ICTP 2019

From measurable dose quantities to risk metrics: approaches and uncertainties

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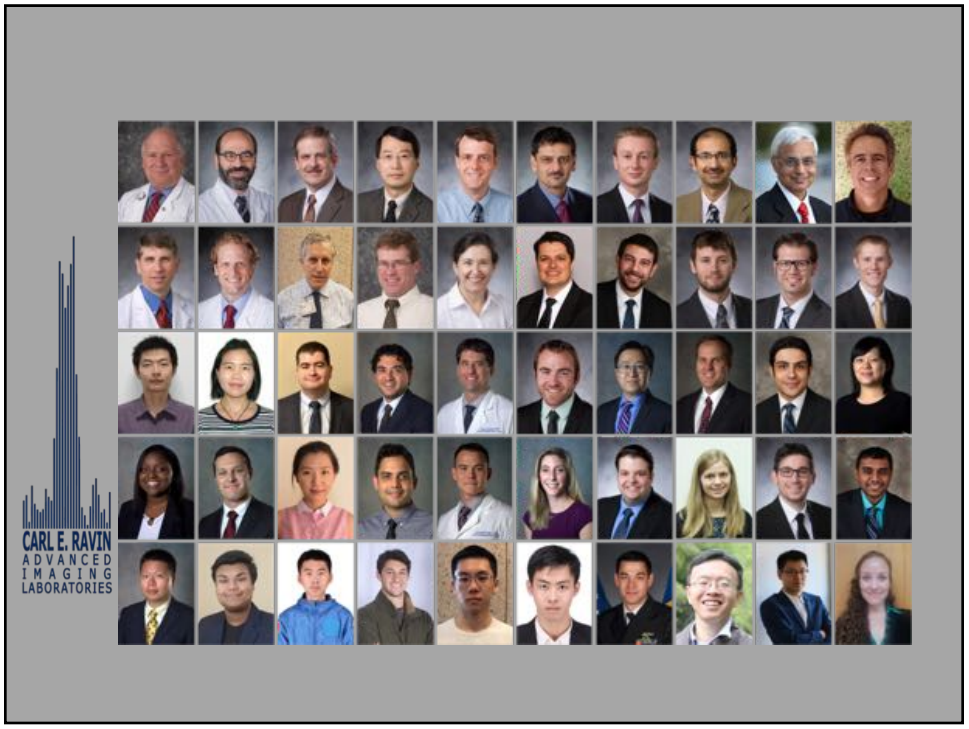
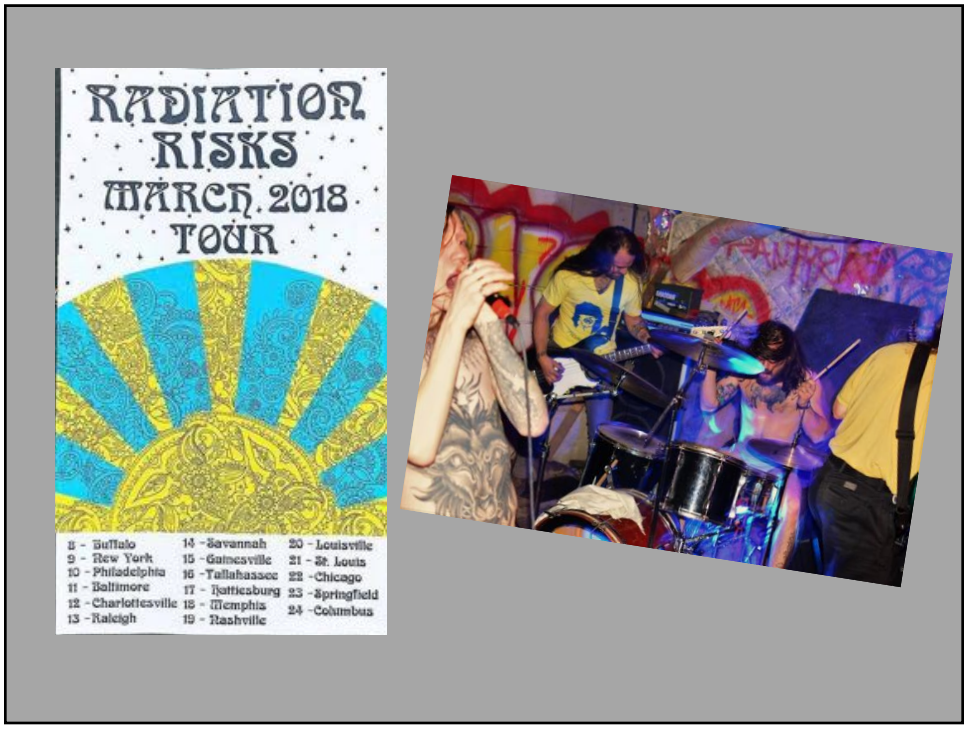
Duke University Health System

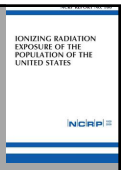


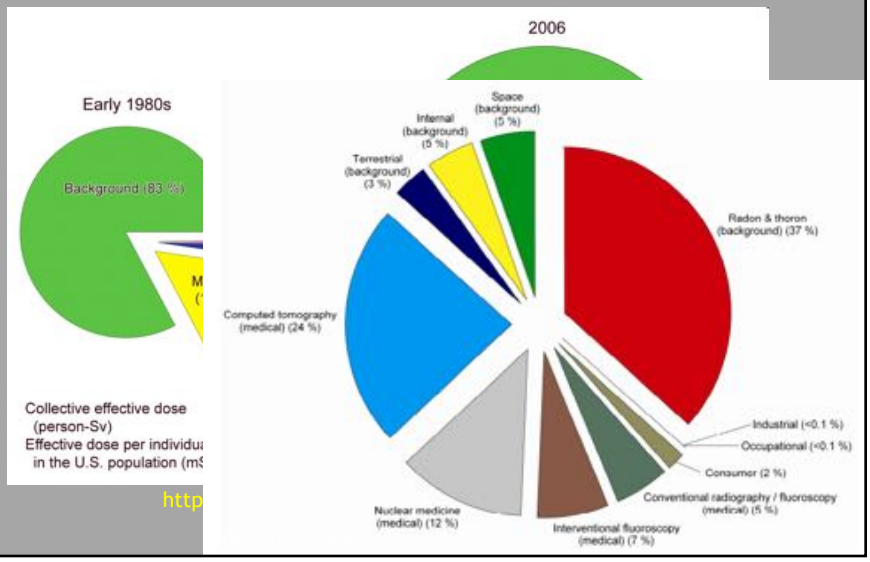


Imaging quality and safety

- Quality: Imaging provides a clinical benefit
  - Diagnostic information
  - Image quality: Universally-appreciated, but unclear how to quantify and use as criteria for optimization
- Safety: Imaging involves a level of "cost"
  - Monitory cost
  - Information excess
  - Radiation "cost"

Increase in Radiation Exposure from Medical Imaging





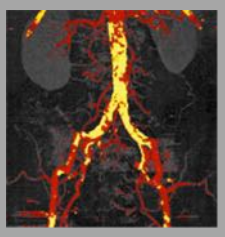
Increased utilization of CT

http://www.aboutcancer.com/xrt_risk_brenner_2007.htm

Cone beam CT

http://istar.jhu.edu/research/

Dual energy angiogram



http://radiology.ucla.edu/body.fm?

Radiation "cost"

- Tissue-deterministic effects (at Gy levels)
- Stochastic effects (at mGy levels)

Outline

- FAQs about imaging radiation risk
- Metrics of risk

7 FAQs about radiation risk

1. Is the increase in the number of imaging exams bad?

- No necessarily so, provided that the exams render the needed medical information
- If benefit > risk, more exams means more benefit!

2. Is low-level radiation dose harmful?

- Inconclusive epidemiological data
- High degree of uncertainty in risk estimates
- No-threshold model questioned
  - AAPM, HPS, IOMP statements (<50 mSv => ???)
- Yet:
  - Defining reference diagnostic levels
  - ALARA: As low as reasonably achievable

We got to sort out our passive/aggressive attitude towards radiation risk

2. Is low-level radiation dose harmful?

Int. J. Epidemiol. Advance Access published October 1, 2010

International Journal of Epidemiology 2010;1–10
doi:10.1093/ije/dyq162

Diagnostic X-rays and risk of childhood leukaemia

Karen Bartley,[1]* Catherine Metayer,[1] Steve Selvin,[1] Jonat

Conclusions The results suggest that exposure to post-natal diagnostic X-rays is associated with increased risk of childhood ALL, specifically B-cell ALL, but not AML or T-cell ALL. Given the imprecise measures of self-reported X-ray exposure, the results of this analysis should be interpreted with caution and warrant further investigation.

British Journal of Cancer (2009) 100, 206–212

www.bjcancer.com

Mortality and cancer incidence following occupational radiation exposure: third analysis of the National Registry for Radiation Workers

CR Muirhead*[,1], JA O'Hagan[1], RGE Haylock[1], MA Phillipson[1], T Willcock[1], GLC Berridge[1] and W Zhang[1]
[1]Health Protection Agency, Centre for Radiation, Chemical and Environmental Hazards, Chilton, Didcot, Oxon OX11 0RQ, UK

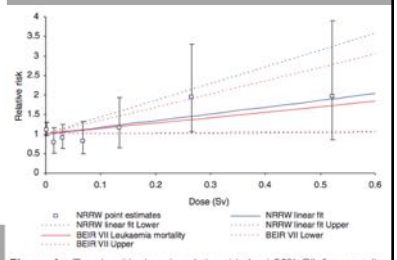


Figure 1 Trends with dose in relative risk (and 90% CI) for mortality from leukaemia excluding CLL.

3. If the benefit > risk, do we need to worry about risk?

- Yes!
- *Primum non nocere,* "first, do no harm"
- We are healthcare providers bound by an ethical obligation
- **In the face of any risk, we are obligated to minimize the likelihood of harm no matter how big is the benefit**

4. Is there such thing as individual risk?

- Yes
- Risk is a statistical construct, likelihood of harm estimated for a population representing the patient
- Population-based estimate ascribed to an individual
- Risk is inherently theoretical and uncertain for the individual - yet that is what the risk is

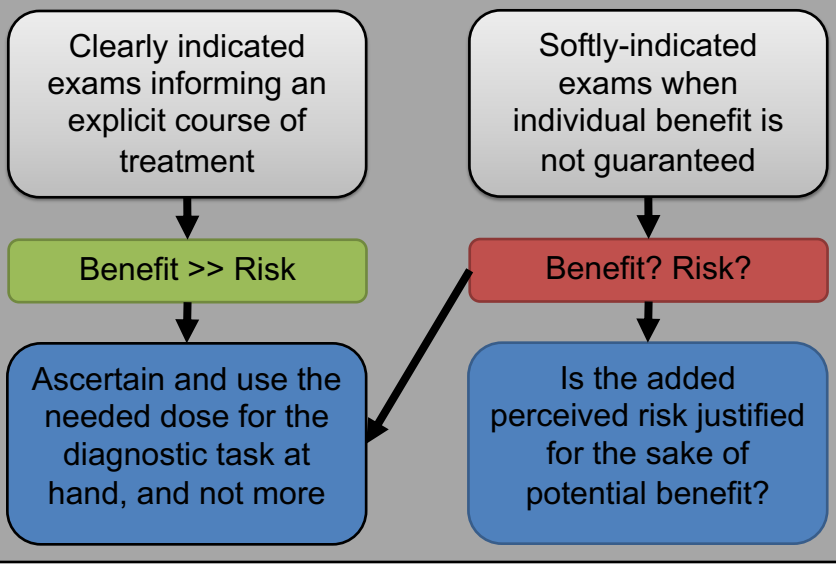
5. Is risk additive?

- Yes!
- Twice the dose means twice the likelihood of harm
- Additiveness is based on the time-frame
  - E.g., doubling a single exam dose means doubling the risk for that encounter
  - Additiveness dependents on the definition of encounter
  - Additional biological effects that can enhance or dampen the effect

6. If the risk is uncertain, do we need to worry about risk?

- Yes!
- Uncertainty ≠ absence
- *Primum non nocere,* "first, do no harm"
- We are healthcare providers bound by an ethical obligation
- **In the face of uncertainty we are morally bound to take the safest path**

7. What about the exams when benefit is uncertain?



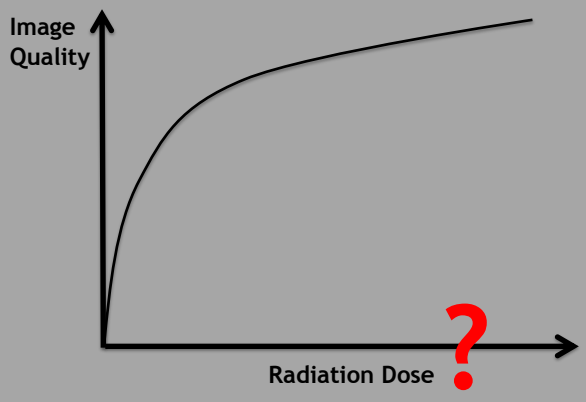
Risk matters!

Patient risk needs to be quantified and op

1. To minimize the likelihood of mismanage
2. To inspire trust by taking ownership of ar perceived risk
3. To lower clinical practice doses that are c unnecessarily high
4. To minimize likelihood of harm to patien
5. To ensure advanced technologies are use care of individual

Frugality, criticality, morality => Op

The challenge of dose optimization: the monotonic relationship between quality and dose!



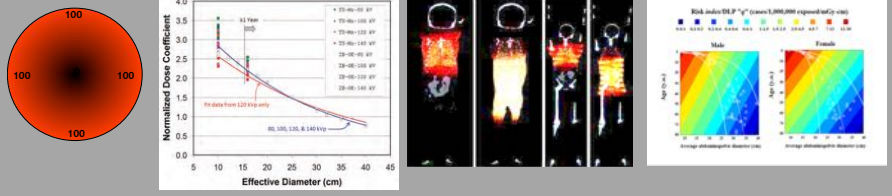
Risk metrics

What is the right safety metric?

What is the right safety metric?

Goal

Device Radiation Output | Dose Outputs | Size-based Dose Outputs | Effective Dose | Patient Organ Dose Estimates | Patient Risk Estimates | Patient Risk



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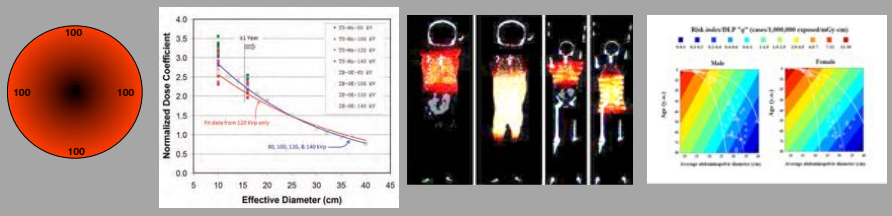


Simple
Relevance inferred

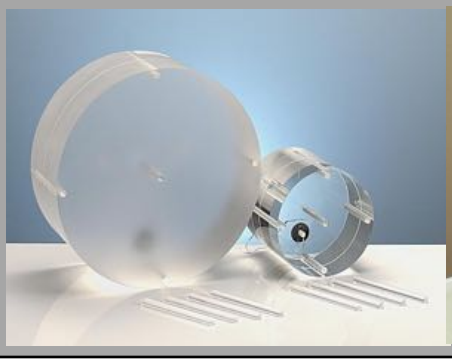
Complex
Relevant

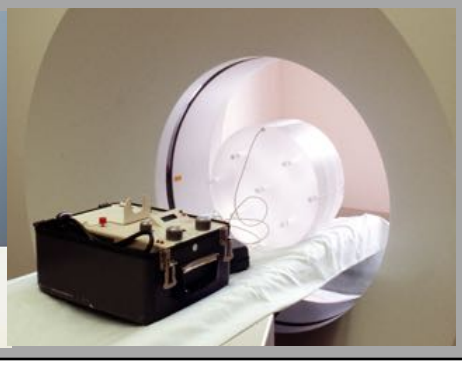
What are the right metrics?

1. **Relevant:** As much as possible, patient-/indication-centric (not modality or machine)
2. **Robust:** To ensure reliability and applicability
3. **Smart:** Maintained balance between robustness and relevance
4. **Relatability:** Surrogates relatable to clinical exam
5. **Practical:** Economic to measure

Dose metrology syntax

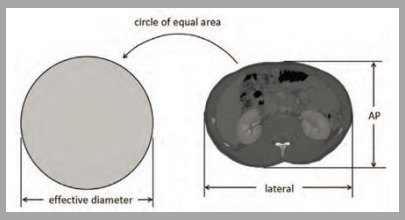
Metric	Definition
CTDI, DAP, Activity, etc	Radiation burden from an imaging system to a standard sized phantom

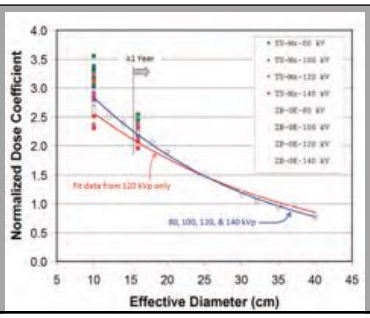




Dose metrology syntax

Metric	Definition
CTDI, DAP, Activity, etc	Radiation burden from an imaging system to a standard sized phantom
SSDE	Radiation output of a CT system adjusted for the average patient size (for chest, abdomen/pelvis scans)

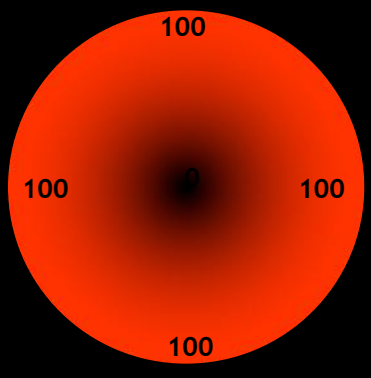




CTDI dose

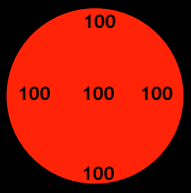
Body

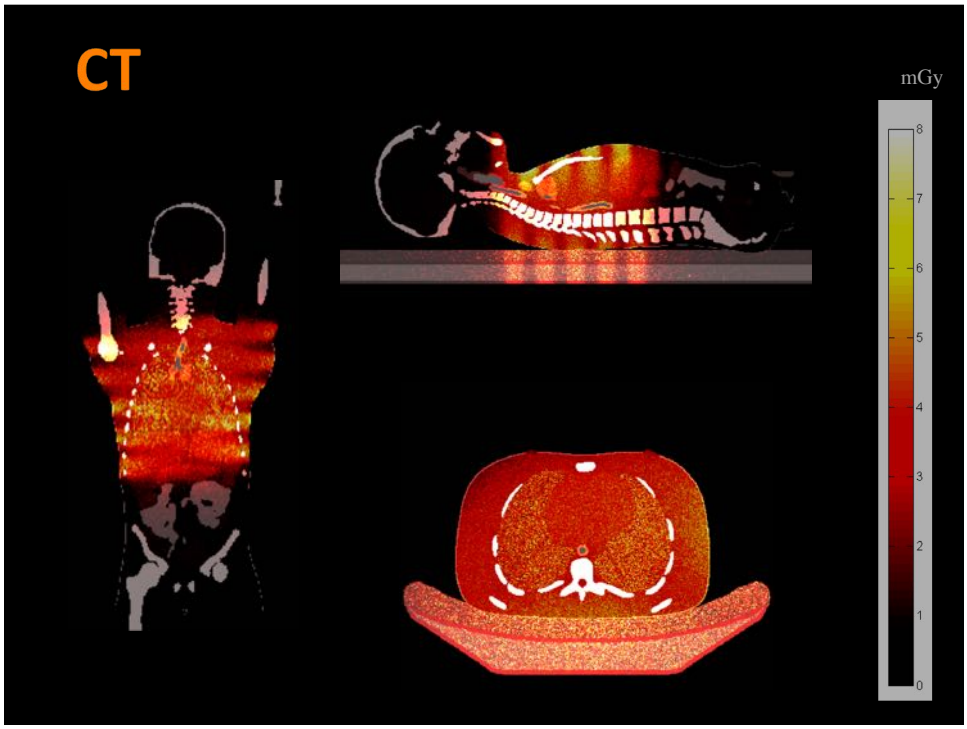
32 cm



Head

16 cm





Dose metrology syntax

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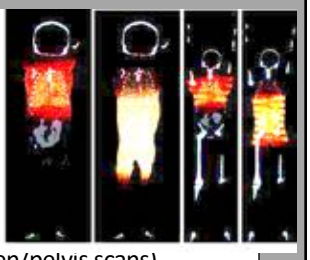
CTDI, DAP, Activity, etc	Radiation burden from an imaging system to a standard sized phantom
SSDE	Radiation output of a CT system adjusted for the average patient size (for chest, abdomen/pelvis scans)
Organ dose	Dose to individual organs; estimated by simulation or experimental measurement

Sahbaee, Samei, MP, in press, 2014

Dose metrology syntax



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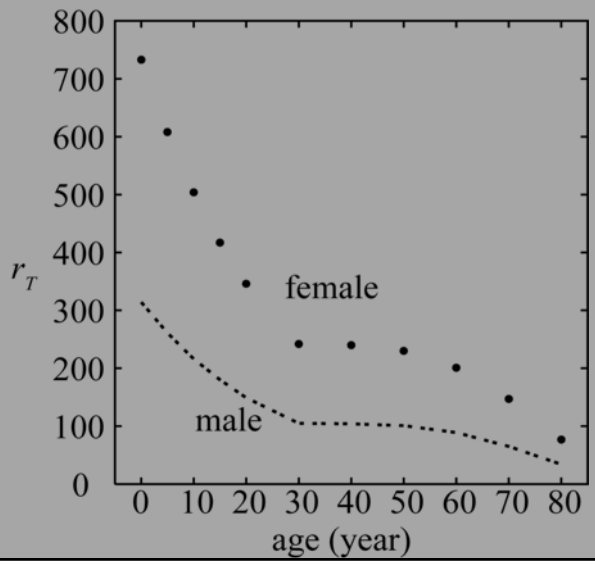
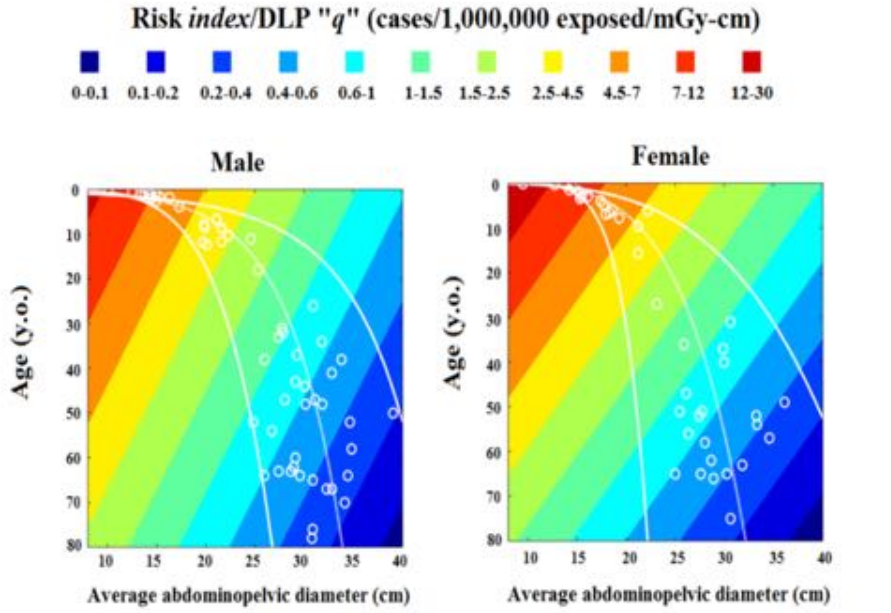
Effective Dose	Weighted sum of organ/tissue equivalent dose for radiation sensitive organs ignoring patient specific factors
Risk index	Weighted sum of organ/tissue equivalent risk for radiation sensitive organs, accounting for age, gender, anatomy

Tian, Samei, PMB, in press, 2014

Cancer incidence per 100,000 persons per 100 mGy (BEIRVII)





Tian, Samei, PMB, 2014

Dose metrology syntax

Metric	Physical (vs derived)	Scanner model and factors	Patient Size	Patient anatomy	Patient age	Patients Gender	Patient total burden
CTDI, DAP, Activity, etc							
SSDE							
Organ dose							
Effective Dose							
Risk index							

Organ dose: WHY?

- The only dose metric that
  - Accounts for specific patient attributes
  - Is an actual physical quantity (measureable)
  - Can be compared across modalities
  - Foundational basis for any risk estimation
- Caveat:
  - Non-scalar metric of radiation burden

Organ dose: HOW?

- Precise estimation possible only if we overcome 4 challenges
  1. Knowing/modeling patient anatomy
  2. Modeling image acquisition process
  3. Knowledge of irradiation condition
  4. Integration into clinical operation

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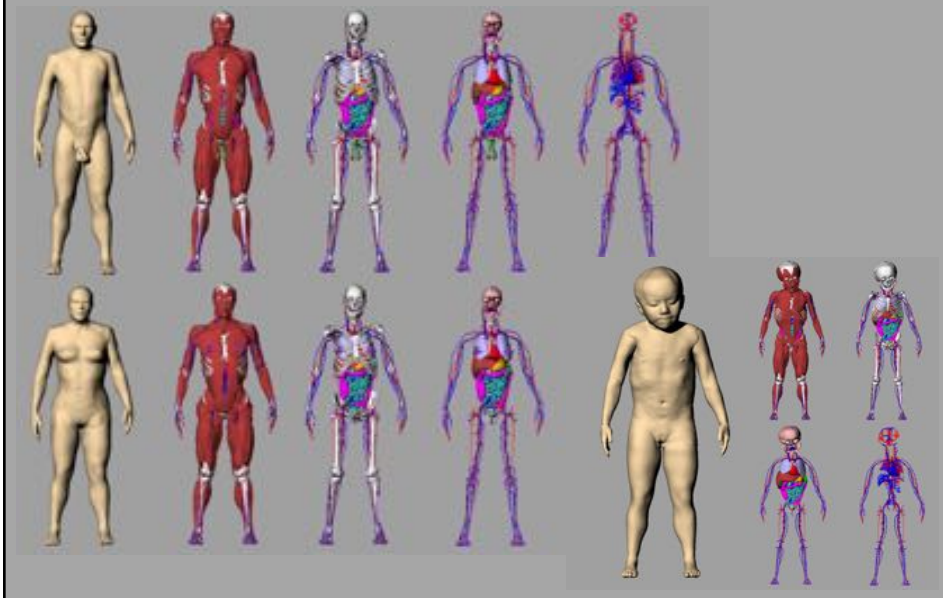
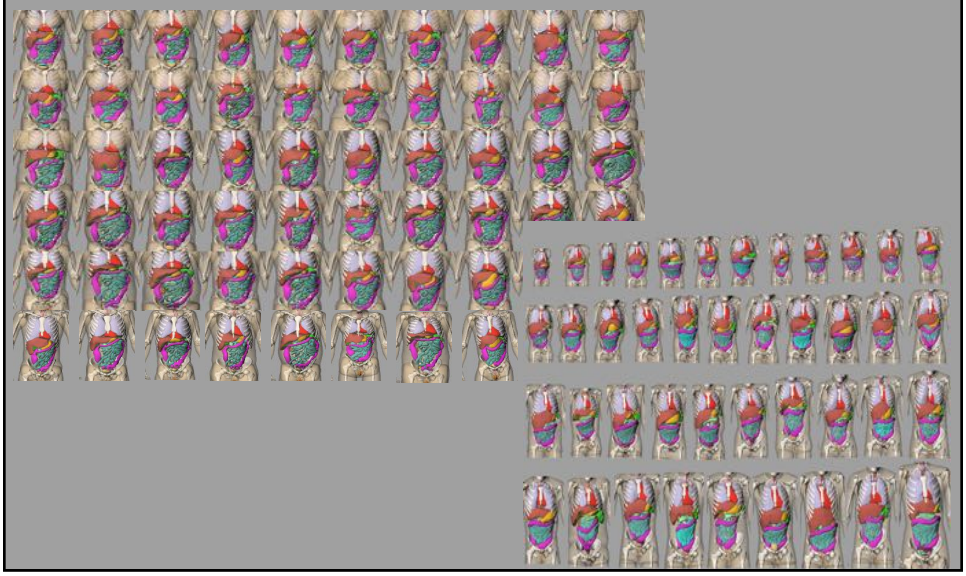
XCAT Virtual Patient Models

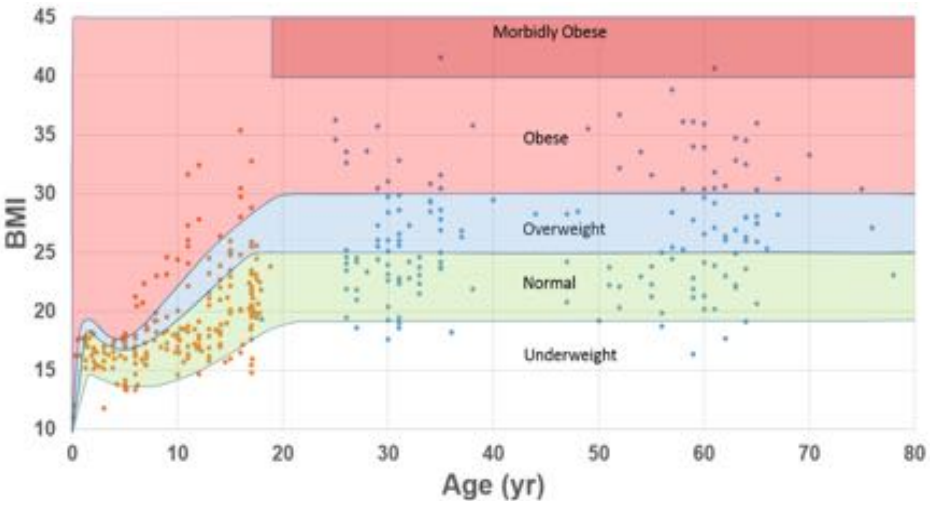


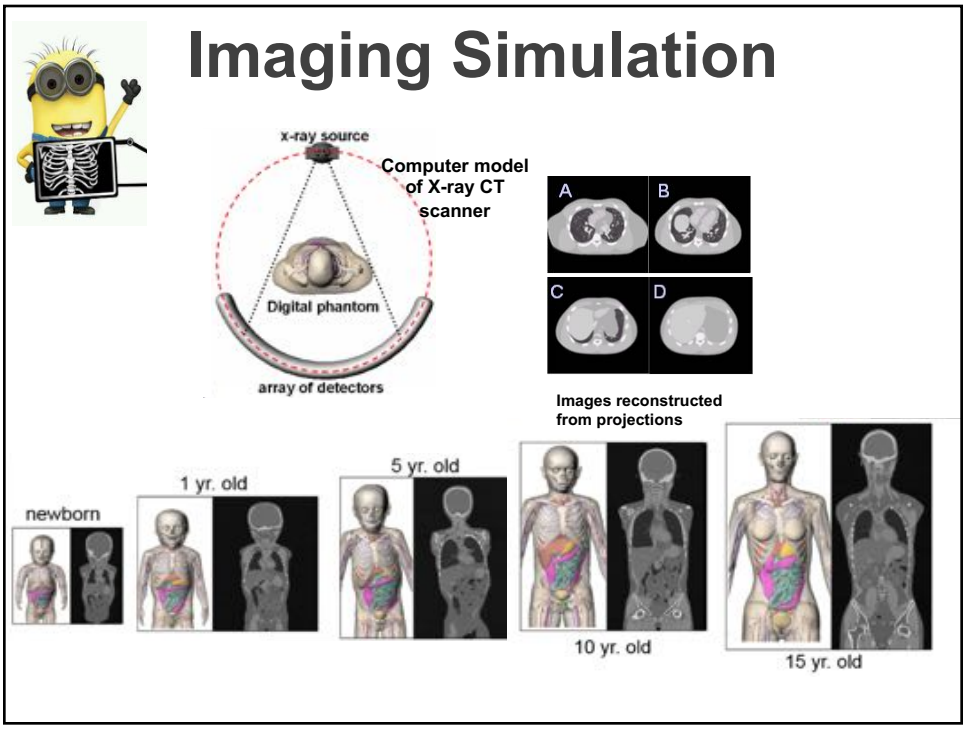
Segars el al, 4D XCAT phantom for multimodality imaging research, Medical Physics, vol. 37 (9), 2010

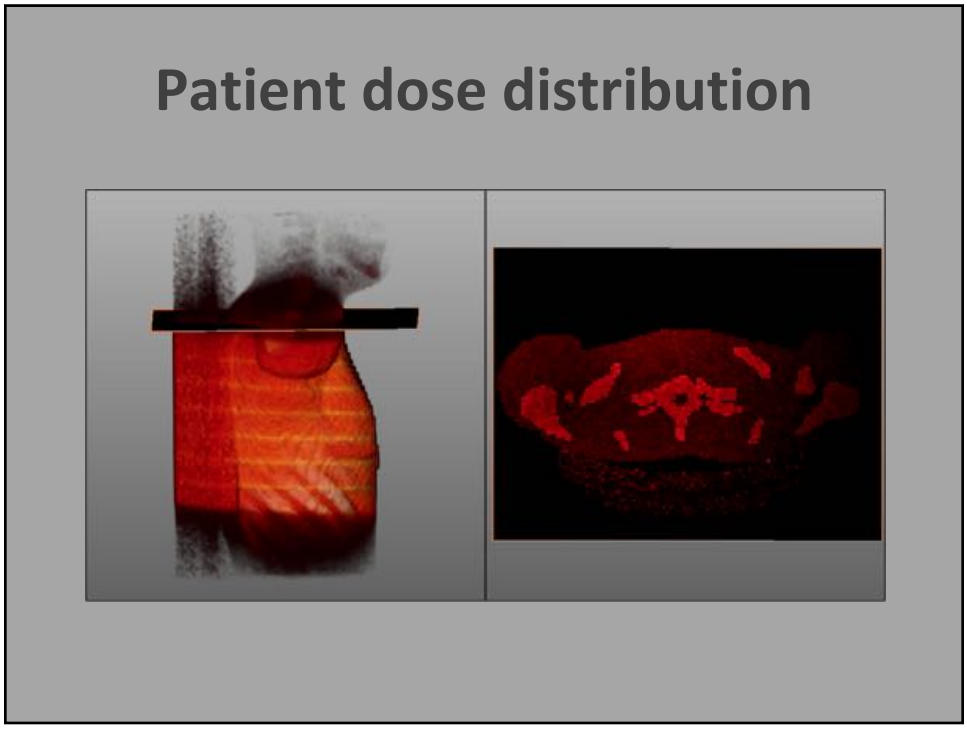
150+ XCAT Computational Patients



Population Representation



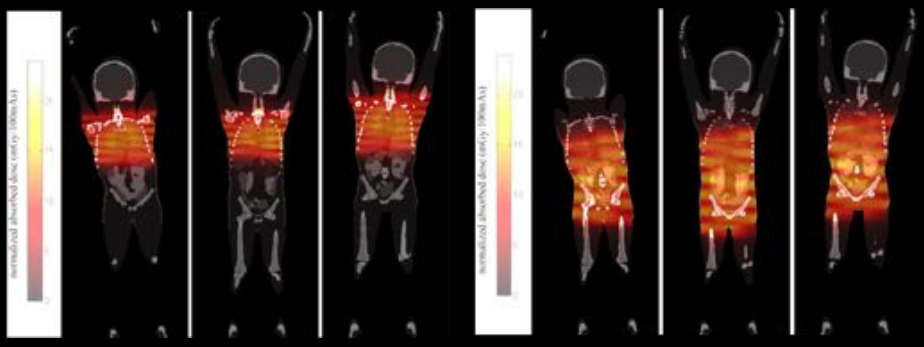




Example Dose Distributions

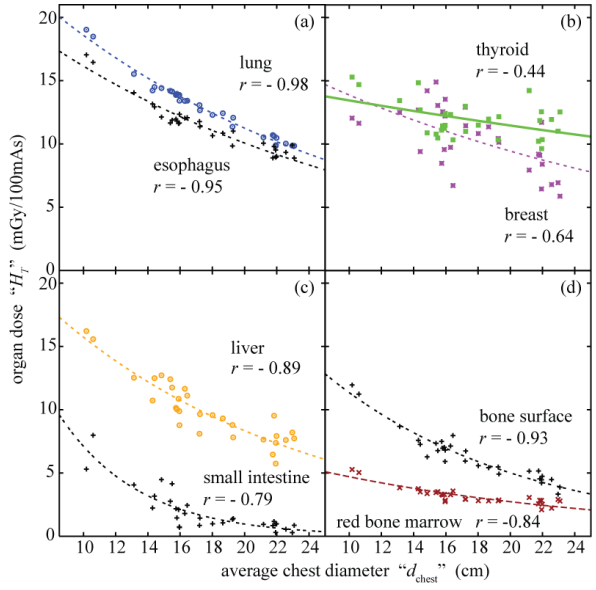
chest exam

abdomen-pelvis exam

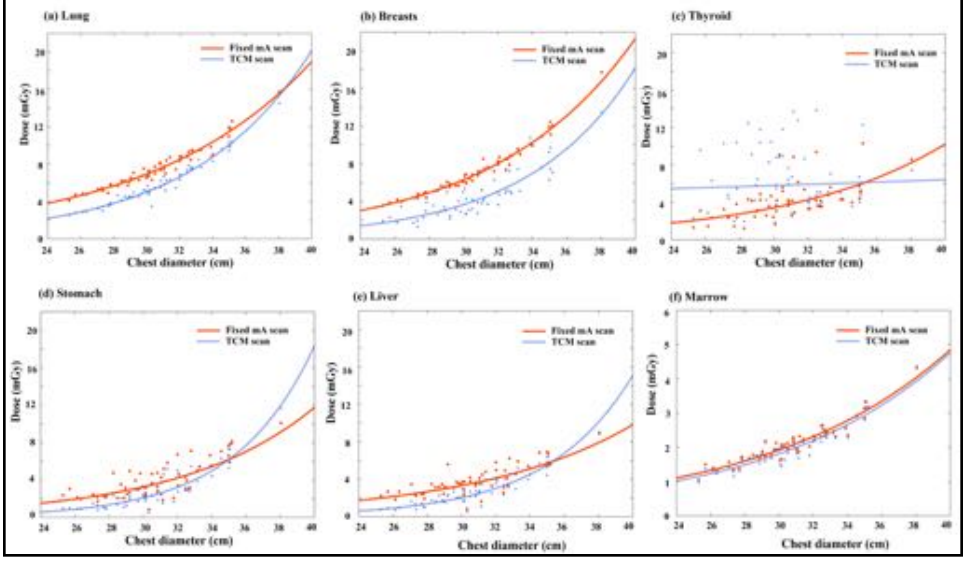


Li, Samei et al., Med Phys, 38(1), 397-407 (2011).
Li, Samei et al., Med Phys, 38(1), 408-419 (2011).

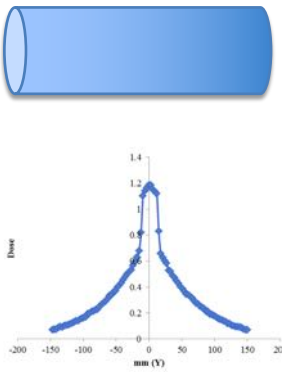
Organ Dose vs Patient Size

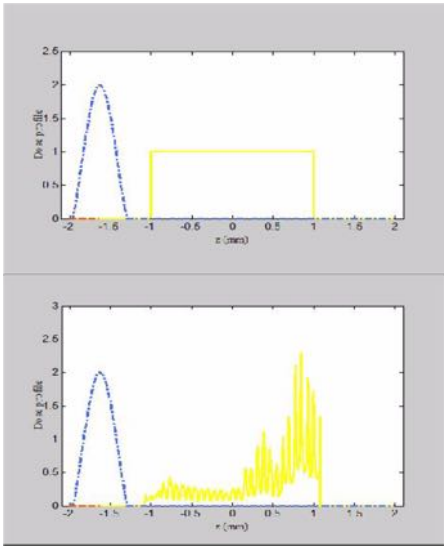


Typical organ dose values (chest CT)



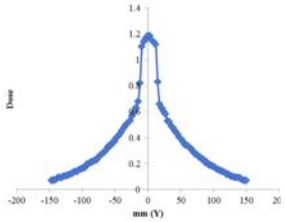
Convolution-based technique in quantifying irradiation field





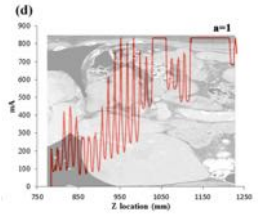
Convolution-based Dose Profile

Dose rate profile

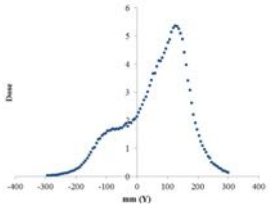


Convolve

TCM profile

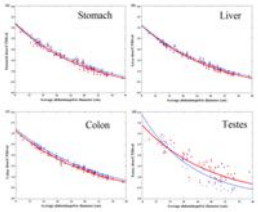


Accumulated dose distribution

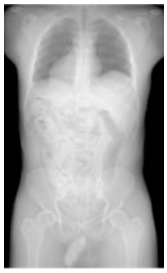


Multiply

Organ dose coefficients

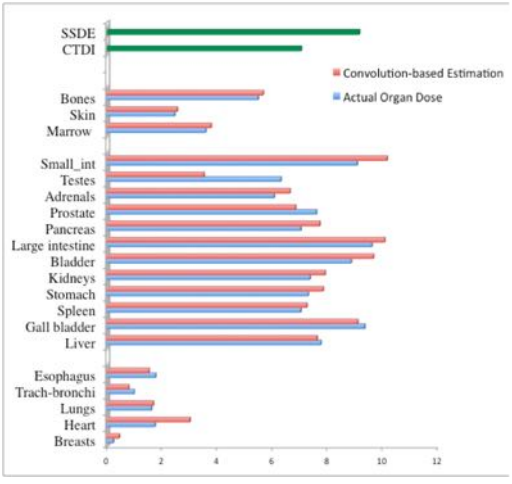


Atlas-based organ dose estimation



Clinical Patient
Gender: male
Age: 63
Weight 72.1 kg

XCAT Model
Gender: male
Age: 47
Weight 76.6 kg



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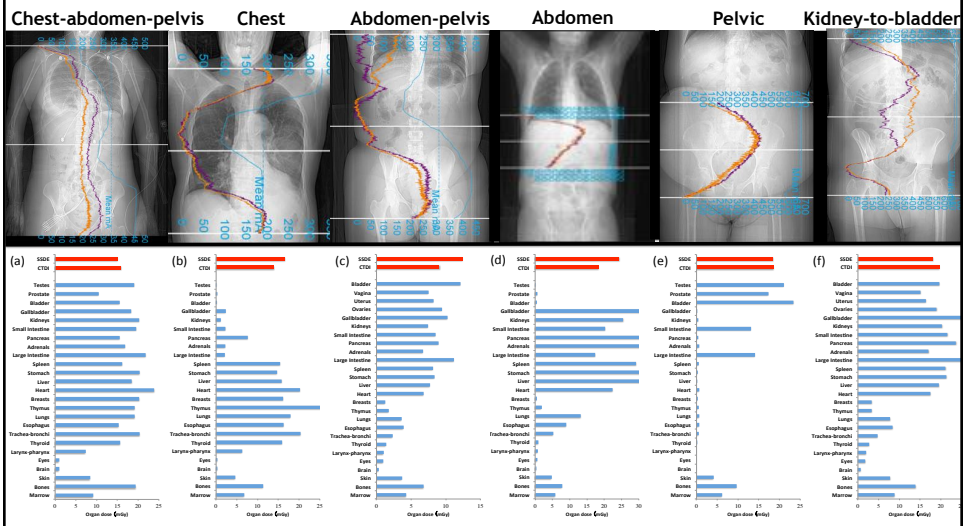


Key references in risk estimation

BEIR VII (organ sensitivities)

ICRP 102 (DLP to effective dose conversion factors)

ICRP 103 (organ specific risk factors)

ICRP 110 (reference phantom)

Standard patient (reference 20 years old patient)

Standard exam ($CTDI_{vol}$: 6.01mGy)

Y. Zhang et al., Medical Physics, 2012

Comparison of 12 Metrics

Metric	Definition
$CTDI_{vol}$	Volume Computed Tomography Dose Index
SSDE	Size-specific dose estimate
DLP	Dose Length Product
$OD_{D,0}$	Defining Organ Dose from ICRP10 phantom
OD_D	Defining Organ Dose
ED_k	DLP based Effective Dose
ED_0	Organ Dose-based Effective Dose from ICRP10 phantom
ED_{OD}	Organ Dose-based Effective Dose
ED'	Organ Dose-based Effective Dose adjusted by age/gender
RI_r	Risk Index for a reference patient
RI_0	Risk Index from ICRP10 phantom
RI	Risk index

Ria et al, RSNA 2018

Can we use effective dose for individual risk?

ICRP TG 79 (2018):

"While risk assessments for individuals based on organ/tissue doses and specific dose-risk models make best use of scientific knowledge, *E* may be used as an approximate indicator of possible risk"

ED' = Risk-adjusted ED

Inspired by new ICRP draft

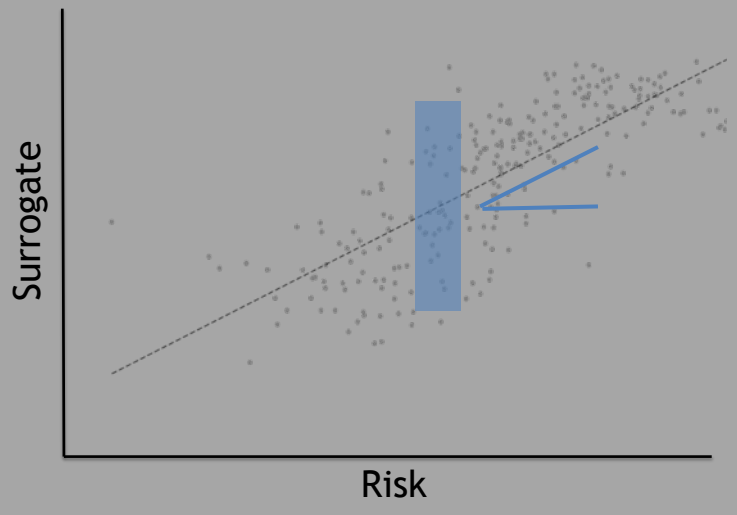
The use of Effective Dose as a Radiological Protection Quantity

ED may be considered as an approximate indicator of possible risk, with additional consideration of variation in risk with age, sex, and population group

$$ED' = f \times ED_{OD}$$

$$f = \frac{Risk\ Index}{Risk\ Index\ for\ the\ reference\ patient}$$

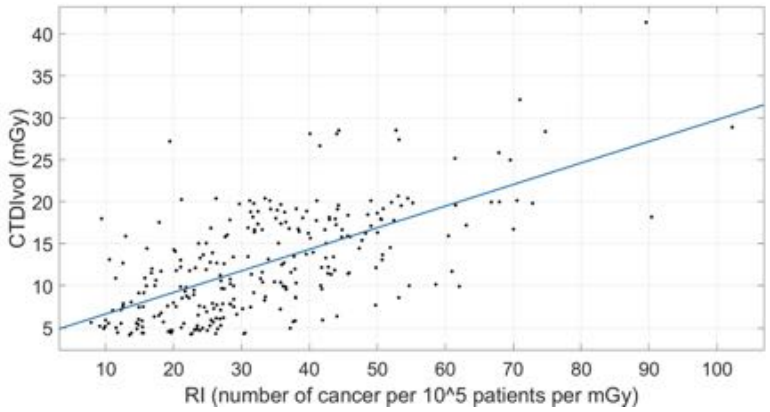
Criteria for goodness of a risk surrogate



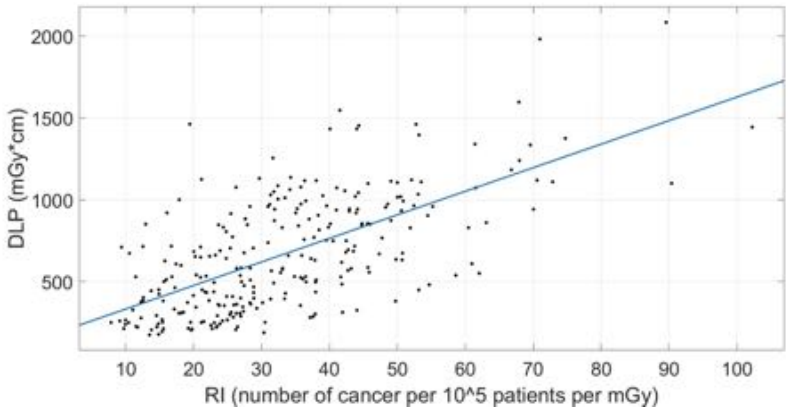
Metric comparison

Metric	slope	intercept	R^2	RMSE	nRMSE	RMSE/slope
$CTDI_{vol}$	0.26	4.07	0.42	4.82	0.38	18.54
SSDE	14.40	187.95	0.42	269.91	0.40	18.74
DLP	0.22	7.20	0.45	3.82	0.26	17.36
$OD_{D,0}$	0.21	2.61	0.43	3.90	0.40	18.57
OD_D	0.07	2.71	0.46	1.17	0.23	16.71
ED_k	0.16	5.84	0.49	2.58	0.23	16.13
ED_0	0.46	5.09	0.44	8.19	0.40	17.80
ED_{OD}	0.08	0.25	0.94	0.30	0.11	3.75
ED'	3.05	23.83	0.84	21.18	0.27	6.94
RI_r	0.27	3.49	0.44	4.90	0.39	18.15
RI_0	3.05	23.83	0.84	21.18	0.27	6.94
RI	1.00	0.0	1.0	0.0	0.0	1.00

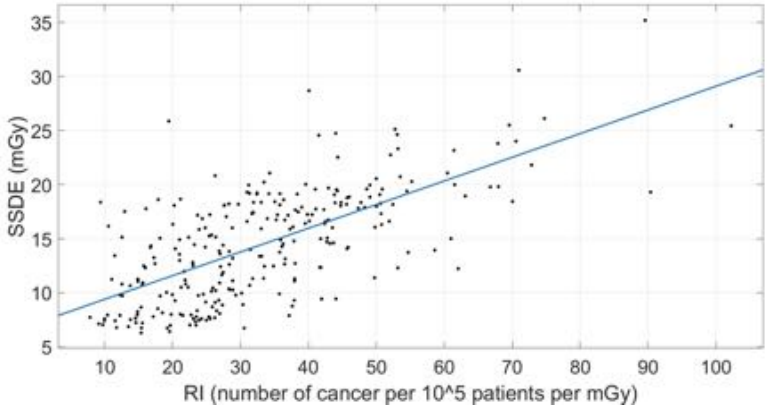
CTDI



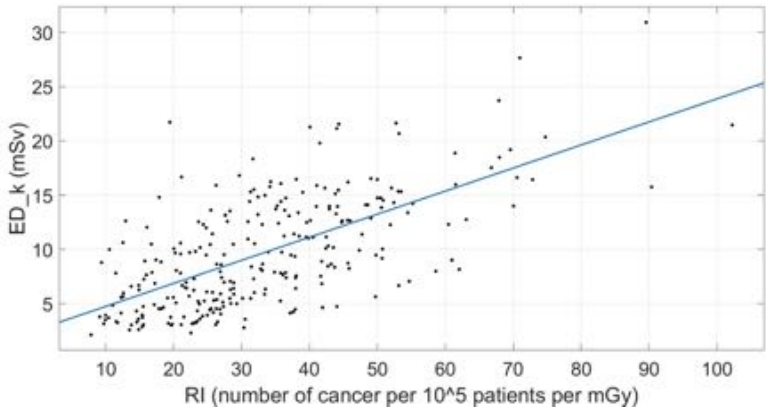
DLP



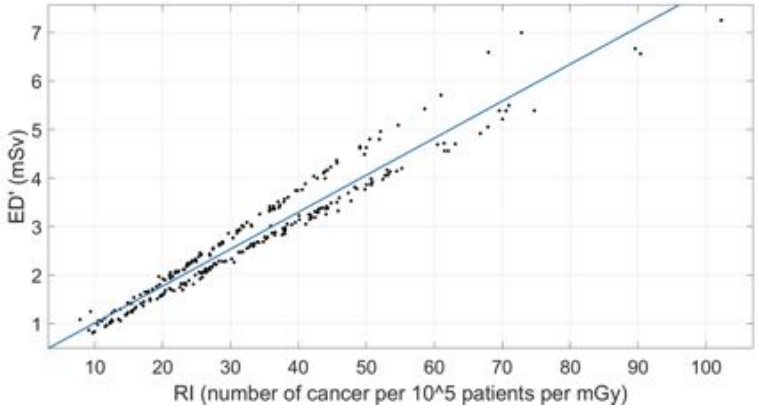
SSDE



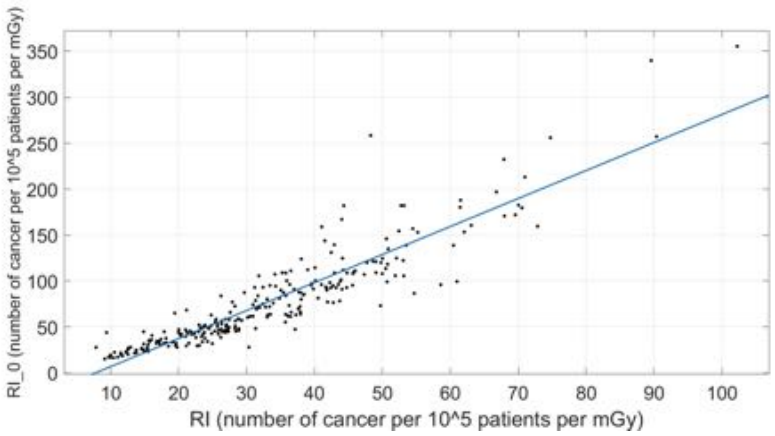
ED_k



ED’



RI_0



Take-home Points

Take-home Points

- The increased use of imaging exams is a positive trend, not a negative one
- Existence of benefit and uncertainty does not negate the moral obligation for risk mitigation
- Imaging optimization requires reasonable metrics of radiation burden
- Different metrics can lead to different characterization of risk
  - Metrics that are not related to patient anatomy (CTDIvol, DLP, EDk) could overestimate or underestimate individual risk

Take-home Points

- Poor risk characterization can negatively affect justification, optimization, and personalization of imaging
- Radiation risk metrology needs to strive for relevance, robust, smart, relatable, practical surrogates
- The most meaningful metrics in order of relevance:
  1. Risk Index derived from organ dose
  2. Risk-adjusted ED

What are the right metrics?

1. Relevant: As much as possible, patient-/indication-centric (not modality or machine)
2. Robust: To ensure reliability and applicability
3. Smart: Maintained balance between robustness and relevance
4. Relatability: Surrogates relatable to clinical exam
5. Practical: Economic to measure

Questions?

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