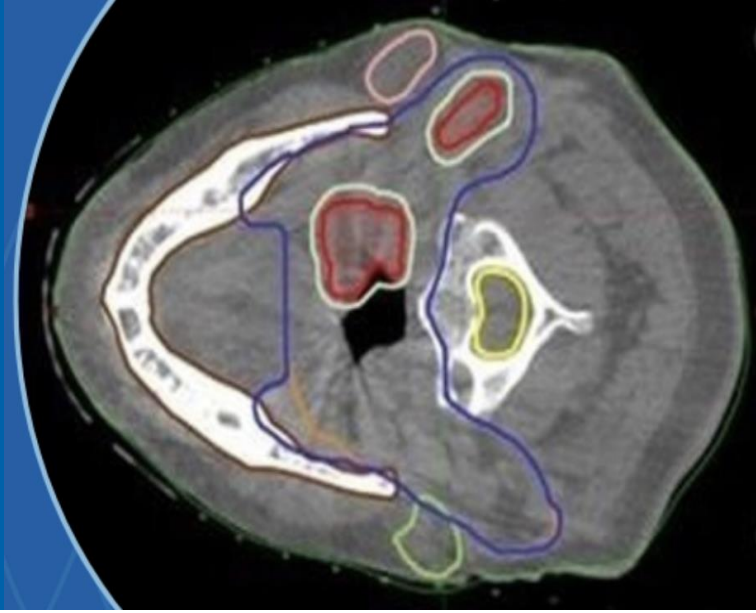
TG 116 WORKSHOP | 8 APRIL 2025 | 12:00 - 14:00 (UTC)

RADIOLOGICAL PROTECTION ASPECTS OF IMAGING IN RADIOTHERAPY



Doses from Imaging Procedures in Radiation Therapy

Jenia Vassileva

ICRP TG116 member

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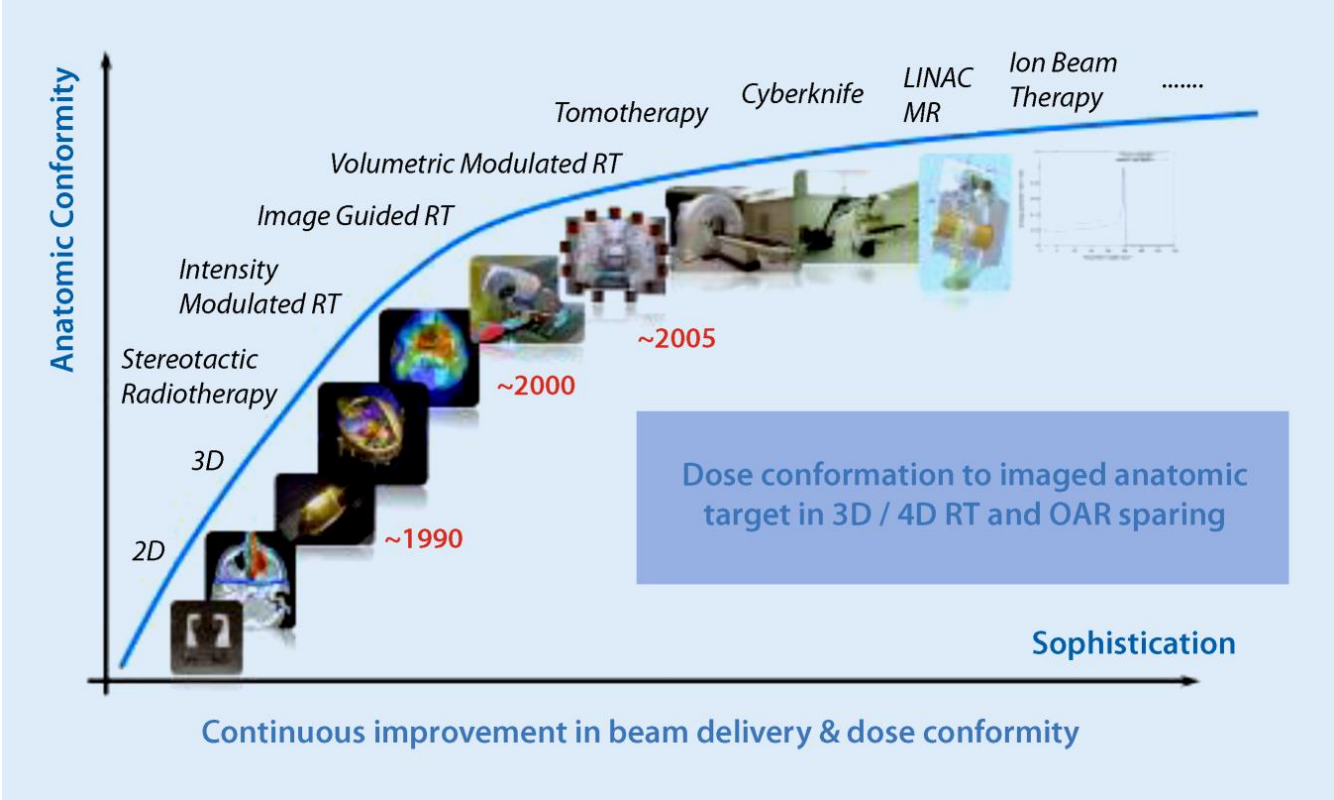
Imaging in modern cancer care

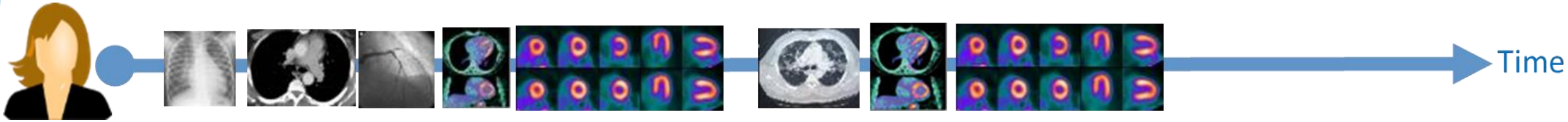
- Imaging dose has traditionally been deemed insignificant as compared to therapeutic dose delivered to tumours and surrounding tissues

- Changes in patterns of imaging, from 2-D to 3-D, with more frequent exposures, creates a potential for more significant cumulative doses to large volumes of normal tissue surrounding the tumour



Picture from: Herrmann H, Seppenwoolde Y, Georg D, Widder J. Image guidance: past and future of radiotherapy. Radiologe. 2019 Dec;59(Suppl 1):21-27. doi: 10.1007/s00117-019-0573-y.

Imaging during the cancer patient journey



Diagnosis and staging	Planning and simulation	Verification and image guidance	Treatment evaluation and follow-up
CT	CT	EPI (MV)	CT
PET-CT	PET-CT	MV-CBCT	PET-CT
SPECT-CT	Radiography	kV-planar	SPECT-CT
Radiography	Fluoroscopy	kV-CBCT	Radiography
Fluoroscopy	MRI	MVCT	MRI
MRI		US	
		Optical imaging	
		MRI	

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Patient dose metrics in medical imaging

Measurable

Modality-specific metrics

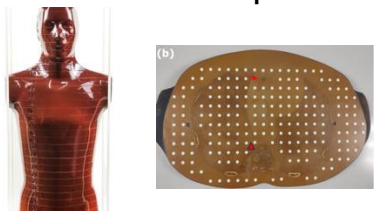
Application	Dose quantity
Plain radiography, including dental	Entrance surface air kerma, K_e Kerma-area product, P_{KA}
Mammography	Incident air kerma, K_i
Fluoroscopy & fluoroscopy guided interventional procedures	Kerma-area product, P_{KA} Air kerma at the interventiona reference point, $K_{a,r}$
Computed tomography	CT air kerma index, C Air kerma-length product, L_{KP}
Nuclear medicine	Administered activity

Calculated from modality-specific metrics

Organ/ tissue dose

Absorbed dose D_T in the volume of a specified organ or tissue T

- Measurements in phantoms



- Patient-representing models Monte Carlo simulations

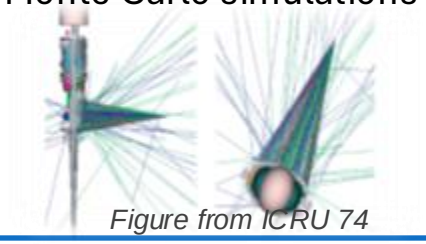


Figure from ICRU 74

Radiation risk index

Effective dose

(for a reference person)

$$E = \sum_T w_T \sum_R w_R D_{T,R}$$

Risk index

patient-specific, accounting for organs exposed, patient age and gender

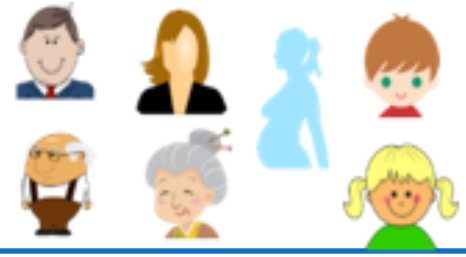
(BEIR 2006, ICRP 2007)

Goal

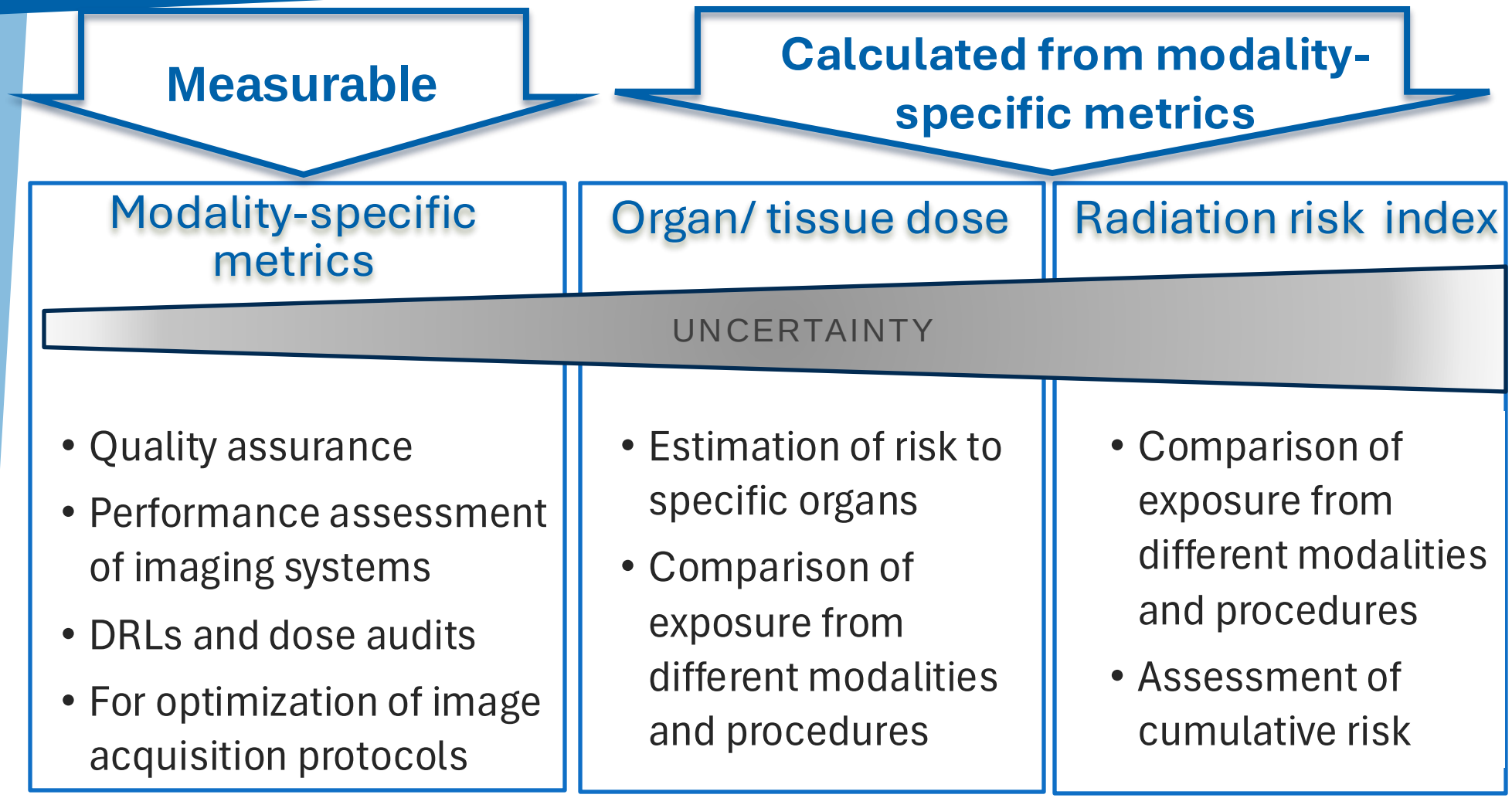
Individual risk (stochastic, deterministic)

To account for the age, sex, body habitus, health status (incl. life expectancy due to a disease…)

Unknowable!

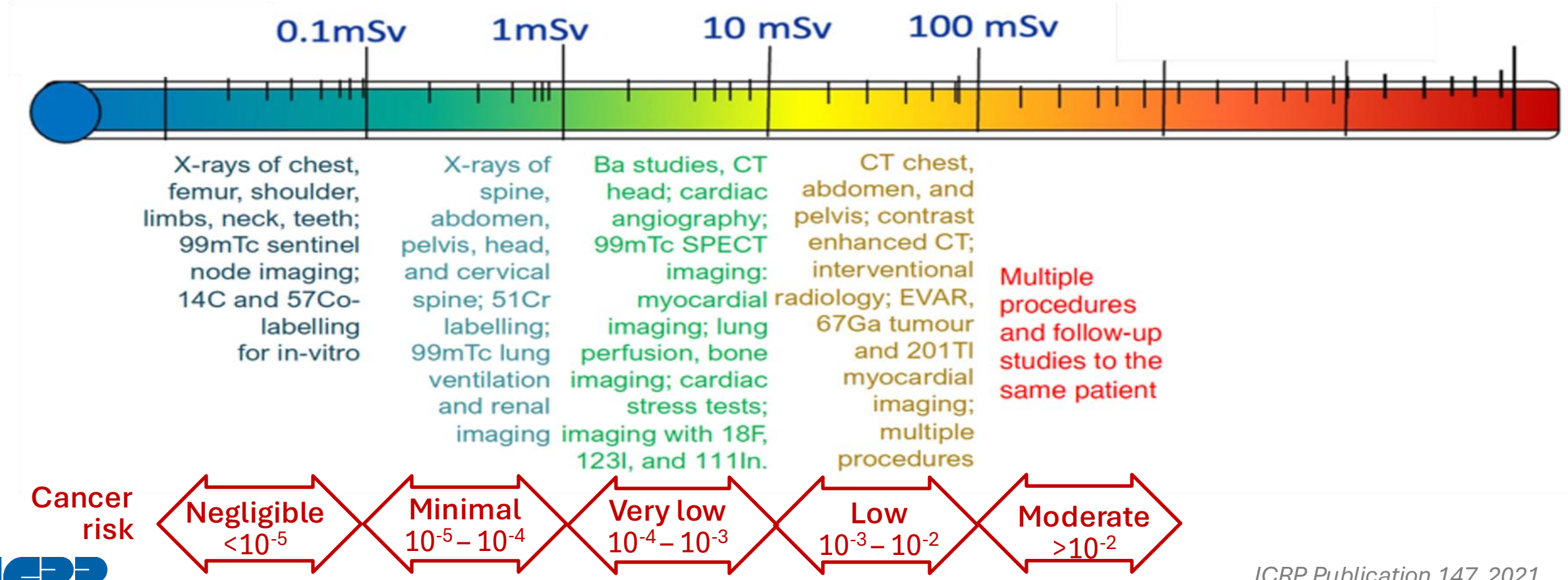


Patient dose metrics



Typical effective doses from imaging

- Typical effective doses from medical imaging procedure (radiology and nuclear medicine) are in the low dose range and risk is negligible to low



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ICRP Publication 147, 2021

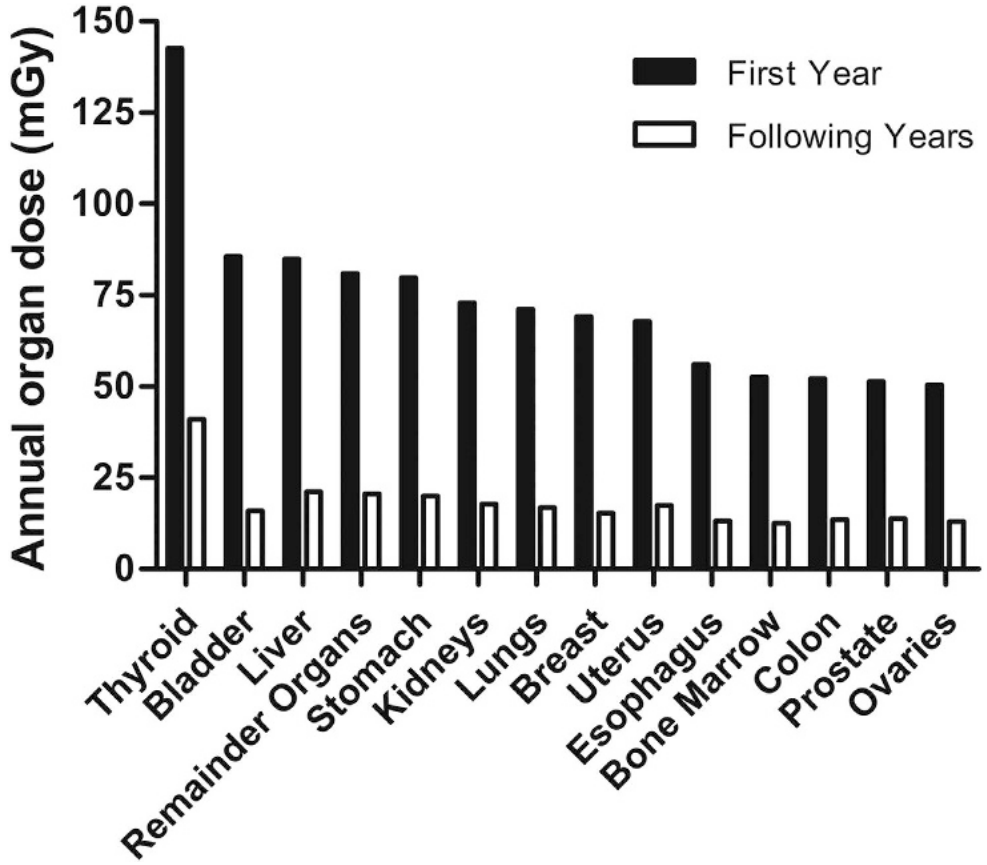
Doses from imaging prior and after treatment

- Cancer patients need more diagnostic procedures prior and after treatment
- Patients with cumulative effective doses >100 mSv from recurrent CT:

  Among them, oncology patients were:
  - 91% (*Rehani et al, 2020, doi: 10. 1007/ s00330-019-06523-y)*
  - 80% (*Jeukens et al (2021, doi: 10. 1136/ bmjopen-2020-041883)*
  - 73% (*Lumbreras et al (2019, doi: 10. 1136/ bmjopen-2019-030905)*
  - 60% (*Sodickson et al (2009, doi: 10.1148/ radiol. 2511081296)*
  - 58% (*Frija et al, 2020, doi: https:// doi. org/ 10. 1007/ s00330- 021- 07696-1)*
  - 31% (*Brambilla et al, 2021, doi: 10. 1007/ s00330- 020- 07665-0)*

Doses from follow-up imaging

- Improved survival rates and improved life expectancy - concerns to risk of second cancer
- Example: Hodgkin lymphoma (HL) and non-Hodgkin lymphoma (NHL) (adults and children): *Fabritius G, Brix G, Nekolla E, et al. 2016; doi: 10. 1038/srep35181*
  - 99 patients
  - Total of 2399 imaging procedures with IR (24.2 per patient, 71% CT)
  - In the first year after diagnosis: average 16 (range 1-55) exams per patient
  - In the following 2-6 years: average 3 (range 0-24) exams per patient per year
  - More imaging was used compared to the recommended by the lymphoma management guidelines



Doses from imaging for planning and simulation

CT
PET-CT
Radiography
Fluoroscopy
MRI

- Doses similar to diagnostic exams (~10-100 mGy to organs)
- Specifics of RT planning CT compared to diagnostic CT: fixed tube kV (to minimise uncertainty in HU units), large bore CT, increased x-ray tube to detector distances.
- Dose surveys of dose indexes from RT planning CT: wide range (by a factor of up to 18) of $CTDI_{vol}$ and DLP (*Wood et al., 2018; Wood et al., 2024)*

Doses from imaging for verification and IGRT

Imaged volume is generally larger than the treatment volume, and tissues and organs outside the therapeutic beams are exposed to imaging radiation

Doses from imaging: EPI (MV), kV-planar, MV-CBCT, kV-CBCT, MVCT

- Earlier reports (e.g. AAPM TG 75, 2007 and TG158, 2017) used also effective dose
- Recent reports (e.g. AAPM &G 180) use tissue/ organ absorbed dose, which can be compared with doses to organs adjacent to the treatment volume from radiotherapy
- Reported doses are
    - measured on/in phantom or on/in patient;
    - simulated with Monte-Carlo methods and calculated

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Doses from imaging for verification and IGRT

Inhomogeneous dose distribution

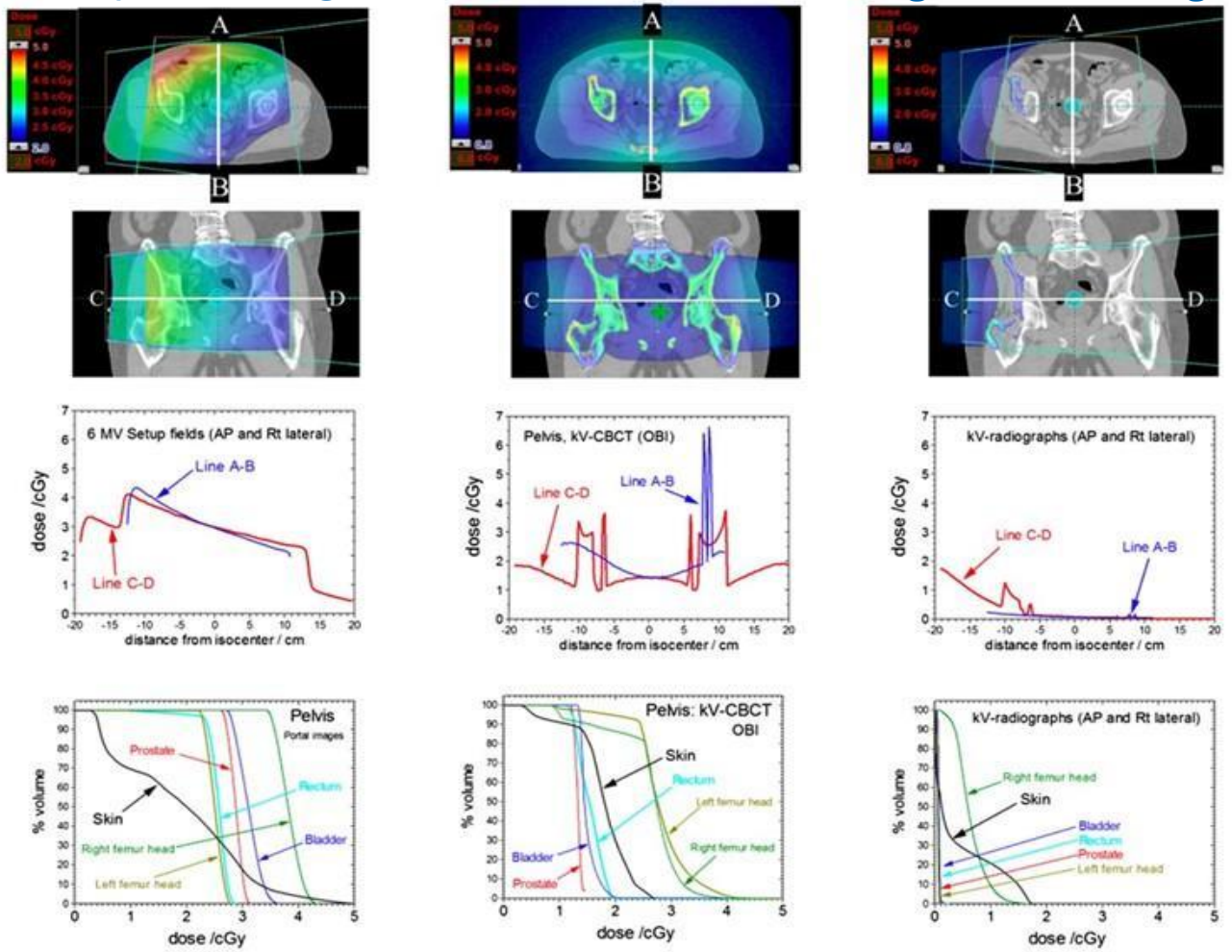
- Dose distribution depends on the mode of image acquisition and the beam energy
- Doses from 3D imaging are relatively uniform
- In 2D kV imaging the maximum dose is located in the skin and superficial tissues and has a steep decline with the depth by a factor of 100 to 1000

Dose distribution in the pelvis for:

one of a pair of 6 MV portal images

kV-CBCT

one from a pair of orthogonal kV radiographs



Ding, G.X., Munro, P., 2013. Radiation exposure to patients from image guidance procedures and techniques to reduce the imaging dose. Radiotherapy and Oncology. 108, 91-98.

Doses from imaging for verification and IGRT

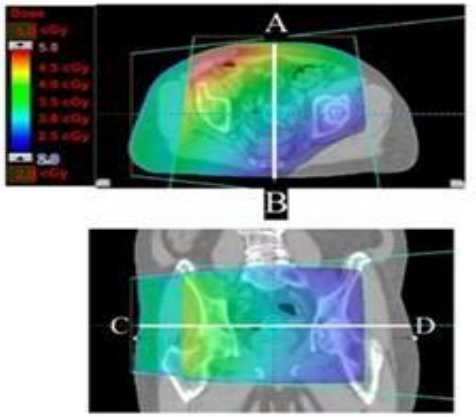
MV electronic portal imaging (EPI)

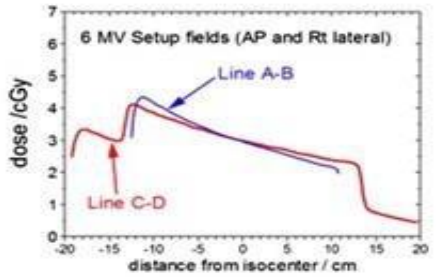
- ICRP Publication 112 (2009): daily absorbed dose of 150-200 mGy from EPI in excess of the prescribed dose ⇨ absorbed dose of 8–10% higher than intended.

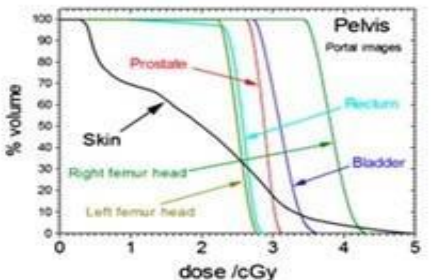
- More recent data (*Ding GX et al, 2013, 2018*):
  Typical pair of orthogonal 6 MV images: 10-50 mGy
  D50 dose (received by 50% of the organ), for treatment site:
  - Pelvis: 30 mGy in prostate, bladder, rectum
  - Head: 43-48 mGy in eyes; 37 mGy in brain stem
  - Thorax: 35 mGy in heart; 38 mGy in right lung

  Dose from a 2.5 MV beam is 50%

Dose distribution in the pelvis by a pair of 6 MV portal images







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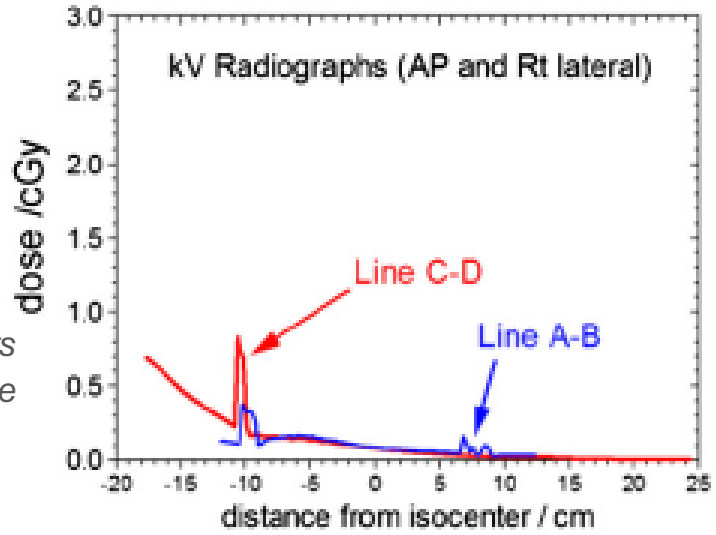
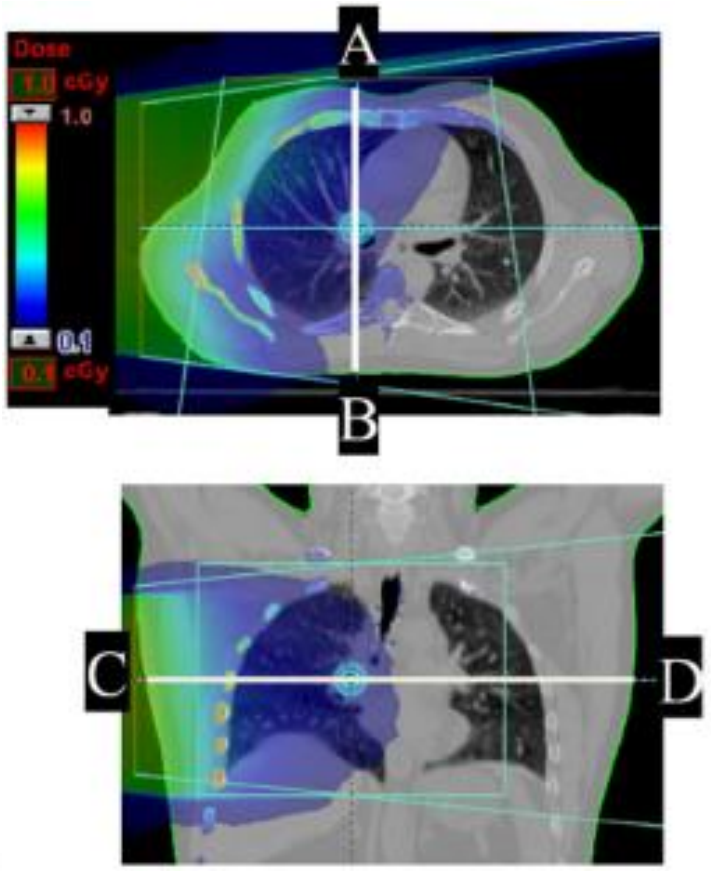
Doses from imaging for verification and IGRT

Planar kV

- Substantially less than that from MV portal imaging (<< 10 mGy/image pair)
- The dose to bone is 2-4 times that of soft tissue
- Dose drop-off is rapid and exit dose is substantially less than that from MV portal imaging



Dose distribution deposited in the lung by a pair of orthogonal kV radiographs



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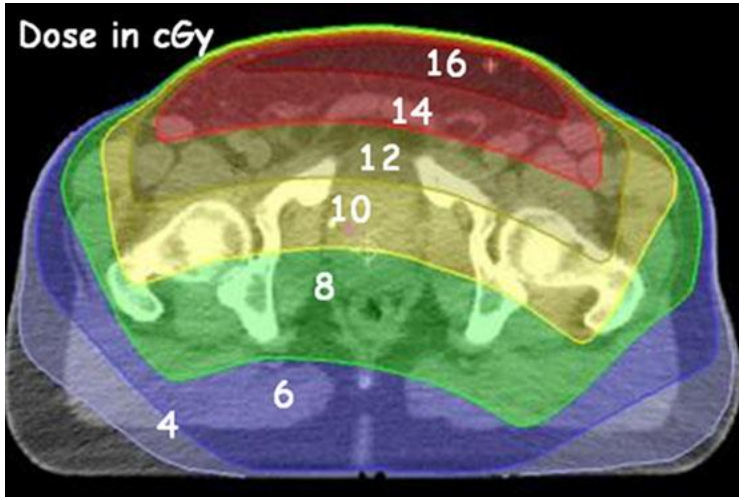
Doses from imaging for verification and IGRT

MV-CBCT

- Siemens (before 2014):
  6 -12 mGy/MU and 2-15 MU per acquisition, or
  10-120 mGy/scan depending on MU setting and model
- Varian's Halcyon:
  20-70 mGy per 5 MU acquisition for various treatment sites (head and neck, left breast and pelvis (*Malajovich et al. 2019*)
  ~70-80 mGy for high quality mode (10 MU total);
  half for low dose mode (5 MU total) (*Li et al. 2018*)
- Tomotherapy® (Accuray):
  10-40 mGy, highest dose in head and neck, lower in thorax and abdomen (*Mege et al. 2016*).

Dose distribution resulting from an MV-CBCT localization procedure of a prostate cancer patient using a 15 MU imaging protocol with a 6 MV beam. Asymmetric dose distribution because of 200 deg gantry angle *(Miften et al. 2007)*

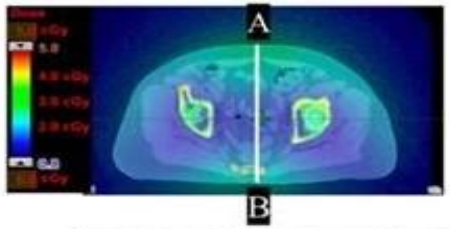


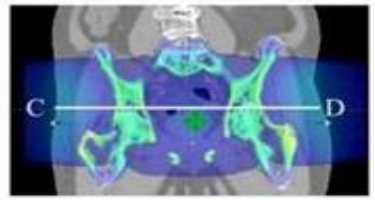
Doses from imaging for verification and IGRT

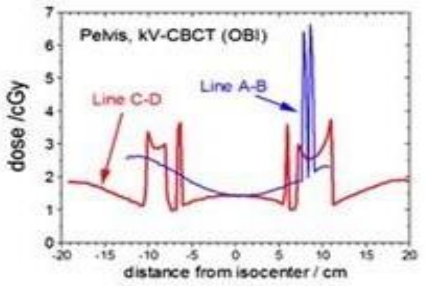
kV-CBCT

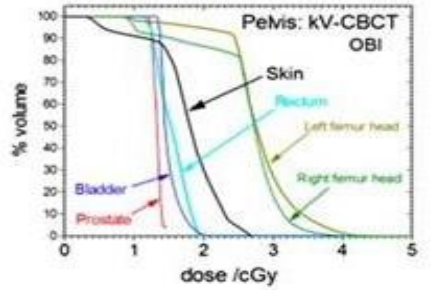
- Lower doses compared to MV-CBCT
- Large variation reported:
  - 0.4 – 31 mGy for head and neck
  - 2 – 29 mGy for thorax
  - 7 – 59 cGy for pelvis
- Less dose in newer systems due to improved hardware and software:
  - 3.6 and 34.5 mGy per image
  - variation by a factor of 10-50 in breast and 5 in prostate imaging (*Siiskonen T. 2017*)
- Dose affected by kVp, mA, filtration, arc start/stop angles, blade setting/cassette size, patient BMI

Dose distribution in the pelvis for kV-CBCT









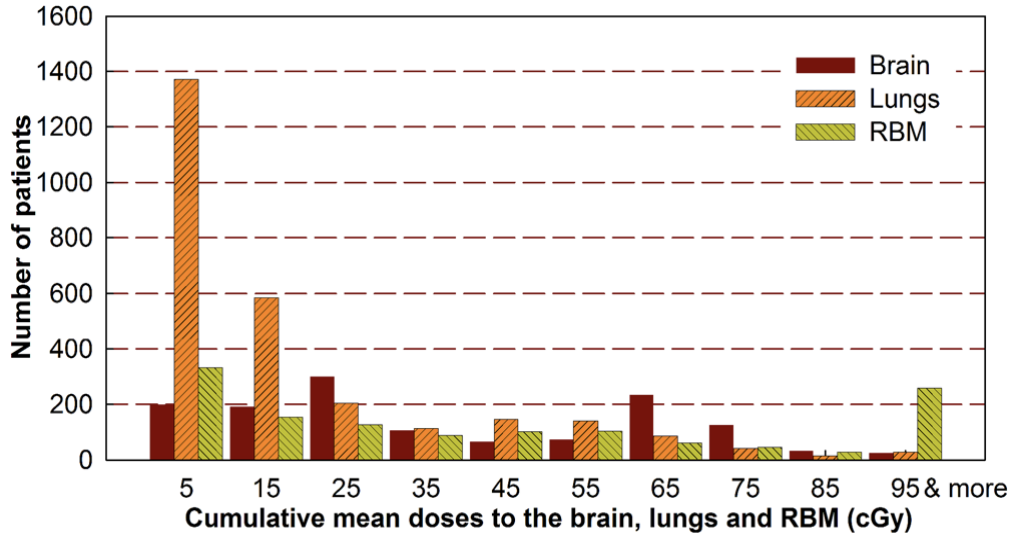
Doses from imaging for verification and IGRT

Cumulative doses

- *Siiskonen T. et al. 2024:* For prostate cancer treatment with kV-CBCT imaging for each fraction, cumulative mean doses were:

Fractions	prostate	rectum	bladder	femoral head
20	184 - 530 mGy	107 - 218 mGy	72-233 mGy	250-690 mGy
39	359 - **1034** mGy	209 - 425 mGy	140–454 mGy	488 - **1346** mGy

- *Zhou, et al. 2018:* Cumulative mean (range) doses from CT planning, verification and image guidance (EPI, kV-planar, kV-CBCT) for 4,832 cancer patients:
  - Brain: 380 (5 – **1773**) mGy
  - Lungs: 188 (4 – **2465**) mGy
  - Red bone morrow: 491 (4–**2744**) mGy



Summary: Doses from imaging

- Doses to organs surrounding the tumour from a single imaging procedure during treatment vary from a few mGy for kV 2D and 3D imaging, to 30-50 mGy for MV imaging.
- The repeated imaging can deliver from 100s mGy to > 2 Gy to these organs.
- Imaging dose to tumour is generally <5 % of the therapeutic target dose, except for some procedures that use MV beams, particularly MV-CBCT.
- The dose to surrounding tissues and OARs has to be considered independently as imaging dose is not conformed to the target volume in the same way as the treatment.

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Summary: Doses from imaging

- The organ dose from imaging can vary by a factor of ten or more for the same treatment, depending on the chosen technique and imaging frequency.
- Doses to children and smaller adults could be 2-3 times higher if exposure factors are not adjusted.
- This combines with doses prior and after the treatment increasing the risk of induction of further cancers.
- Awareness and optimization of the imaging dose in image-guided radiotherapy should be strengthened.

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