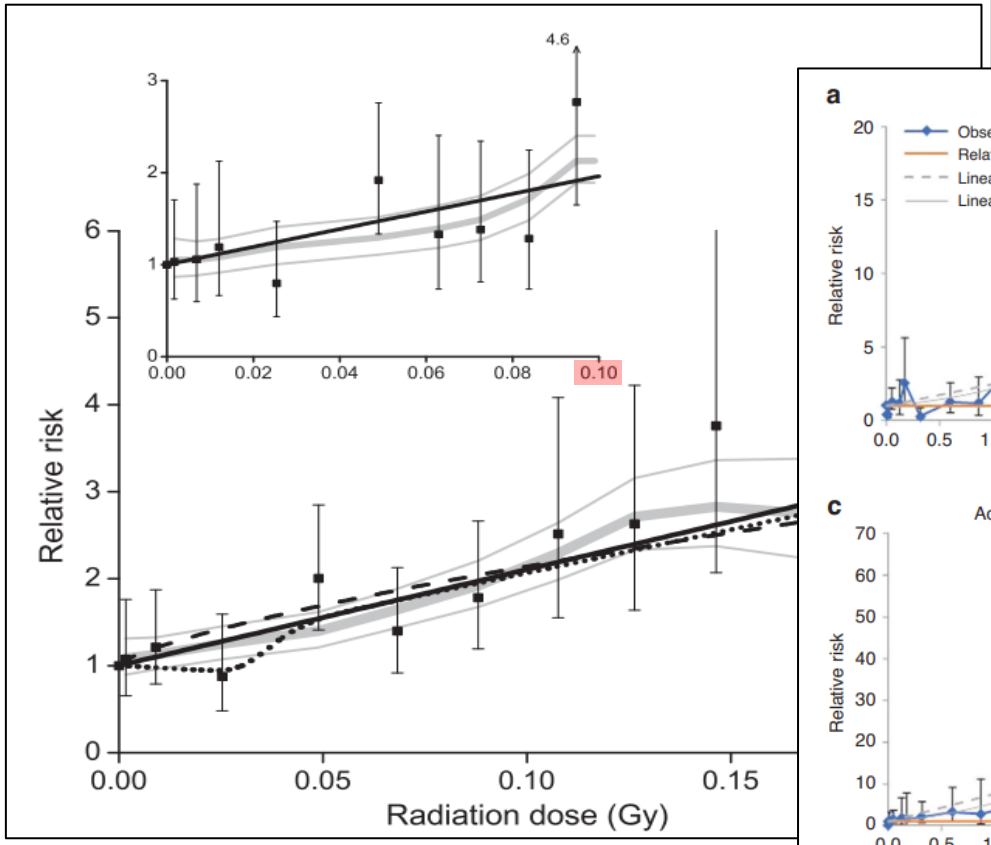


Kendall et al., Leukemia. 2013

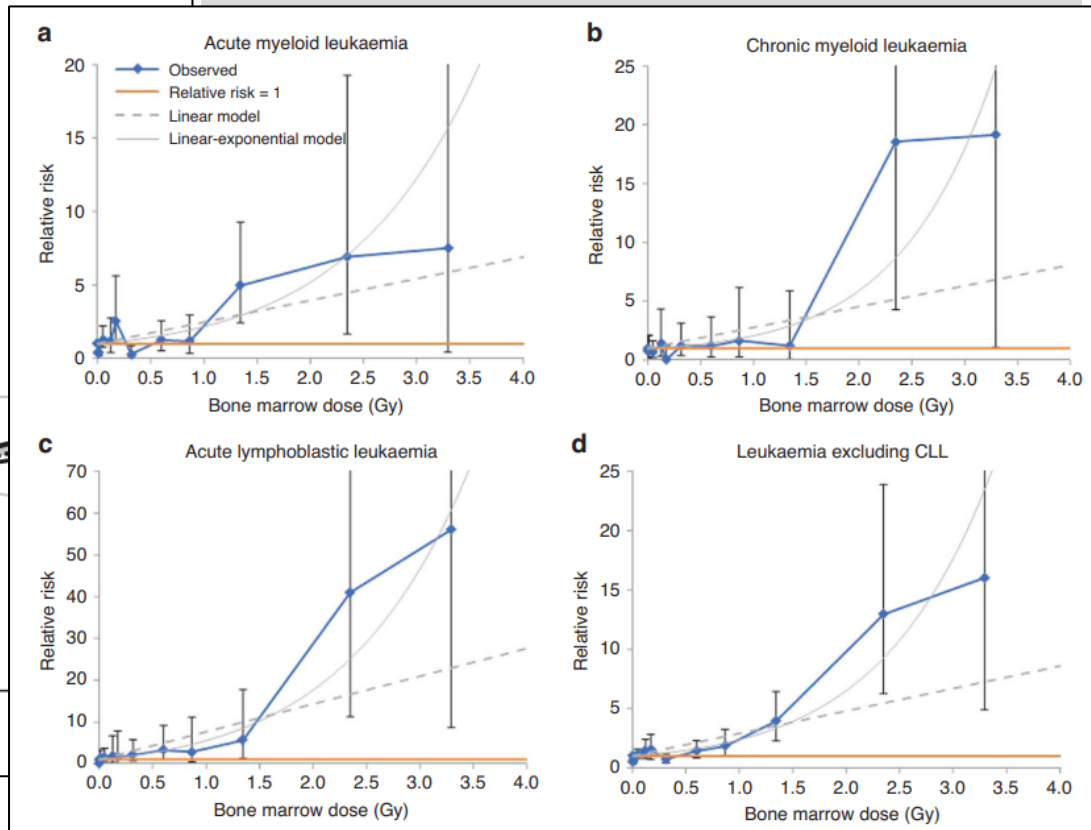
통합 분석 연구 (갑상선암, 백혈병)

- 국제 9개 코호트 자료 통합/21세 이전 노출자 (262,573-310,905)
- 평균 추적 기간: 19.6년, 평균 누적 골수/갑상선량: 19.6mGy/31mGy (0-200mGy)

Lubin et al., J Clin Endocrinol Metab. 2017; Little et al., Br J cancer. 2023

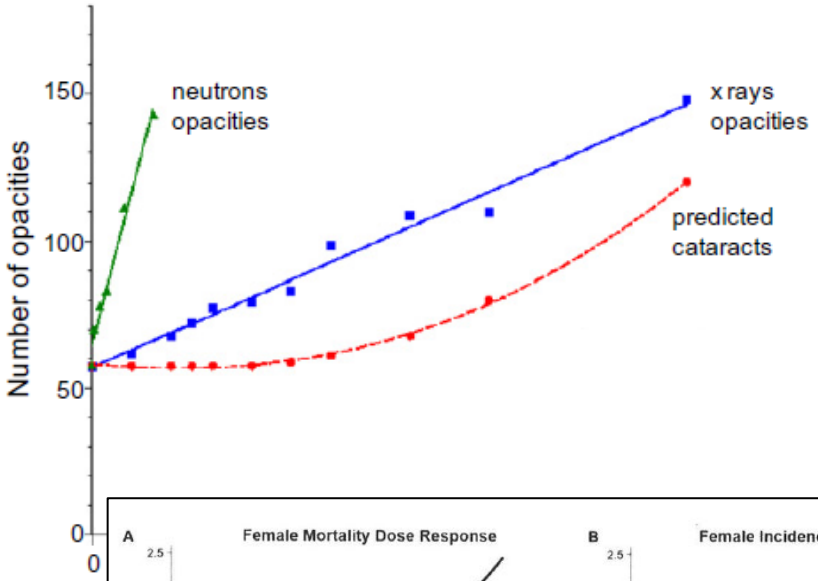


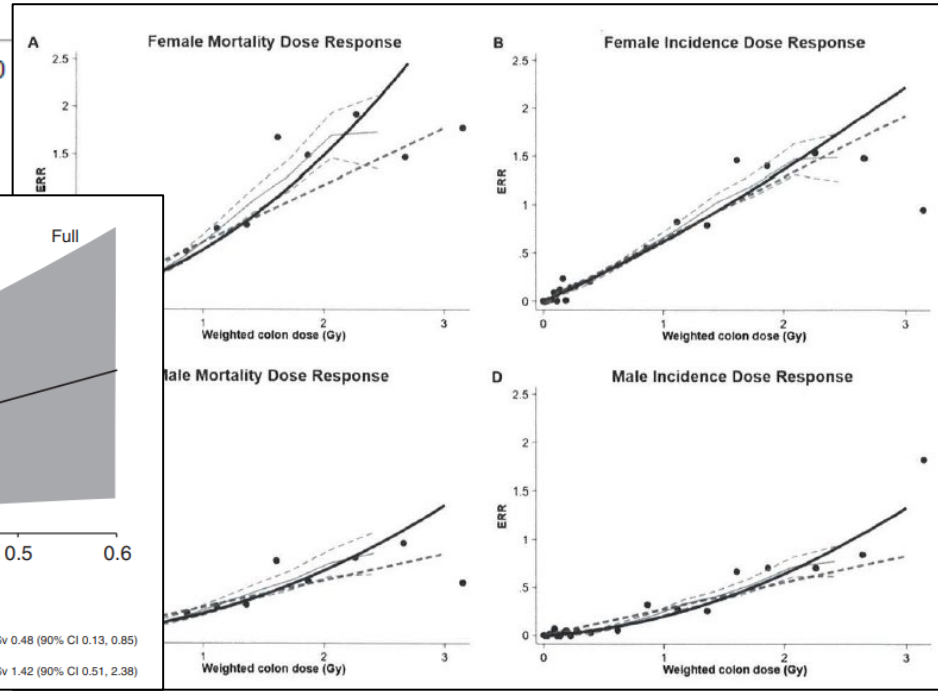
Type of cohort study

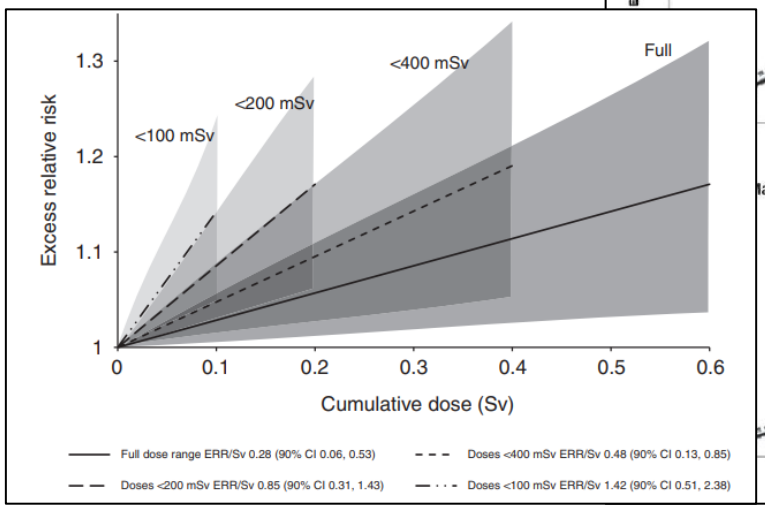


다양한 선량-반응의 역학적 요인

- **건강 영향의 종류**
  (endpoint)
- **건강 지표의 종류**
  (mortality/incidence)
- **선량 범위**
  (low-dose/total dose)
- **추적 기간**
  (follow-up)
- **성별 등**







방사선 역학 연구 고찰 (과학적 근거)

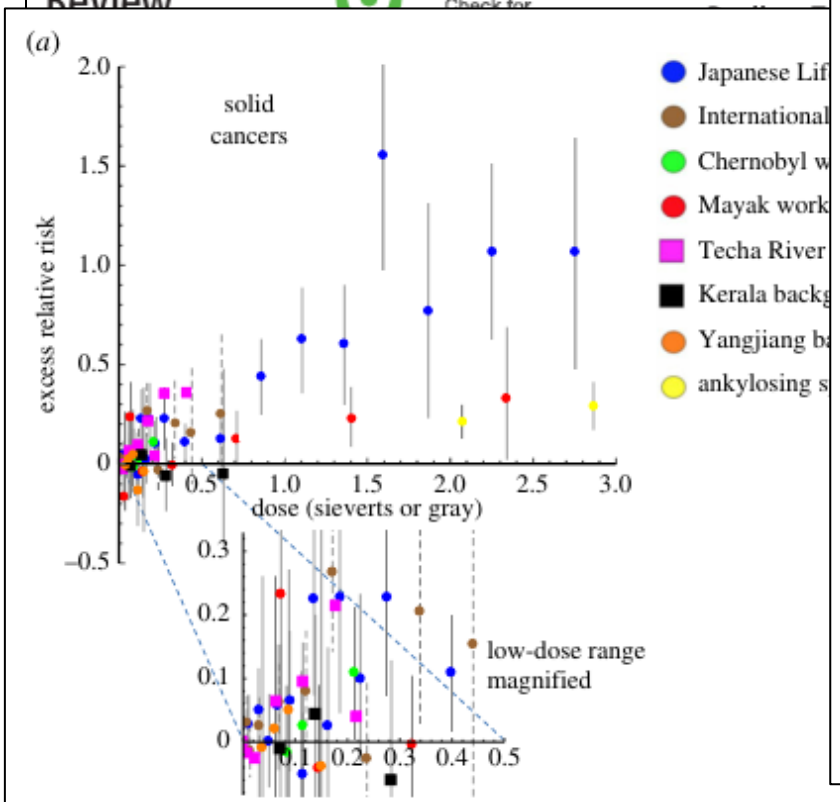
PROCEEDINGS B

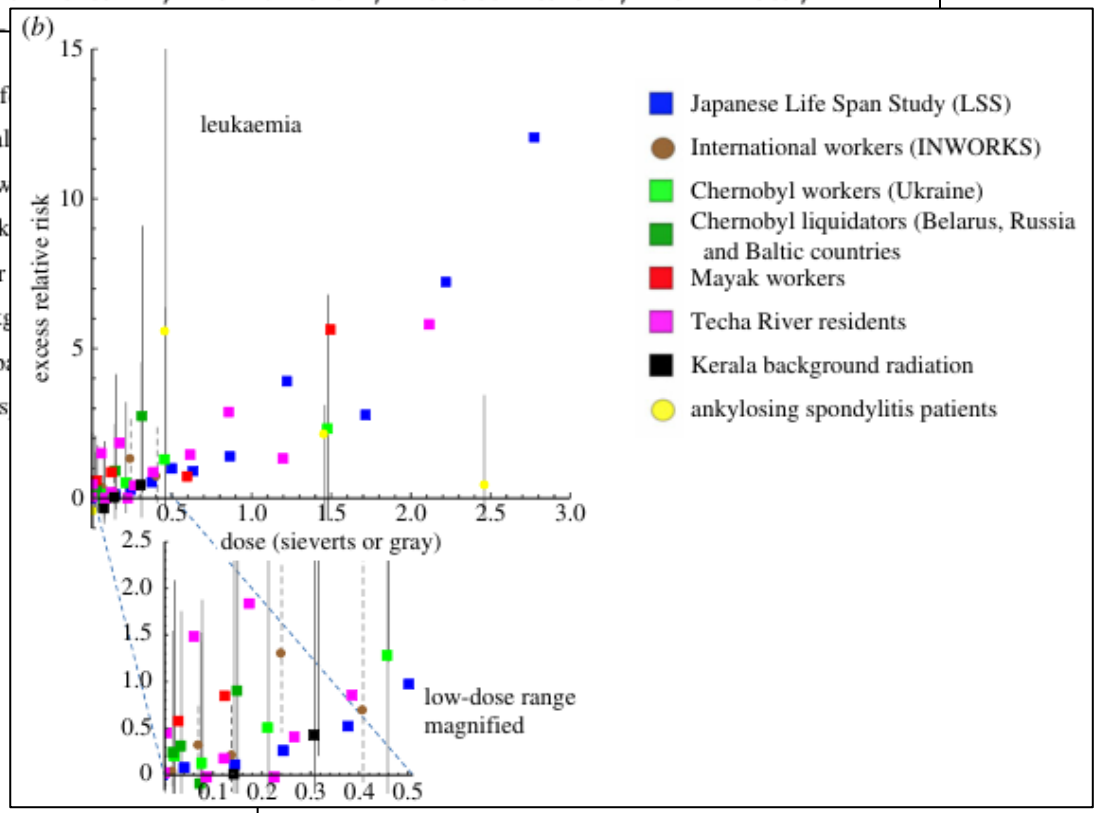
rspb.royalsocietypublishing.org

A restatement of the natural science evidence base concerning the health effects of low-level ionizing radiation

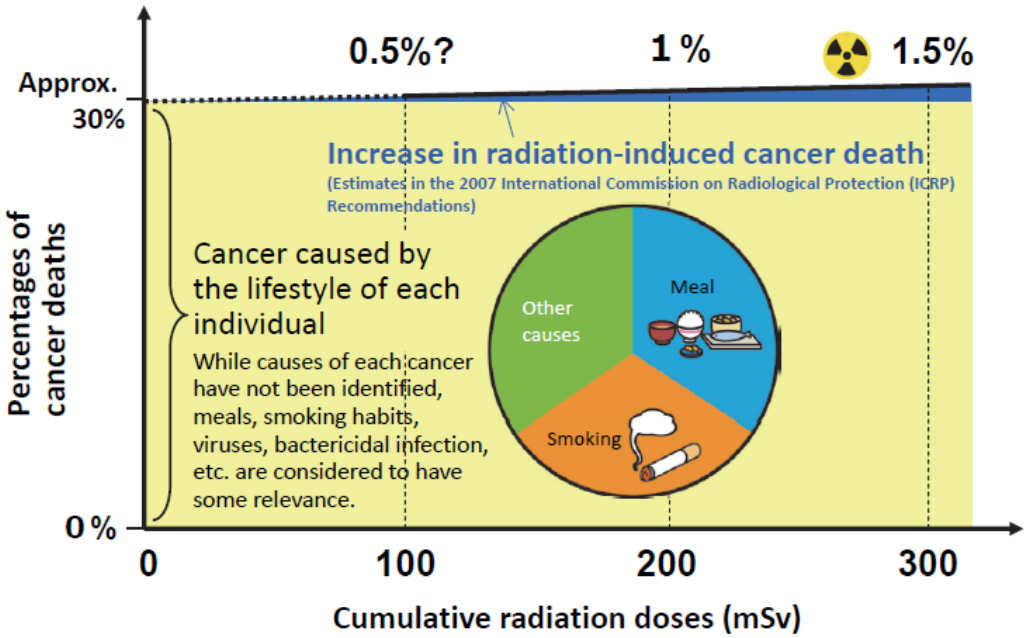
Angela R. McLean[1,2], Ella K. Adlen[2], Elisabeth Cardis[3], Alex Elliott[4],

Review





방사선 노출과 위해도 크기



- 저선량 방사선 노출과 악성종양
  - 역학적 인과성 존재
  - 적은 위험도 크기
  - INWORKS 연구 논평

Lee WJ. Lancet Haematol. 2024

Study	Cancer (index)	Excess Relative Risk	Absolute risk	Reference
INWORKS	Solid ca. (mortality)	0.52/Gy (90% CI: 0.27-0.77)	1/1,000 workers	Richardson et al. 2023
	Leukemia (mortality)	2.68/Gy (90% CI: 1.13-4.55)	1/10,000 workers	Leuraud et al. 2024
EPI-CT	Brain ca. (incidence)	1.27/100 mGy (95% CI: 0.51-2.69)	1/10,000 children	Hauptmann et al. 2023
	Hematological ca. (incidence)	1.96/100 mGy (95% CI: 1.10-3.12)	1.4/10,000 children	Bosch de Basea Gomez et al. 2023

마무리 (take-home message)

- **역학 (epidemiology)**
  - 인구집단 차원에서의 근거 (방사선과의 인과성, 위험도 크기)
  - 다양한 선량-반응 관련성 제시

    (남녀, 노출시 연령, 추적기간, 질병종류, 사용지표, 인구집단, 노출 특성 등)
  - 연구 축적에 따른 학문적 심화 및 변화 (사례: 원폭 생존자 연구)

- **LNT (liner no-threshold model)**
  - 방호 차원의 현실적 판단 (practical purposes of radiation protection)

    (여러 모델 중 가장 유용함: best though imperfect)
  - 과학 외 가치판단 고려 (value judgement)