

LNT와 역학

(LNT & epidemiology)

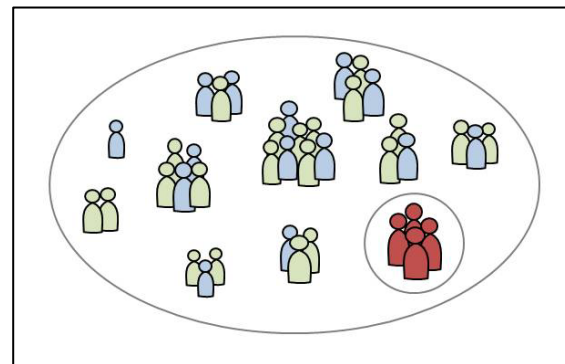
한국원자력학회
(2025. 5. 21)

이 원 진

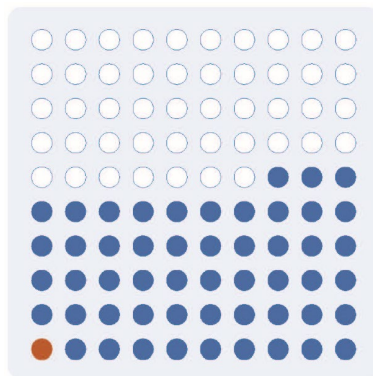
고려대학교 의과대학 예방의학교실

발표 내용

- 역학 연구의 의미와 한계
- 선량-반응에 대한 역학적 근거



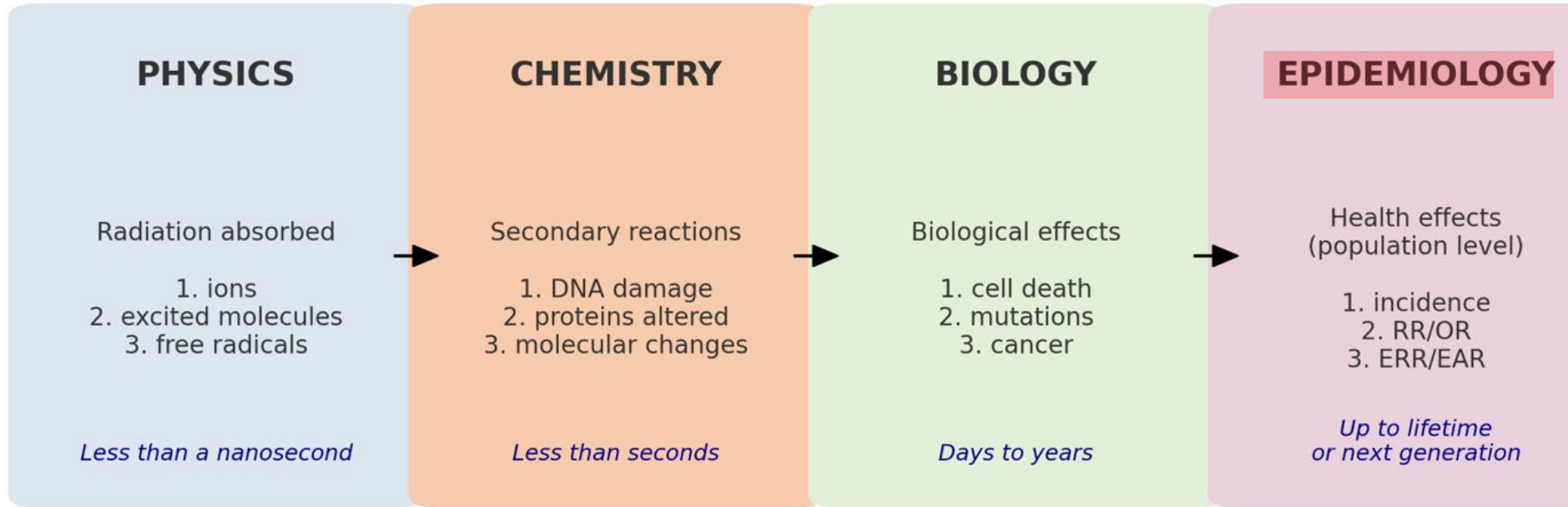
- UNSCEAR 보고서
- 원폭 생존자 연구
- 직업노출 연구
- 의료노출 연구
- 환경노출 연구
- 통합분석 연구



- 방사선 위험도의 크기

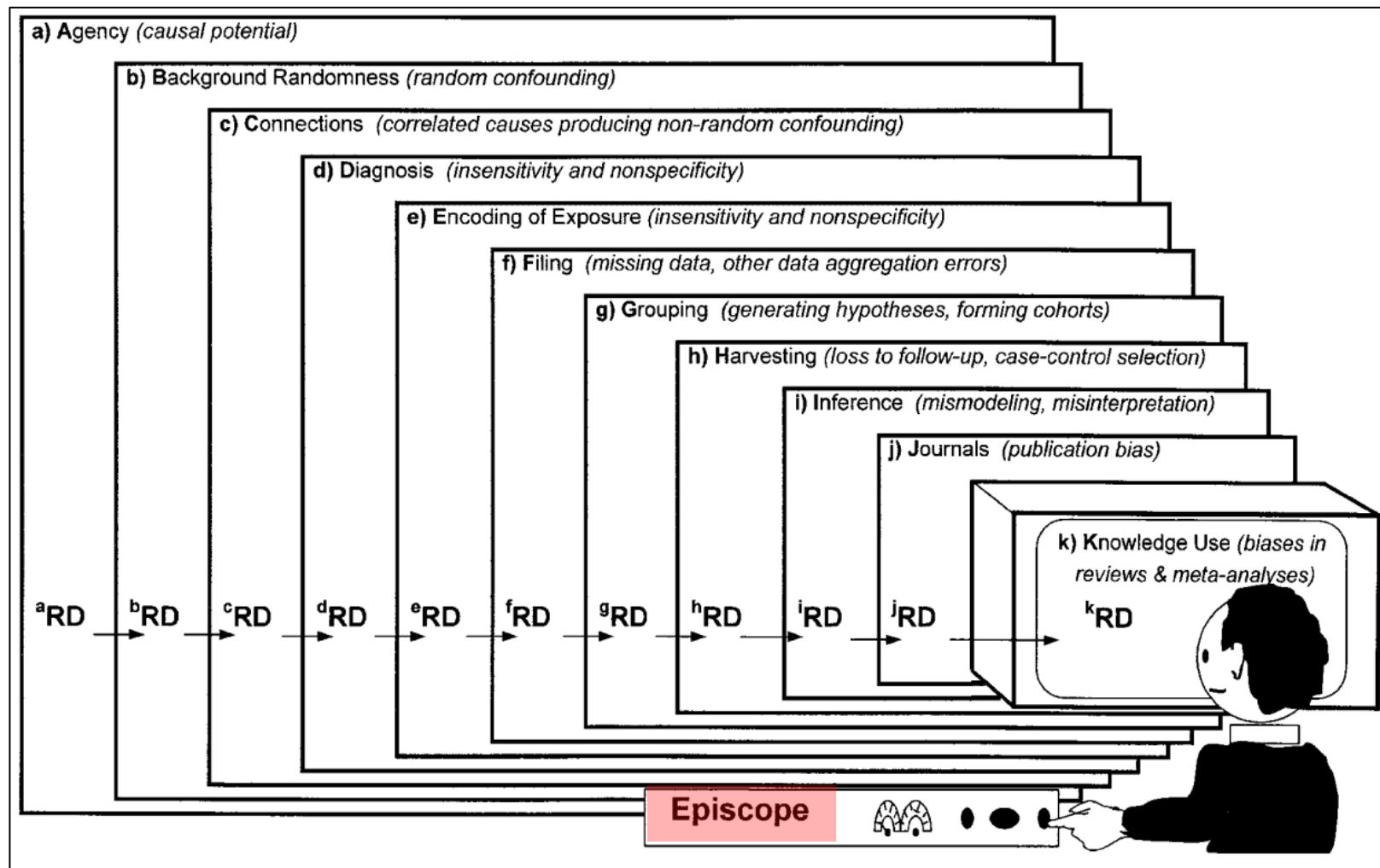
본 발표와 이해충돌 없음

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


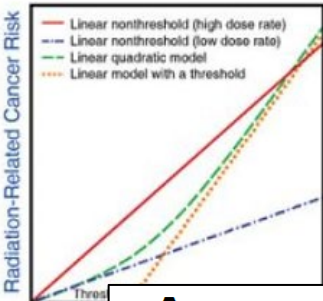


- 연관성(association) vs. 인과성(causation)

선량-반응 관련성에 대한 역학적 고찰

NCRP COMMENTARY No. 27

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



Annals of the ICRP

ICRP PUBLICATION XXX

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


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

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^c Centre for Occupational

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

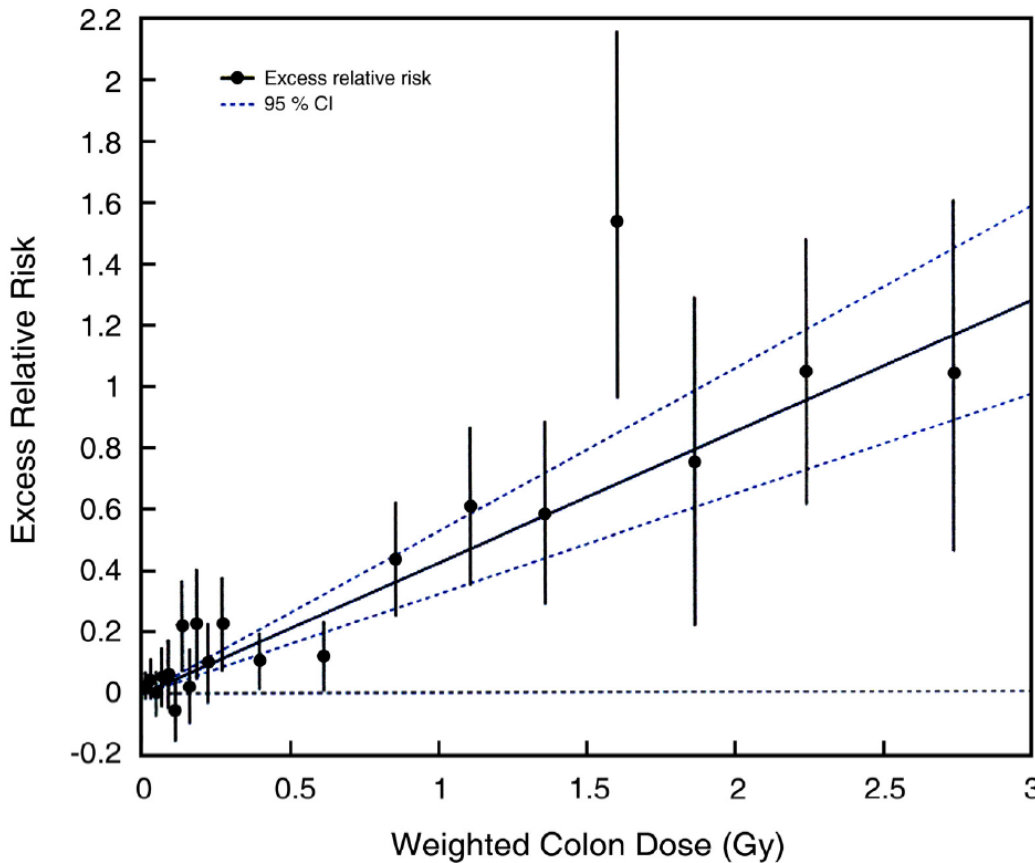
EPIDEMIOLOGICAL STUDIES OF
IONIZING RADIATION AND CANCER

악성 종양과 역학 결과 종합 (UNSCEAR)

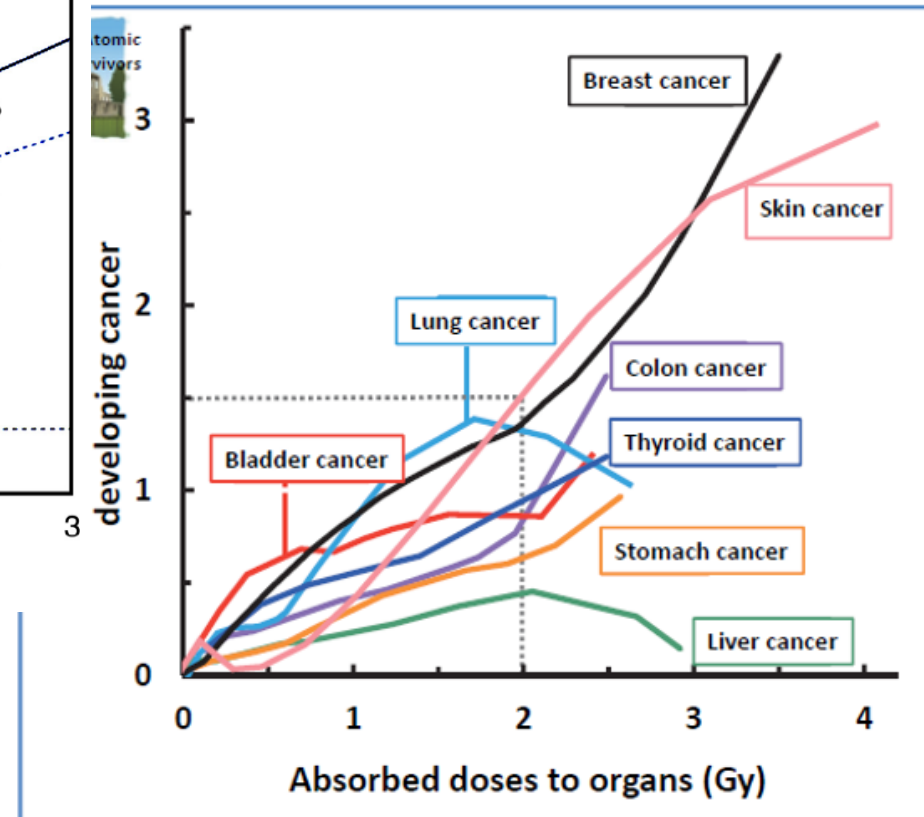
Cancer site	Weight of evidence	Dose-response
Esophagus	Sufficient	Non-linearity
Stomach	Sufficient	Linearity
Colon	Sufficient	Linearity
Thyroid	Sufficient	Linearity
Ovary	Sufficient	-
Pancreas	Limited	Linearity
Lung	Sufficient	Linearity
Non-melanoma skin	Sufficient	Upward curvature
Leukemia	Sufficient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

Sufficient (15), Limited (9), Inadequate (3)

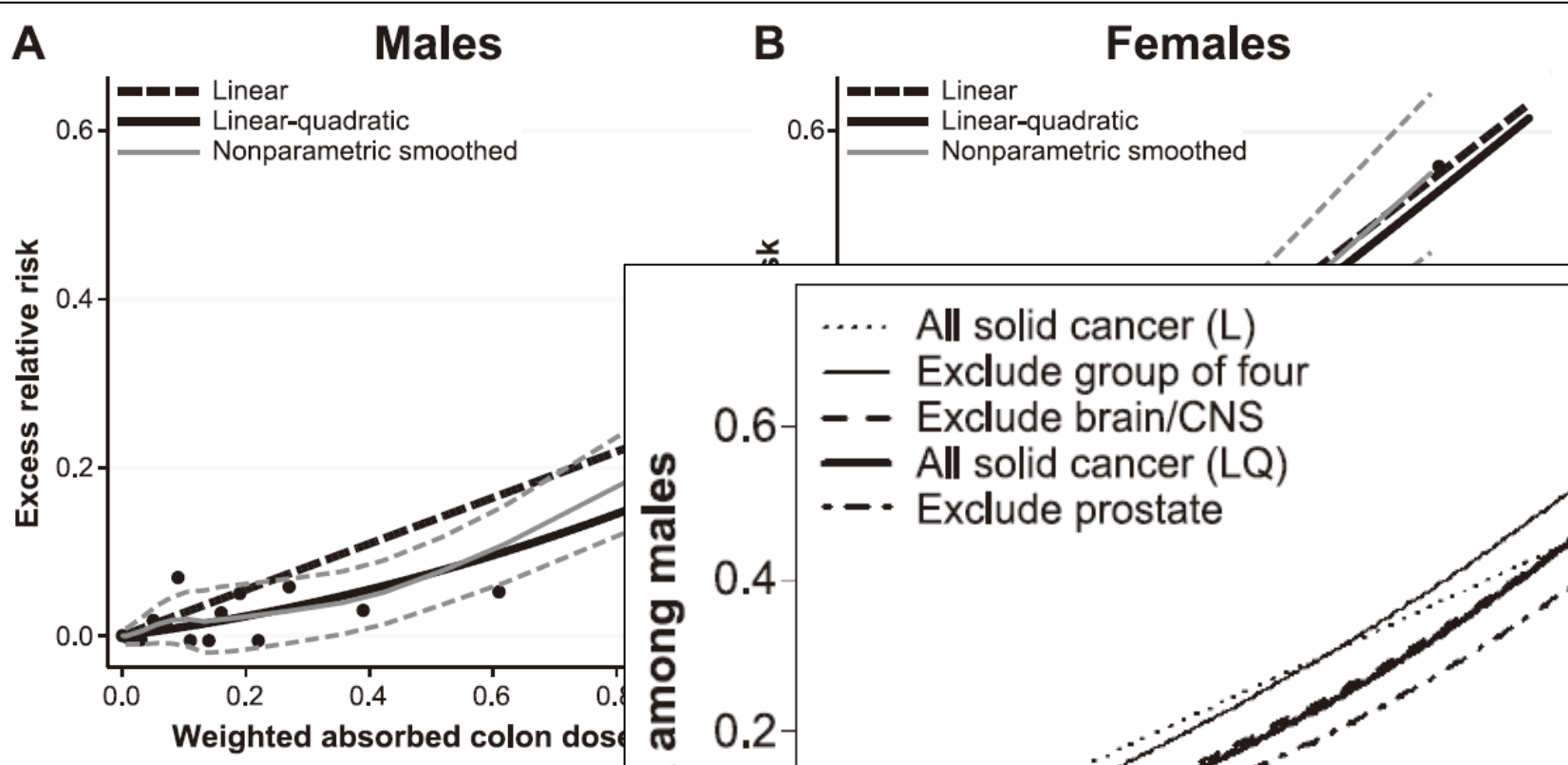
원폭 생존자 연구 (암사망, 1950-2003)



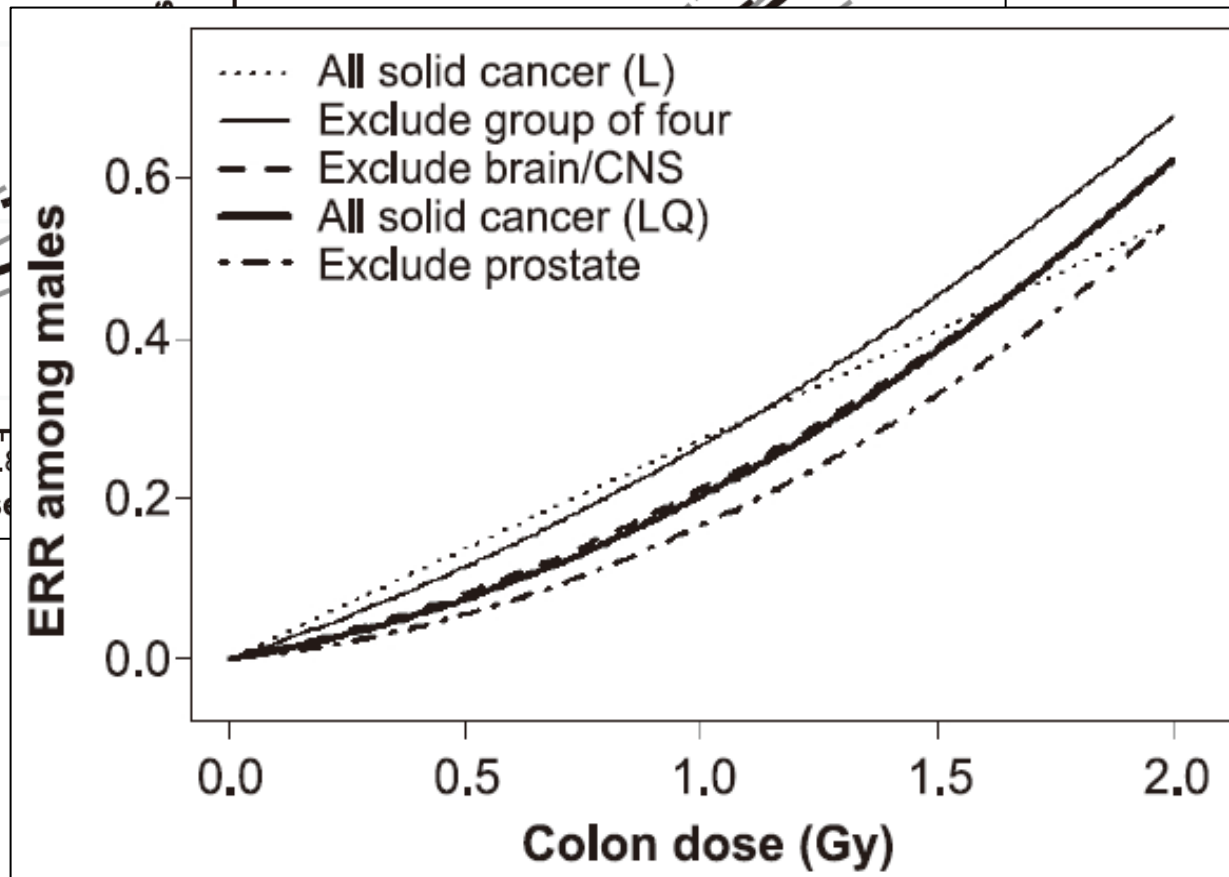
Ozasa et al. Radiat Res. 2012



원폭 생존자 연구 (암발생, 1958-2009)

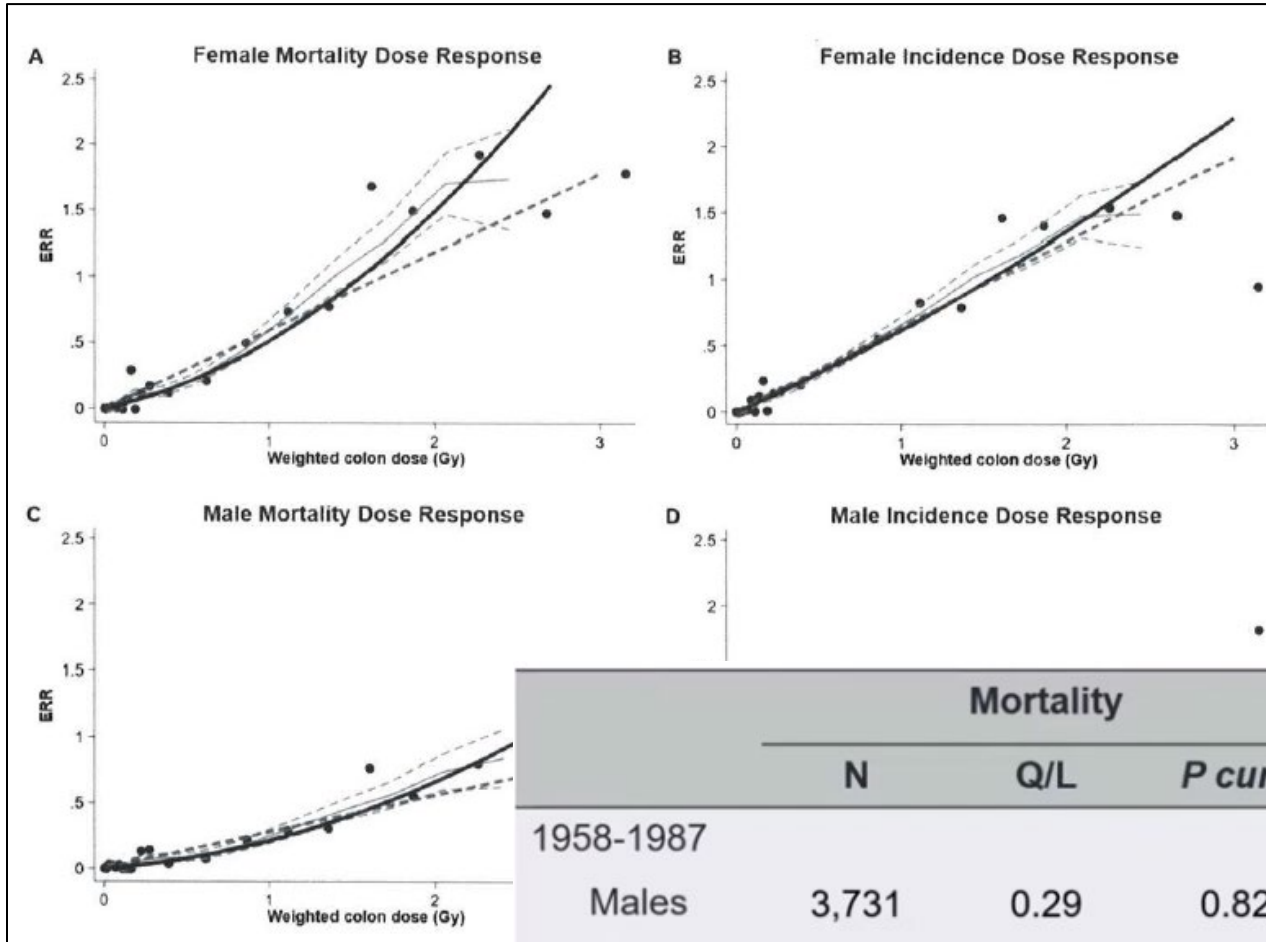


Grant et al., Radiat Res. 2017



Cologne et al., Radiat Res. 2019

원폭 생존자 연구 (암발생 및 사망, -2009)



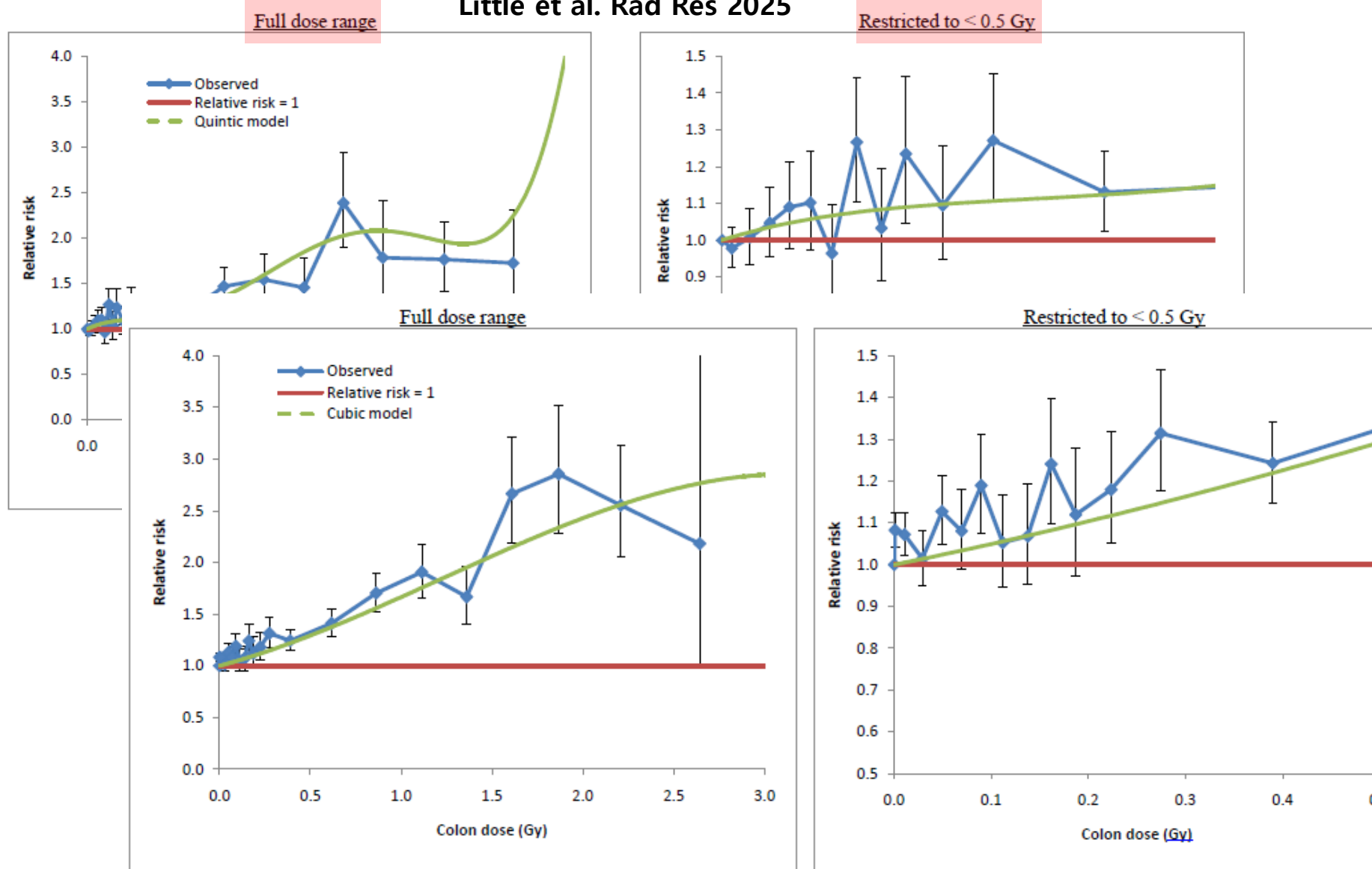
- 암종별 구성 차이
 - 성별
 - 발생과 사망
 - 개별 암종 구성
- 최근 추가된 암종의 영향 (어린 나이 노출자)

Brenner et al. Rad Res 2022

	Mortality			Incidence		
	N	Q/L	<i>P</i> <i>curv</i>	N	Q/L	<i>P</i> <i>curv</i>
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)



National cohort
n = 59 003

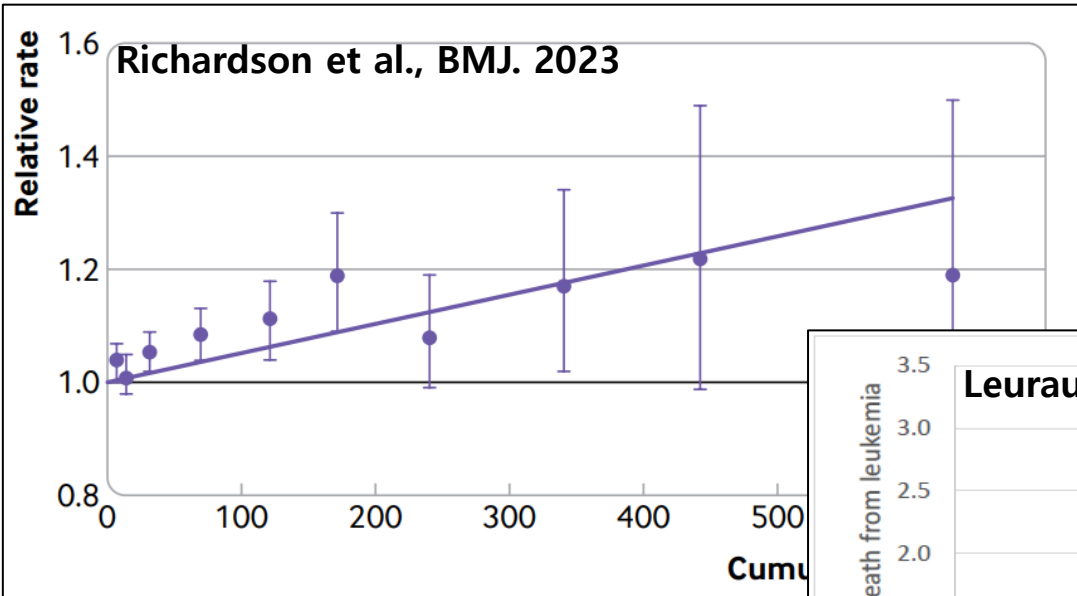


UK NRRW
n = 147 866



US combined cohort
n = 101 428

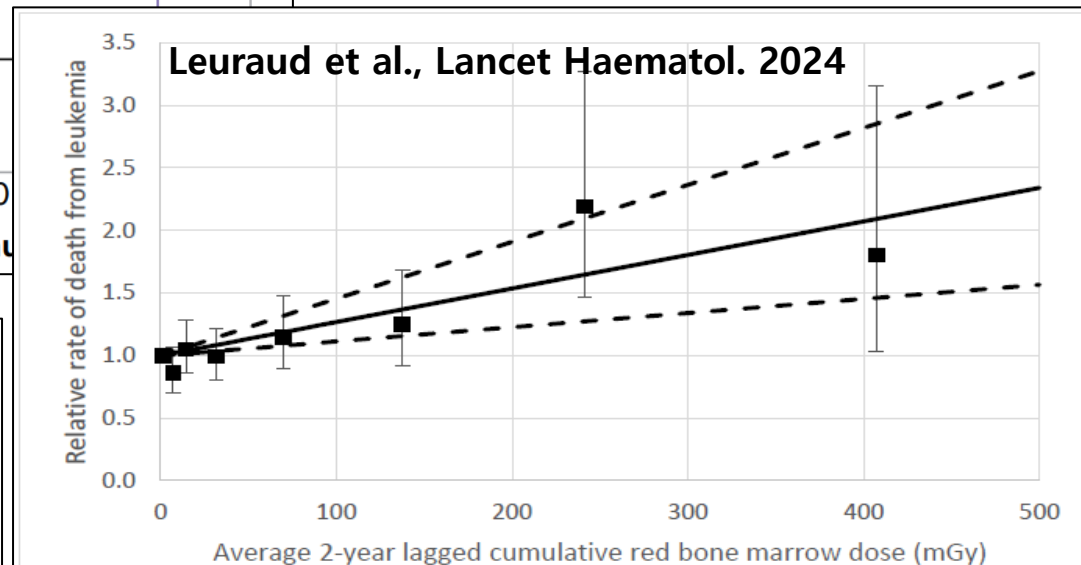
- IARC 주관 후향적 코호트
- 원전종사자 약 30만명
- 평균 대장 및 골수선량:
20.9mGy/15.9mGy
- 선량-반응 관련성 (선형)



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-Chef⁹
and Ausrele Kesminiene⁹

International Journal of Epidemiology, 2016,



의료노출 (EPI-CT, 소아암)

International Agency for Research on Cancer | EPI-CT: International pediatric CT scan study

World Health Organization | EPI-CT

NEWS AND EVENTS | CONSORTIUM | SCOPE | PUBLICATIONS | MEMBERS



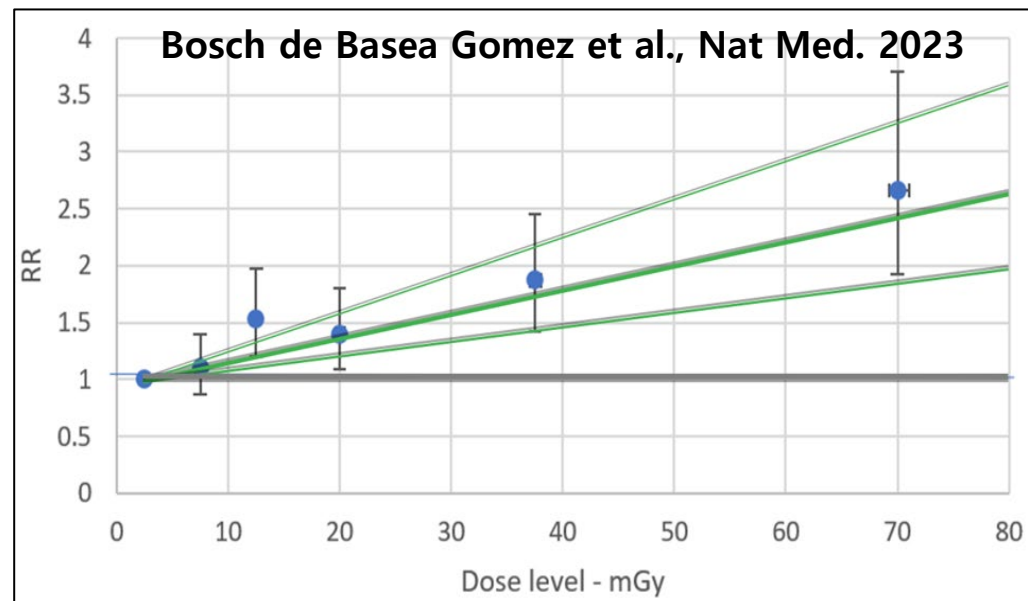
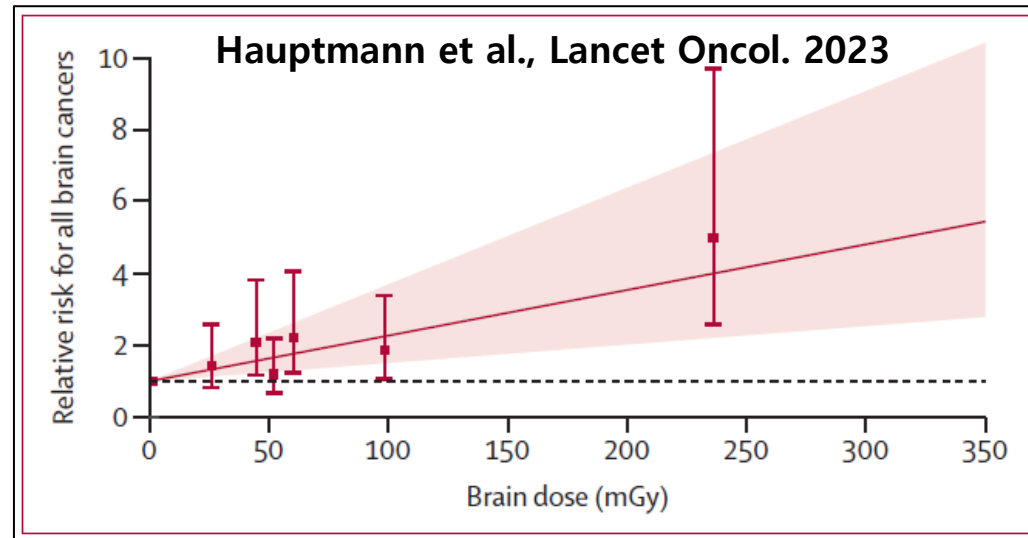
You are here: Home

Diagnostic radiation represents an indispensable tool for modern medicine. Physicians see benefits of using computerized tomography (CT) scanning in their daily clinical practice. The growth of CT use in children has been driven primarily by the reduction in the time needed to perform a scan. As a consequence, it is now possible to perform more examinations in a given time, extend the scope of some examinations, as well as introduce some new techniques and examinations. The ease of acquisition of images results sometimes in unnecessary exposure of patients to radiation, particularly in developed countries. Furthermore, organ doses from CT scanning are considerably larger than those from corresponding conventional X-ray. For example, a dose to the stomach from a conventional abdominal X-ray examination is approximately 0.25 mGy, which is at least 50 times smaller than the corresponding stomach dose from an abdominal CT scan (Brenner & Hall, 2007).

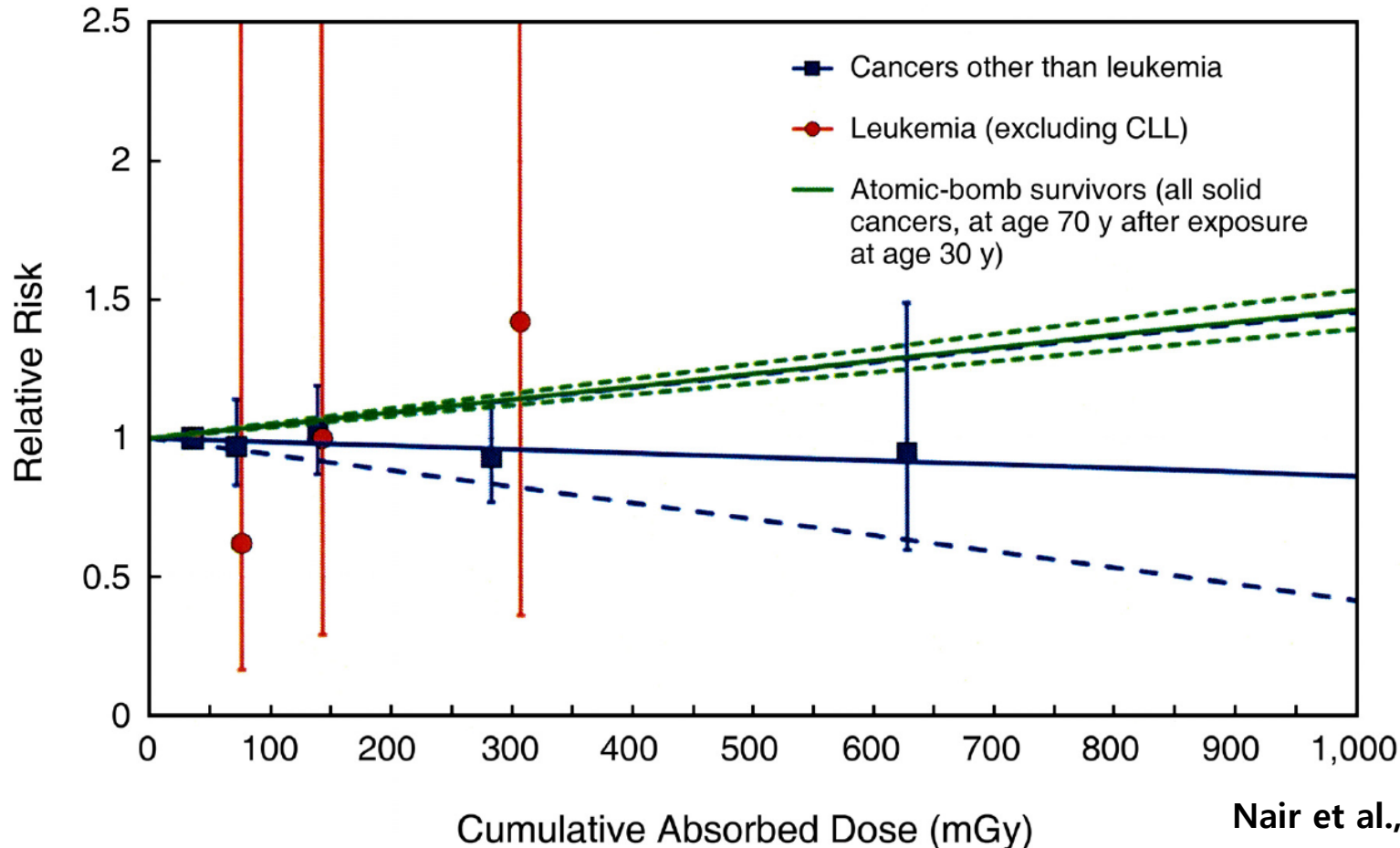
The growing use of CT technology despite the introduction and wider use of other modalities, such as magnetic resonance imaging, raises concerns in radiological protection, especially for children and adolescents. Children are generally more sensitive to the carcinogenic effects of ionizing radiation than adults. In addition, they may receive even higher radiation doses from a CT procedure than an adult. Empirical evidence supporting such concerns comes from recent epidemiological studies in the UK and Australia that have reported statistically significant increased risks of cancer associated with paediatric CT scans. Direct estimation of the health impact of CT radiation remains imprecise, however, and further large-scale epidemiological studies with more accurate dosimetry and assessment of potential biases and uncertainties are needed. The "Epidemiological study to quantify risks for paediatric computerized tomography and to optimise doses" (EPI-CT) was set-up to investigate the relationship between the exposure to ionizing radiation from CT scans in childhood and adolescence and possibly attributable late health effects. Eighteen centres from Belgium, Denmark, Germany, Finland, France, Luxembourg, the Netherlands, Norway, Spain, Sweden and the United Kingdom will cooperate in this project to enrol approximately one million patients. The knowledge gained on current and past CT examination practice will help to propose strategies for further dose reduction.



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

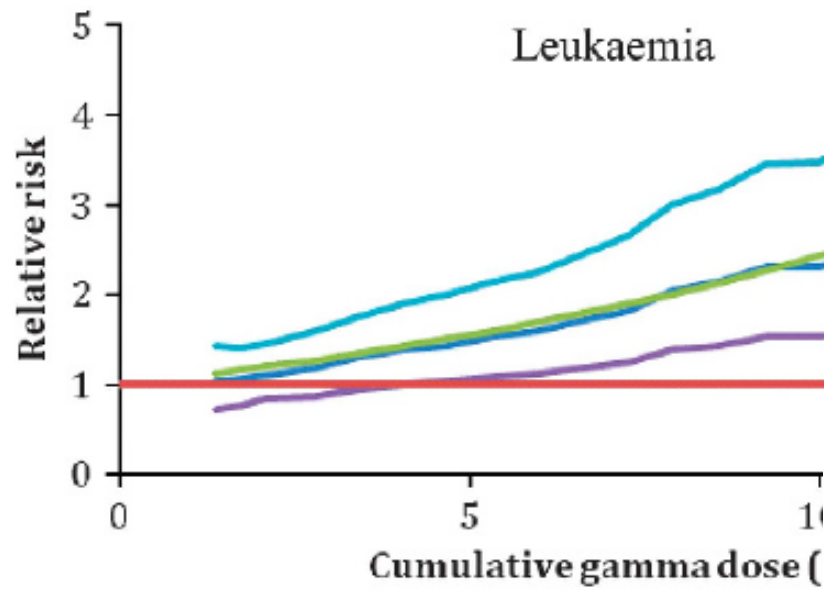


환경 노출 (자연 방사선, 성인)



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

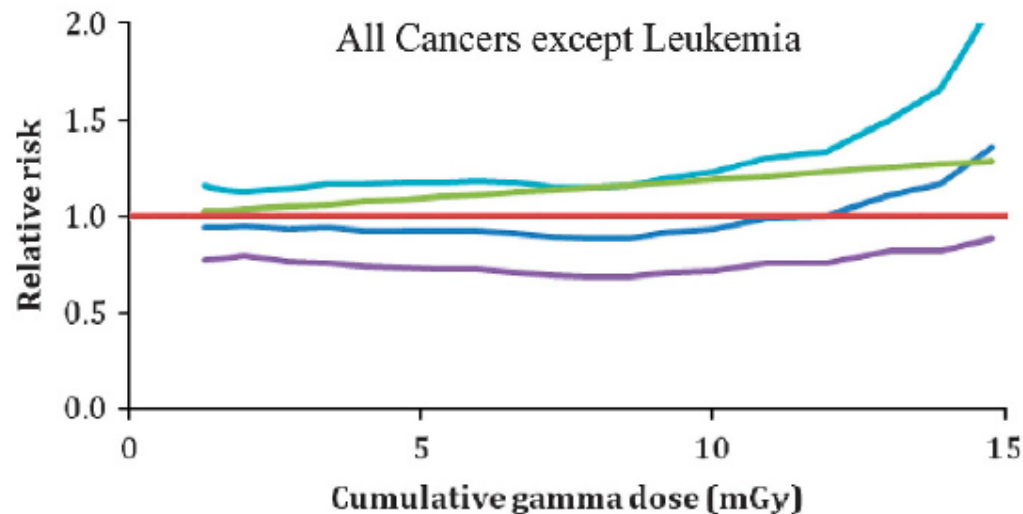
환경 노출 (자연방사선, 소아)



— Observed
 — Observed upper 95% CI
 — Observed lower 95% CI
 — Modelled fit
 — Relative risk=1

Kendall et al., Leukemia. 2013

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



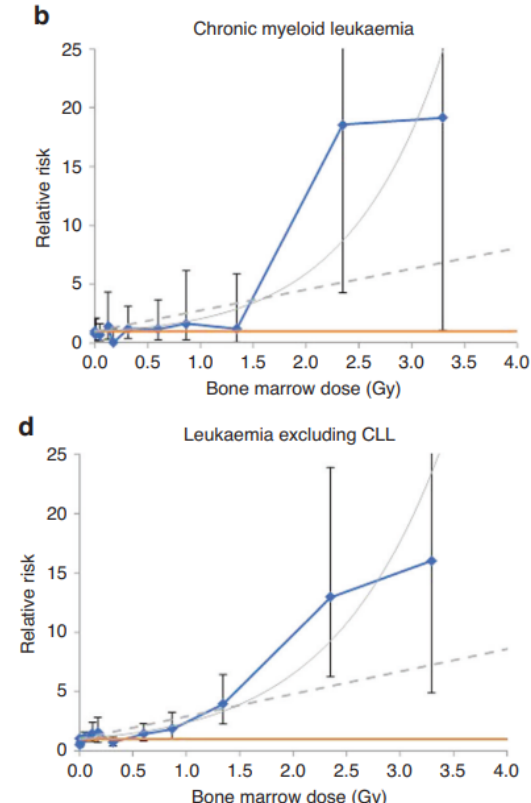
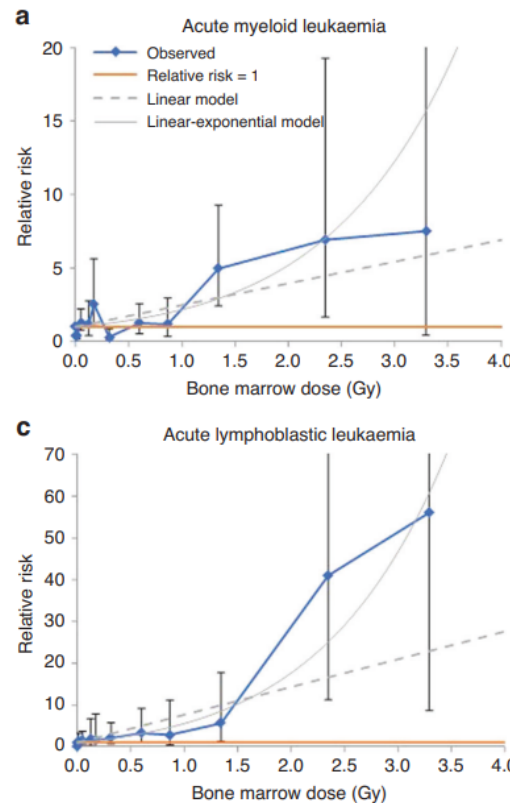
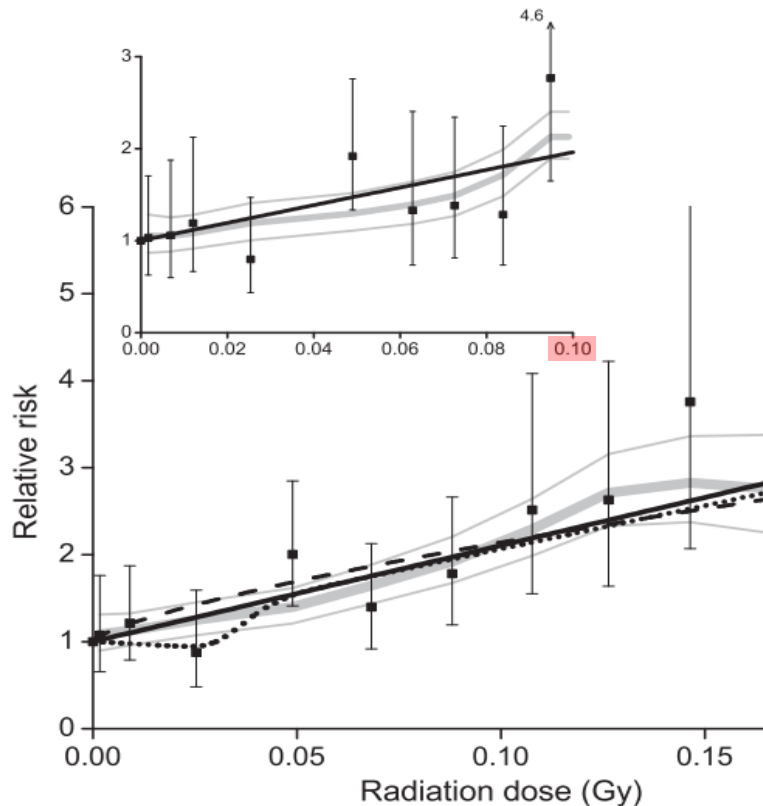
— Observed
 — Observed upper 95% CI
 — Observed lower 95% CI
 — Modelled fit
 — Relative risk=1

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)

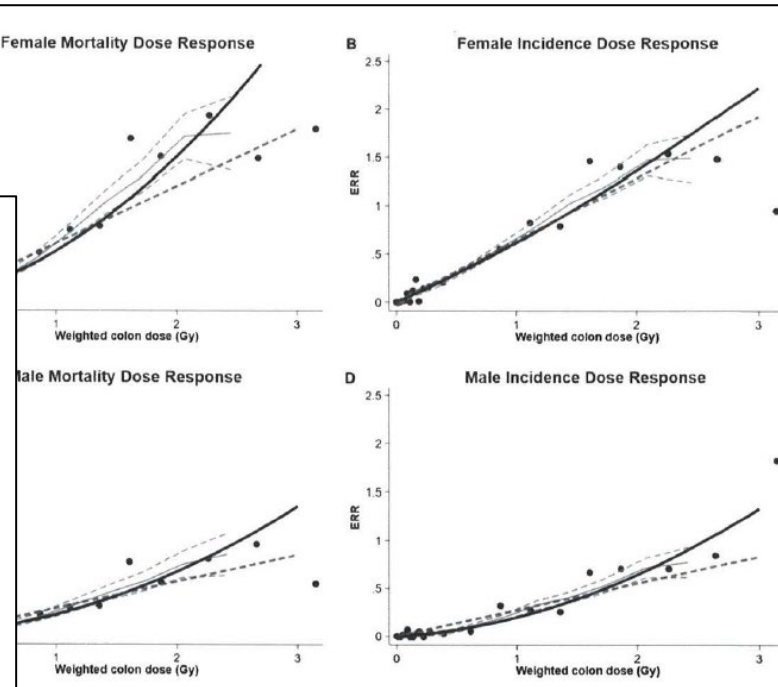
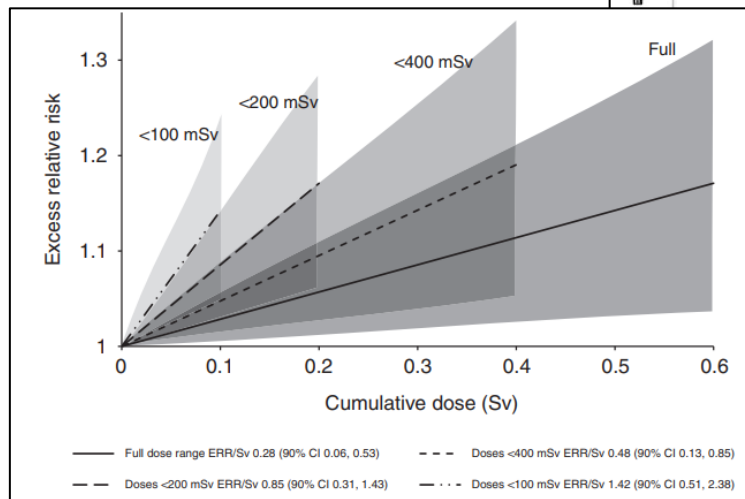
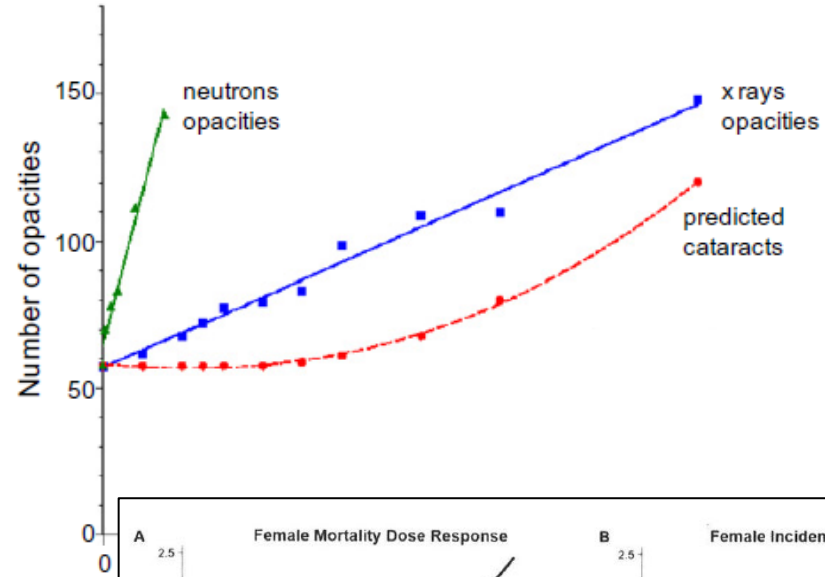
Lubin et al., J Clin Endocrinol Metab. 2017; Little et al., Br J cancer. 2023

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

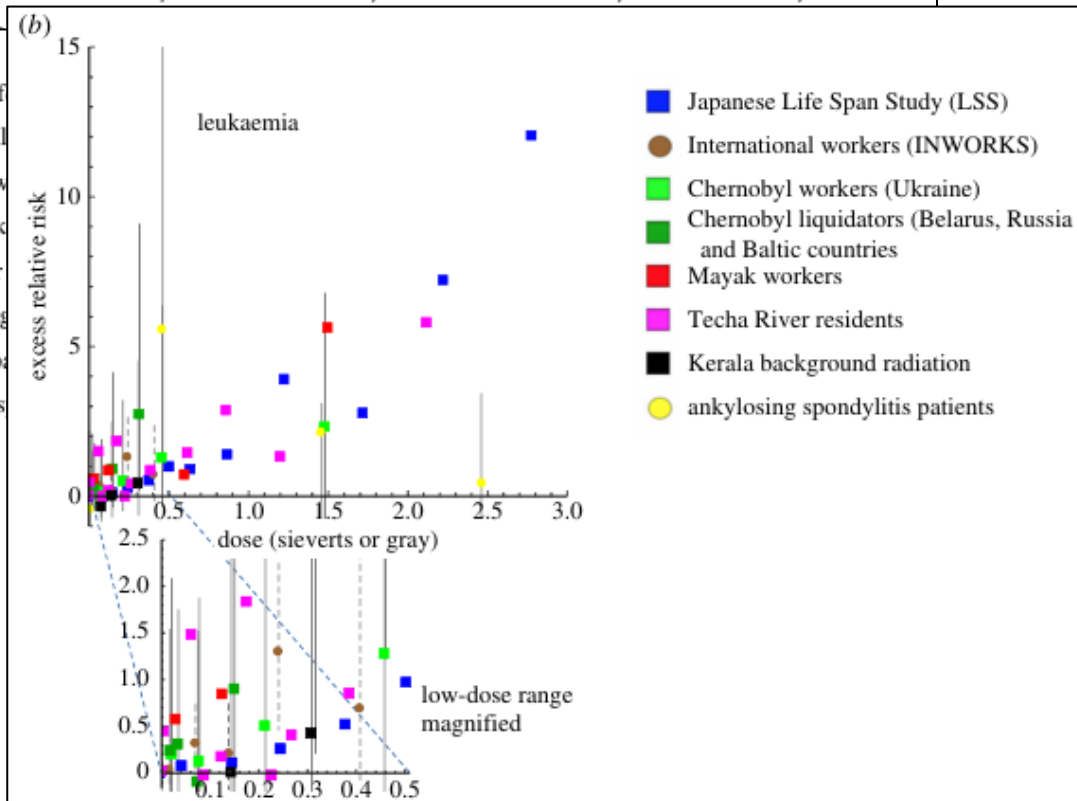
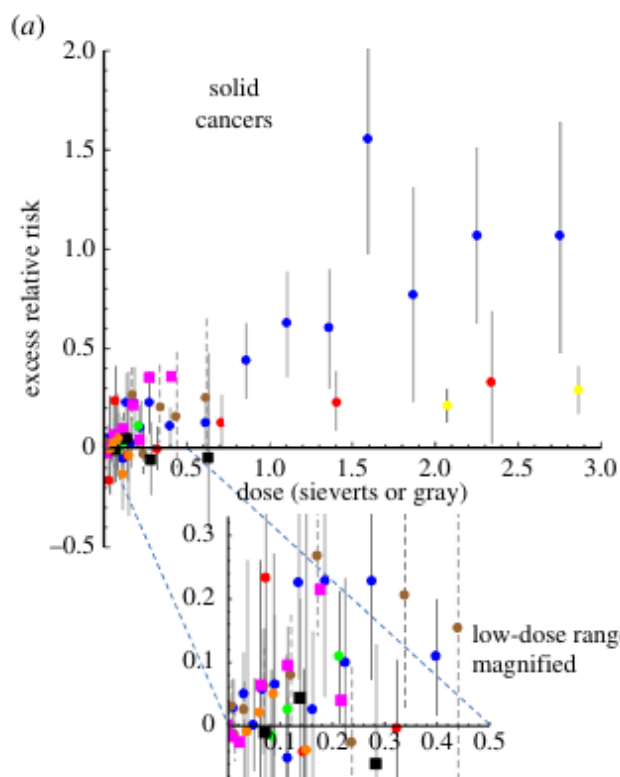
rspb.royalsocietypublishing.org

Review

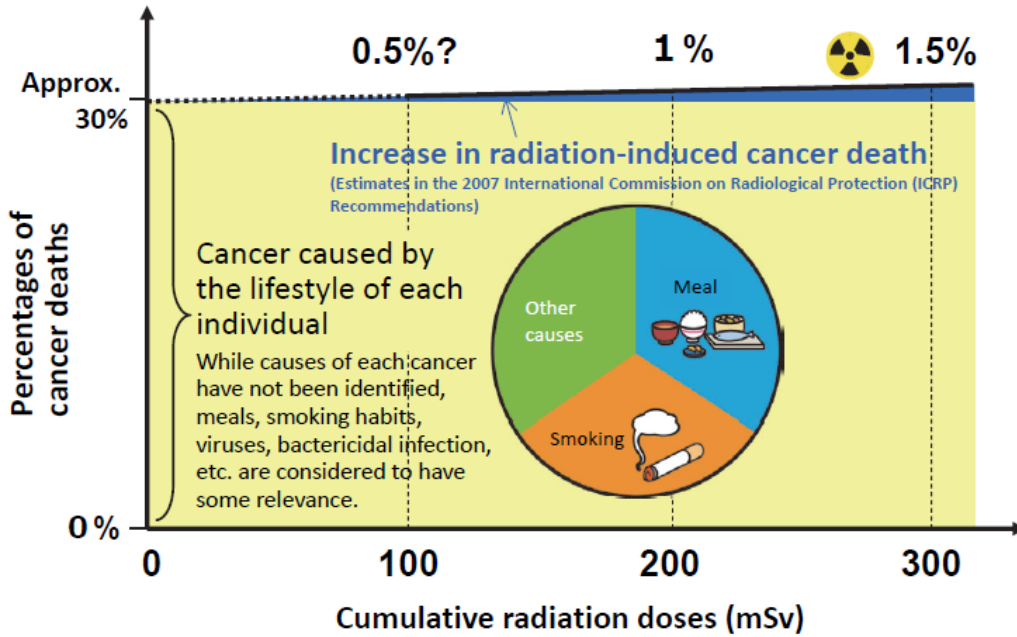


A restatement of the natural science evidence base concerning the health effects of low-level ionizing radiation

Angela R. McLean^{1,2}, Ella K. Adlen², Elisabeth Cardis³, Alex Elliott⁴,



방사선 노출과 위험도 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 (linear 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)