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What is the best metric to quantify and qualify imaging radiation dose?

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DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

Duke Clinical Imaging Physics Group

1

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Disclaimers

Material presented is a proposal not yet endorsed by any of the affiliated professional bodies (eg, AAPM, IAEA, IOMP, NCRP, ICRP)

Thank you for attending!

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References

European Radiology
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PHYSICS

Comparison of 12 surrogates to characterize CT radiation risk across a clinical population

Francesco Ria[1,2] • Wanyi Fu[2] • Jocelyn Hoye[2] • W. Paul Segars[2] • Anuj J. Kapadia[2] • Ehsan Samei[1,2,3]

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Abstract

Objectives Quantifying radiation burden is essential for justification, optimization, and personalization of CT procedures and can be characterized by a variety of risk surrogates inducing different radiological risk reflections. This study compared how twelve such metrics can characterize risk across patient populations.

Methods This study included 1394 CT examinations (abdominopelvic and chest). Organ doses were calculated using Monte Carlo methods. The following risk surrogates were considered: volume computed tomography dose index ($CTDI_{vol}$), dose-length product (DLP), size-specific dose estimate (SSDE), DLP-based effective dose (ED_k), dose to a defining organ (OD_D), effective dose and risk index based on organ doses (ED_{OD}, RI), and risk index for a 20-year-old patient (RI_{rp}). The last three metrics were also calculated for a reference ICRP-110 model ($OD_{D,0}$, ED_0, and RI_0). Lastly, motivated by the ICRP, an adjusted-effective dose was calculated as $ED_r = \frac{RI}{RI_{rp}} \times ED_{OD}$. A linear regression was applied to assess each metric's dependency on RI. The results were characterized in terms of risk sensitivity index (RSI) and risk differentiability index (RDI).

Results The analysis reported significant differences between the metrics with ED_r showing the best concordance with RI in terms of RSI and RDI. Across all metrics and protocols, RSI ranged between 0.37 (SSDE) and 1.29 (RI_0); RDI ranged between 0.39 (ED_k) and 0.01 (ED_r) cancers × 10^3patients × 100 mGy.

Conclusion Different risk surrogates lead to different population risk characterizations. ED_r exhibited a close characterization of population risk, also showing the best differentiability. Care should be exercised in drawing risk predictions from unrepresentative risk metrics applied to a population.

Key Points

• *Radiation risk characterization in CT populations is strongly affected by the surrogate used to describe it.*
• *Different risk surrogates can lead to different characterization of population risk.*
• *Healthcare professionals should exercise care in ascribing an implicit risk to factors that do not closely reflect risk.*

Ria et al. Eur Rad, 2021

MEDICAL PHYSICS INTERNATIONAL Journal, vol.10, No.1, 2022

TOWARDS POTENTIAL HARM ASSESSMENT FROM THE INDIVIDUAL PATIENT RADIATION DOSES IN IMAGING PROCEDURES: A PROPOSAL FOR A NEW QUANTITY

Ehsan Samei[1], Kimberly Applegate[2], Francois Bochud[3], Mahadevappa Mahesh[4], Colin Martin[5], Francois Paquet[6], M. Antonia Lopez Ponte[7], Filip Vanhavere[8], Weihai Zhuo[9]

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(Final version submitted 4/7/2022. Opinions expressed do no represent the official endorsement of the ICRP.)

Abstract — **Imaging procedures continue to advance rapidly and offer unprecedented benefits in health care. Even so, the potential harm from the associated radiation exposure has remained relevant and subject to strong public scrutiny. This necessitates a quantity to gauge this potential harm in such a way that it is reflective of the attributes of the patient, the imaging procedure, and the latest science on radiation effects. The current metrics fall short of such objectives, as they are either procedure-centric (not relatable across imaging modalities), or negligent of the patient attributes, such as size, sex and age that are known to strongly influence the potential harm. Without a relevant quantity, the (often minor) potential risk associated with imaging procedures cannot be reliably put into perspective with the (often significant) benefit from the procedures, nor can that potential be properly monitored, communicated, or researched.**

In this white paper, we propose a new quantity that alleviates some of the shortcomings of existing measures. The quantity, which may be termed potential radiation harm or detriment, builds upon the foundation of effective dose and its numerical

benefit from the procedures, nor can that potential be properly monitored, communicated, or researched.

In this white paper, we propose a new quantity that alleviates some of the shortcomings of existing measures. The quantity, which may be termed potential radiation harm or detriment, builds upon the foundation of effective dose and its numerical quantification with additional inclusion of patient and exam attributes. The new quantity is devised to enhance the assessment, optimization, and communication related to medical imaging procedures, with potential for extension to other conditions or practices where individualizations of irradiation is needed.

II. WHY SHOULD WE QUANTIFY PATIENT RADIATION DOSE IN MEDICAL IMAGING?

There is a prevailing assumption in the scientific

Samei et al. Med Phys Int, 2022

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State of imaging dose

- Optimum imaging needs a measure of dose to best manage the practice
- Current dose metrics are either
  - unrelatable across imaging modalities, not directed towards the actual individual being exposed
  - negligent of the patient attributes of size, sex, or age, factors that are known to strongly influence the potential harm
- What are the requirements for a metric that can best gauge the radiation burden of imaging procedures in such a way that it is reflective of the patient, the imaging procedure, and the latest science?

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Outline, answering 9 questions….

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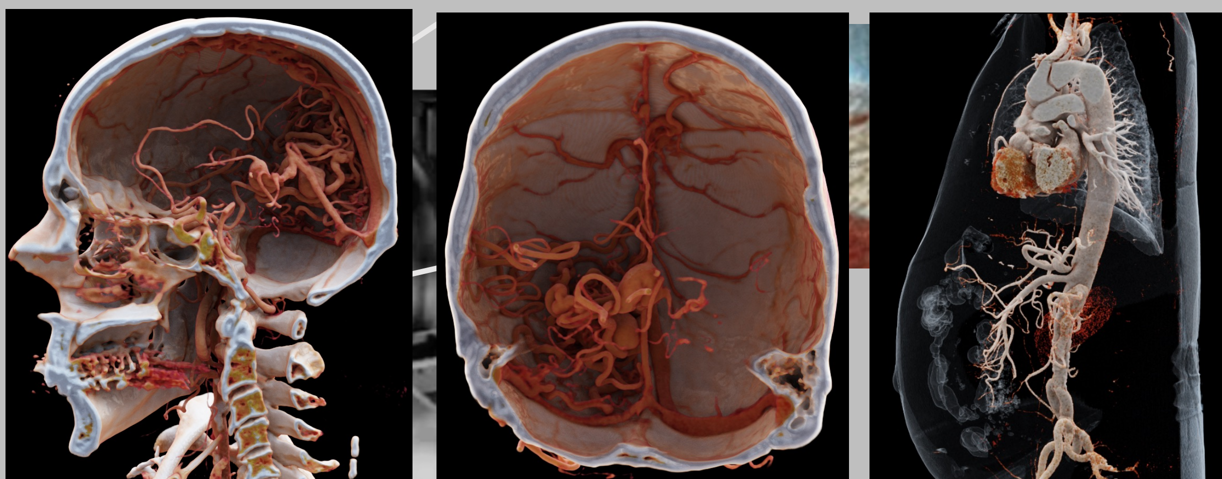
Medical imaging

Imaging procedures continue to advance, offering crucial benefits to healthcare



Courtesy of Centre Cardio-Thoracique de Monaco, Monaco, Siemens Heathineers, and Medical University of South Carolina

Imaging dose

- Considering patient exposure in imaging is founded on one assumption:
  - Radiation exposure (can) imparts a non-negligible level of harm to the patient.
- While the magnitude of this harm has been questioned and debated, without a presumption of harm, patient exposure would be of no relevance.

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Dealing with imaging dose

- Stating there is no risk is not scientific
- An ethical imperative: “First do no harm”
- A professional imperative: Strong and sustained public scrutiny
- Avoiding a proper quantification only leads to the presumption of higher risk than actuality

Healthcare providers are *required* to assure optimum use of radiative energy (its assessment, minimization, and optimization) to extract care-relevant information

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Measures of imaging dose

- Modality-based metrics:
  - CTDI, DLP, SSDE, ESE, DAP, Administrated Activity
  - Convenient, but not directly relatable to the patient risk
  - Effective dose based on an idealized human model
- Patient-based metrics:
  - Radiation risk
  - Effective dose as made relatable to radiation risk

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Measures of imaging dose

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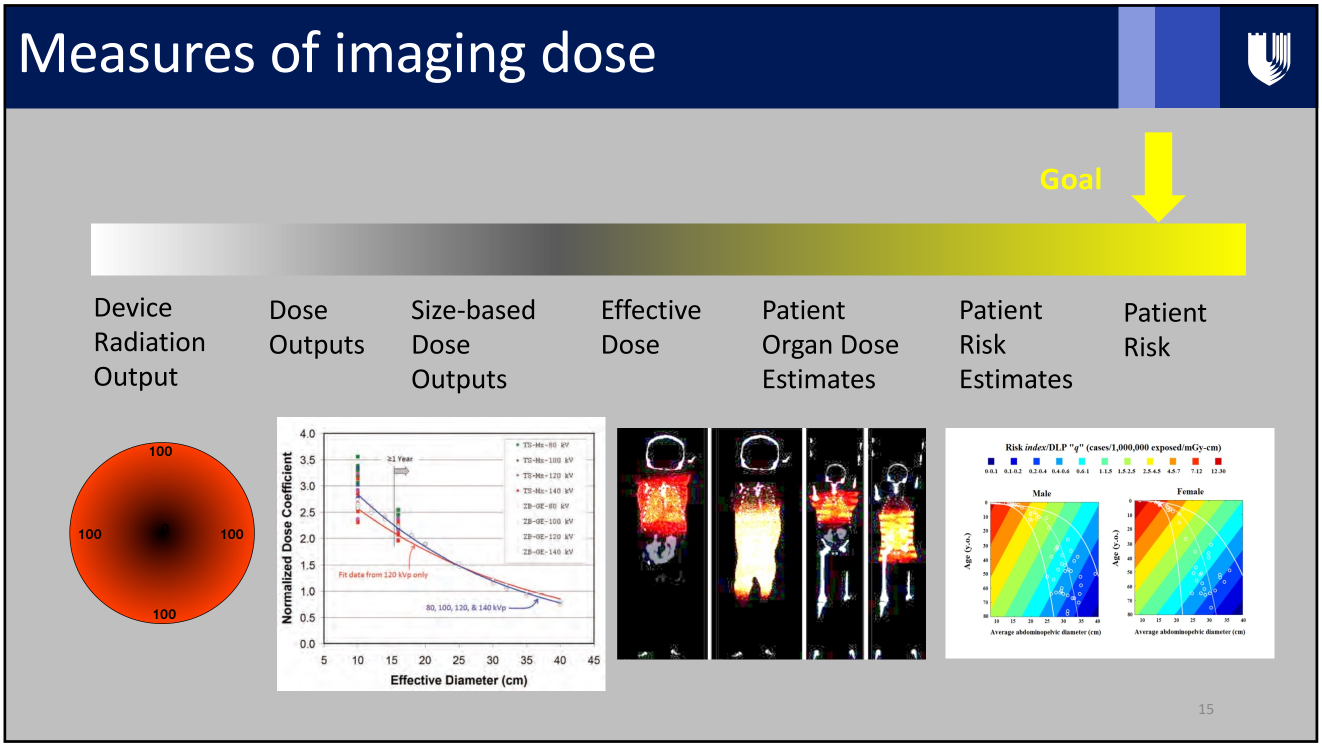
Measures of imaging dose
Goal
Device Radiation Output
Dose Outputs
Size-based Dose Outputs
Effective Dose
Patient Organ Dose Estimates
Patient Risk Estimates
Patient Risk
100
100
100
100
Normalized Dose Coefficient
Effective Diameter (cm)
Fit data from 120 kVp only
80, 100, 120, & 140 kVp
Male
Female
Age (y.o.)
Average abdominopelvic diameter (cm)
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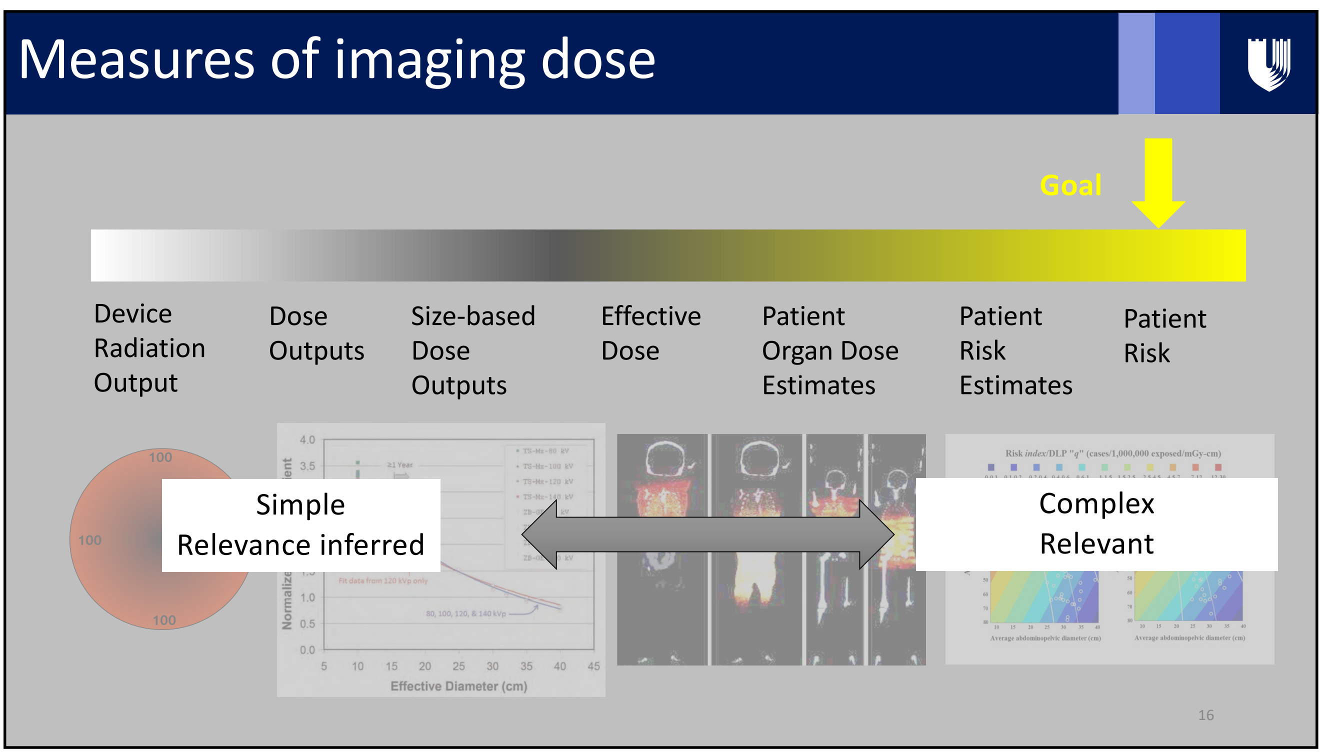
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Simple
Relevance inferred
Complex
Relevant
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Why a new quantity? Effective dose?

- Defined primarily for quantifying occupational and public doses
- Lack of better quantities has led to broad application to patient radiation dose
- Non-commissioned and unguided use has led to diverse calculations and implementations across medicine, causing major confusion and inconsistences

No two millisieverts are created equal!

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Why a new quantity?

- Medical exposures remain by far the leading source of artificial radiation exposure in the world (UNSCEAR 2022).
- The non-orthodox, unrepresentative, and variable application is a consequence of a lack of clear guidance for a better alternative.

Community of radiation scientists has the *opportunity* and the *responsibility* to define a quantity that can better gauge imaging radiation dose

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Key ingredients of the new quantity

1. Surrogating potential harm, as that is the foundation of the need
2. Surrogating potential harm at the individual patient level
3. Accounting for unique patient attributes
4. Accounting for unique exam attributes
5. Accounting for dose at individual organ and tissue levels
6. Accounting for known factors of radiation risk: size, age, sex, ...

If exposure worth measuring, it should be related – relatable to patient risk

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Risk as a metric is not ideal

1. Hypothetical: individual risk is population based
2. Overconfidence: Assuming too much certainty
3. Speculative: Assuming a futuristic likelihood of harm
4. Practicality: Different time scale of value and radiation risk
5. Alarming: Mortality units can be terrifying

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Desired quantity should....

- Take advantage of the prevalence, familiarity, and quantitative values of ED
- Be relatable to potential radiation risk – echoing the philosophy that led to the definition of ED in the first place.
- Not be called Effective Dose, to avoid adding more variability to ED
  - ***Potential Radiation Detriment (PRD)***
  - ***Irradiation Index (I_x)***
  - ***Relative Effective Dose (ED_r)***

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Relative Effective Dose (ED_r)

Estimate individual organ dose values and uncertainties

Age-sex-... risk coefficients per organ

Added modifiers: race, relative-absolute risk, etc

Risk per organ +/- uncertainties

Integration across organs

Scaling to ED

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Impetus

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

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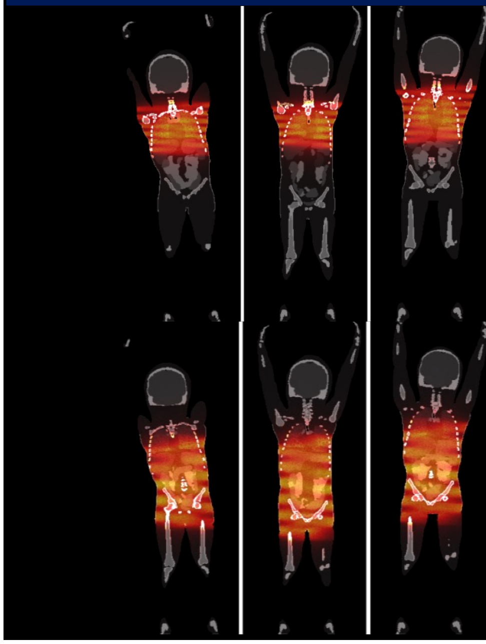
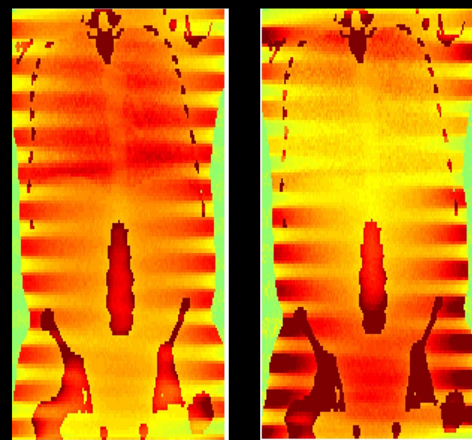
Organ dose estimation



Fixed mA TCM



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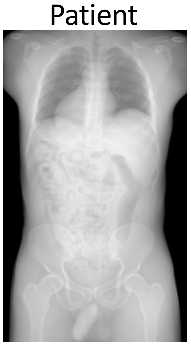
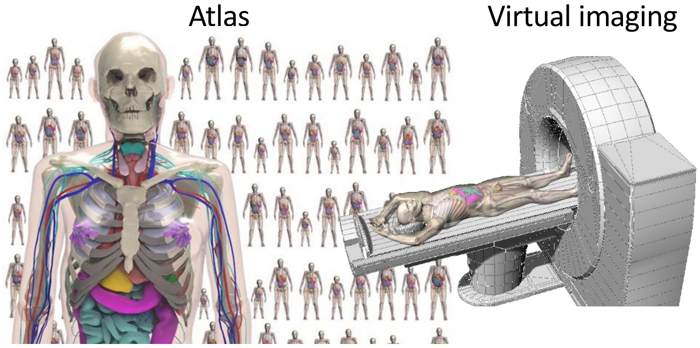
Individualized organ dose estimation

Fu et al. AJR, 2021

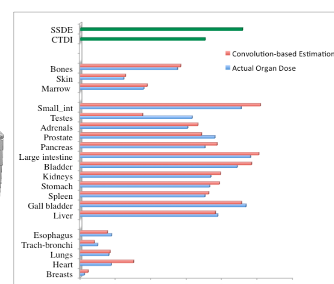
Patient



Atlas / Virtual imaging



Organ dose estimates



Clinical Patient
Gender: male
Age: 63
Weight 72.1 kg

XCAT Model
Gender: male
Age: 47
Weight 76.6 kg

ED estimates (ICRP 102, 103, 110)

Risk estimates per patient age and sex (BIER VII)

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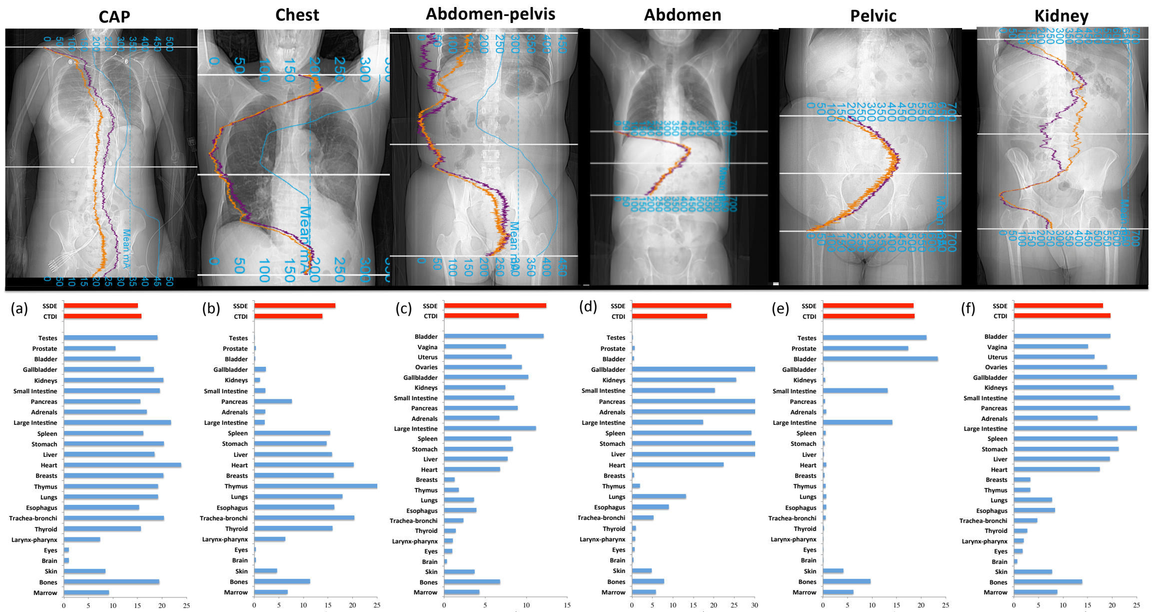
Individualized organ dose estimation



A case study comparing 12 risk metrics

Ria et al. Eur Rad, 2021

Index	Definition	
$CTDI_{vol}$	volume Computed Tomography Dose Index	*Implied indices of risk*
DLP	Dose Length Product	
SSDE	Size-specific dose estimate	
OD_D	Defining Organ Dose	*Organ dose reflections: directly influence risk*
$OD_{D,0}$	Defining Organ Dose from reference phantom	
ED_k	DLP based Effective Dose	*Different ways of computing effective dose*
ED_{OD}	Organ Dose-based Effective Dose	
ED_0	Organ Dose-based Effective Dose from reference phantom	
RI_0	Risk Index from reference phantom	*Aim to be most representational of individual risk accounting for age and sex*
RI_r	Risk Index for a reference patient	
ED_r	Risk-adjusted organ-based ED $ED_r = RI/RI_0 \times ED_{OD}$	
RI	Risk Index (per BIER risk coefficients), *Li et al, Rad 2011*	

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Comparative analysis of differing metrics

- Linear regression to assess each metric's dependency to RI across 1430 clinical Chest and AP CT exams
- Metric's sensitivity

  Risk Sensitivity Index ($RSI = \frac{Slope}{\overline{RI/metric}}$)

- Metric's differentiability of radiation burden across CT exams

  Risk Differentiability Index ($RDI = \frac{RMSE}{Slope}$)

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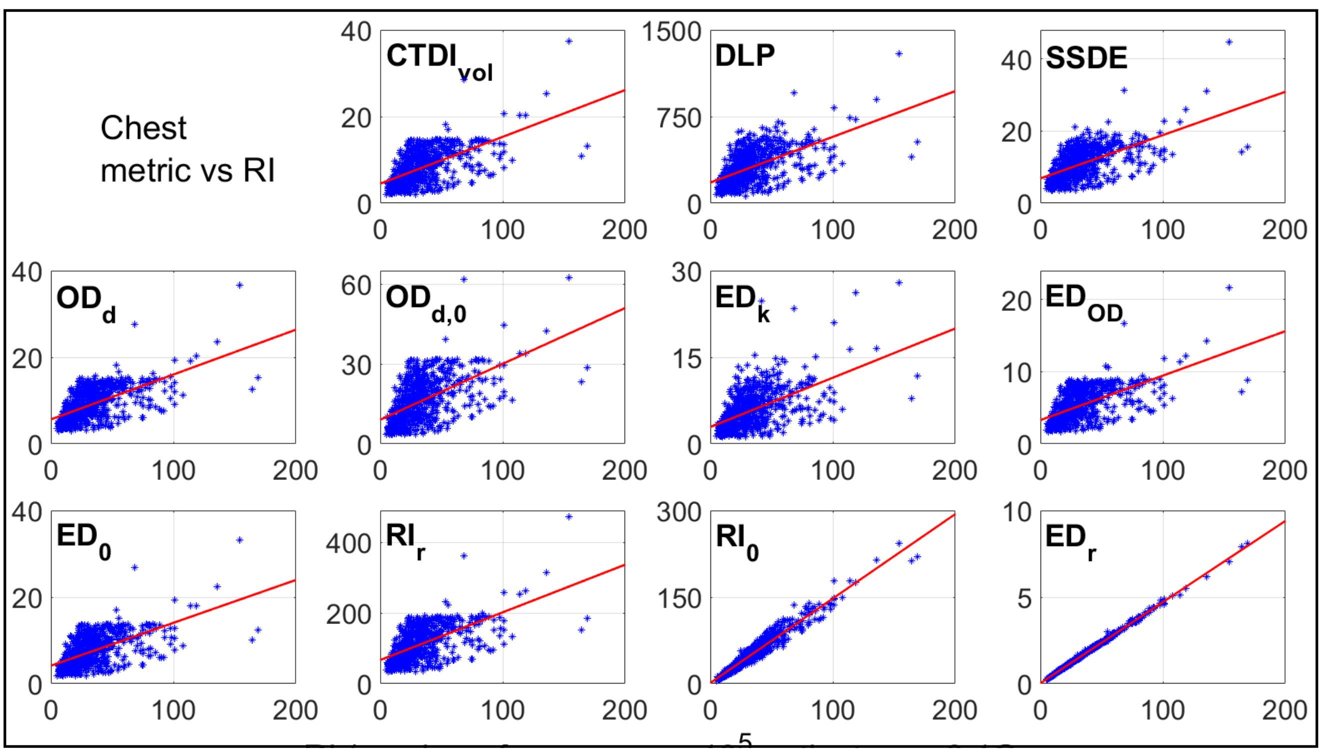
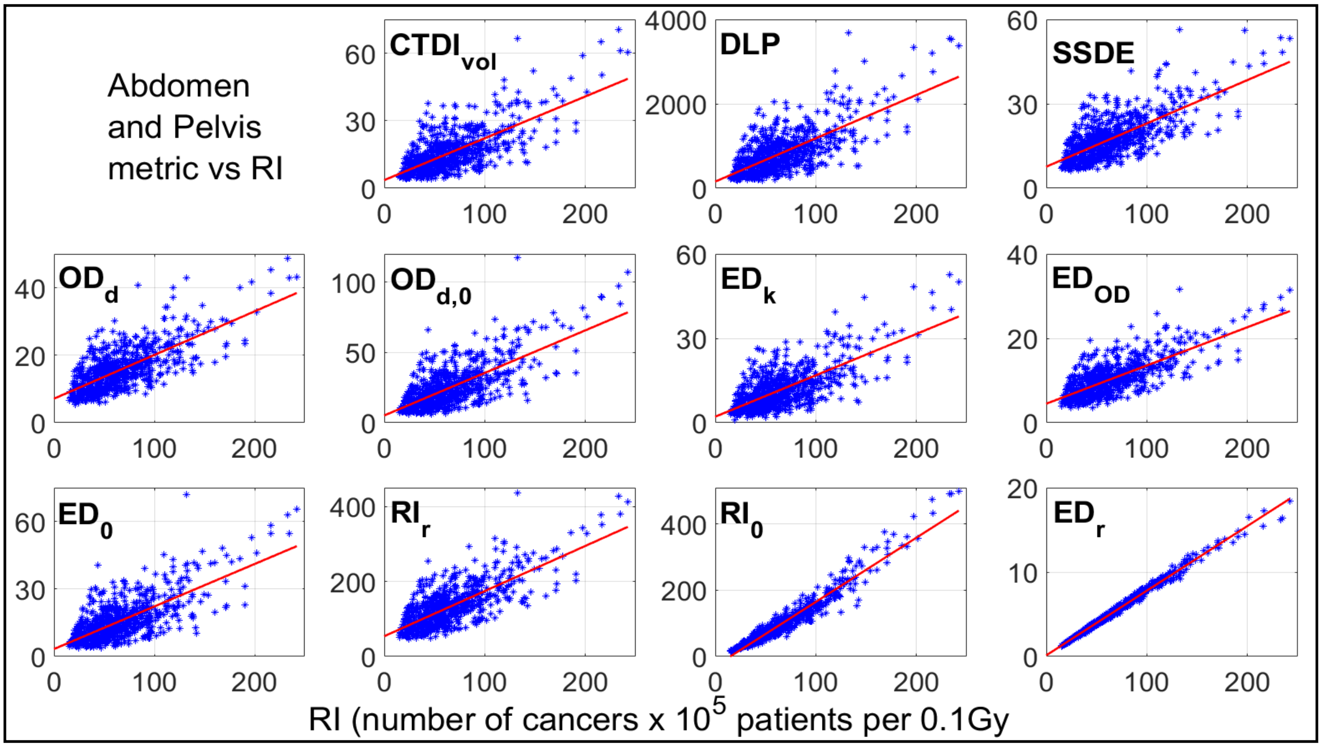
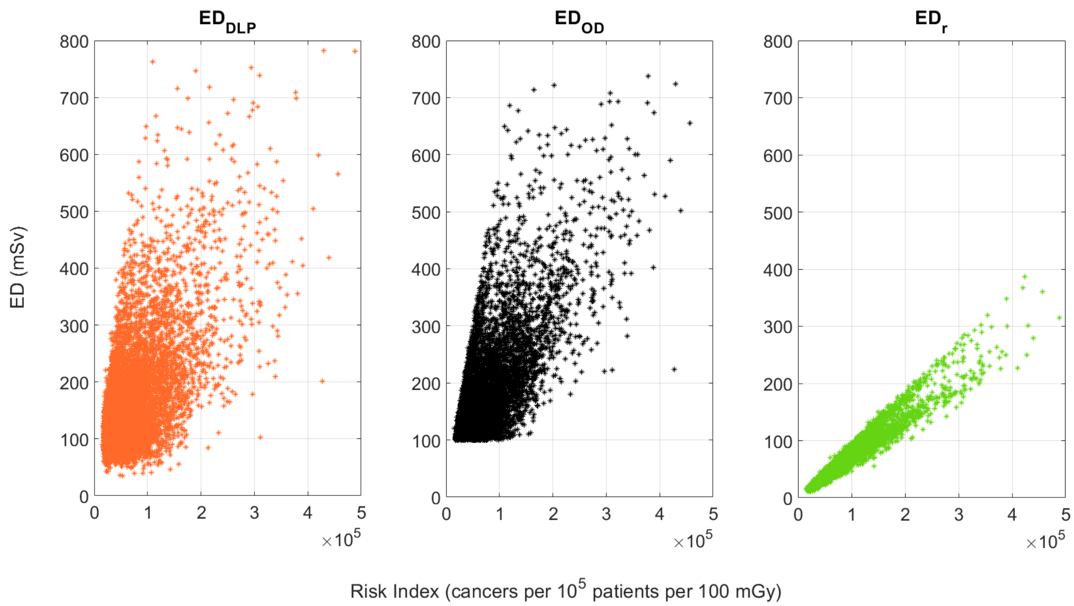




	Chest			Abdomen and Pelvis		
metric	R^2	RSI	RDI (cancers per 1000 patients per 100 mGy)	R^2	RSI	RDI (cancers per 1000 patients per 100 mGy)
ED_r	1.00	0.98	0.01	0.99	0.97	0.03
RI_0	0.94	0.97	0.05	0.94	1.29	0.09
OD_D	0.36	0.38	0.30	0.51	0.54	0.35
RI_r	0.35	0.40	0.30	0.55	0.59	0.32
$CTDI_{vol}$	0.34	0.45	0.30	0.49	0.77	0.36
ED_{OD}	0.34	0.39	0.31	0.55	0.57	0.32
SSDE	0.34	0.37	0.31	0.50	0.57	0.35
ED_0	0.34	0.44	0.31	0.50	0.79	0.35
DLP	0.32	0.43	0.32	0.49	0.81	0.36
ED_k	0.30	0.49	0.34	0.49	0.82	0.39
$OD_{D,0}$	0.30	0.44	0.34	0.50	0.79	0.35

Trial across 8952 clinical cases

Data from *Zewde et al. Eur Rad, 2022*



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Extendable beyond medical irradiation?

- Possible but need to start where there is the greatest need

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Required processes to get there

1. New name and new units
2. Accuracy in modeling the patient
3. Accuracy in modeling the irradiation condition
4. Standardized description of the methodologies deployed
5. Benchmarking process
6. Incorporation of uncertainty in the quantity and its derivation
7. Practical approximation to accommodate resource-limited settings

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Conclusions

- Different risk surrogates lead to different characterization of radiation burden
- Unrepresentative risk metrics can mislead practice and its optimization
- Existing measures (including current ED) do not provide a measure of patient dose that is patient-relevant, technology-agnostic, and communication-intelligent
- ICRP-motivated, organ-based, risk-adjusted ED (aka, ED_r, RPD, I_x)
    - Incorporates organ sensitivities
    - Accounts for age- and sex-specific risks
    - Exhibits close characterization and differentiability of radiation burden

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Thank you for attending!

Acknowledgments

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