Managing the imaging dose during Image-guided Radiotherapy

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Radiographic image guidance has emerged as the new paradigm for patient positioning, target localization, and external beam alignment in radiotherapy.

Motivation for this review

- all radiographic image guidance techniques give a radiation dose to the patient.
- The philosophy for dose management adopted by the diagnostic imaging community is summarized by the acronym ALARA - i.e., As Low As Reasonably Achievable (NCRP 1990).
- In order to evaluate and manage the dose one must know what it is.
- This review is condensed from the report of AAPM Task Group 75

Goals of the lecture

- Review the issues in dose estimation
- Illustrate the varieties of transmission imaging in IGRT (emission imaging such as PET and SPECT will not be included)
- Summarize the doses associated with various imaging modalities and setups
- Present the methodology for summing dose
- Discuss the evaluation of risk
- Recommend management strategies

Difficulties in determining imaging dose

- Data for the dose delivered by the various radiographic imaging modalities being used during radiation therapy are presently scattered widely through the literature, making it difficult to estimate the total dose that the patient will receive during a particular treatment scenario.
- IGRT systems often are configured differently than diagnostic imaging setups.

Difficulties in summing total dose

- Air kerma is the frequently measured dose quantity but absorbed dose is the biologically-significant quantity.
- different imaging scenarios deliver dose in fundamentally different ways, making it difficult to sum dose in a radio-biologically consistent manner.

Diversity in imaging dosimetry

- We distinguish
  - Local dose from integral doe
  - Planar from axial imaging
  - kV from MV radiation

Diversity in dosimetry

- Local dose depends only on fluence; integral dose depends on fluence and area/volume of exposure.
- planar dose is evaluated as entrance (skin) dose in air kerma, without scattering; axial dose (CT) is evaluated as CTDI, with scattering
- For kV, air kerma and absorbed dose are essentially the same; for MV they are not the same in regions of electronic dis-equilibrium (e.g., air/tissue boundaries).

Difficulties in interpreting risk

- Two categories of risk:
  - deterministic risk – e.g., skin injury, cataracts – has an approximate threshold that can be observed on an individual basis.
  - stochastic risk –e.g, the increased risk of a secondary cancer – is probabilistic and is extrapolated from population-based data.

Difficulties in interpreting risk

- Diagnostic imaging and image-guided surgery introduce ionizing radiation, while IGRT adds it to an already considerable therapeutic exposure.
- Increased imaging dose during IGRT can reduce normal tissue exposure to the treatment beam, thus reducing overall concommitant dose.

Difficulties in interpreting risk

- not everyone has the same sensitivity – children are 10 times more sensitive than adults; girls are more sensitive than boys, women have different organ sensitivities than men.
- Not everyone is in the same risk category – a seventy year old man undergoing image-guided prostate treatments is in an entirely different risk situation than a 15 year old undergoing image-guided radiosurgery for an AVM on the spinal cord.

Important note on units

- Local dose is measured in Grays (Gy); effective dose is measured in Sieverts (Sv). These are not equivalent quantities.
- Radiation therapy uses cGy; Radiology uses mGy. There is risk of confusion here.
- Although the target audience here is radiation therapy we will follow the radiological imaging convention and express local dose in mGy. Beware!

IGRT transmission imaging procedures

- CT for planning and follow-up
- Pretreatment fluoroscopy of organ motion
- Portal and kV for daily setup on bony landmarks and fiducials
- MVCT, CBCT, CT on rails for daily setup of soft-tissue targets
- Intra-fraction radiography
- Intra-fraction fluoroscopy for respiratory motion
- Fluoroscopy for brachytherapy seed implantation

In-room radiography examples

- CyberKnife
- BrainLab ExacTrac

CyberKnife

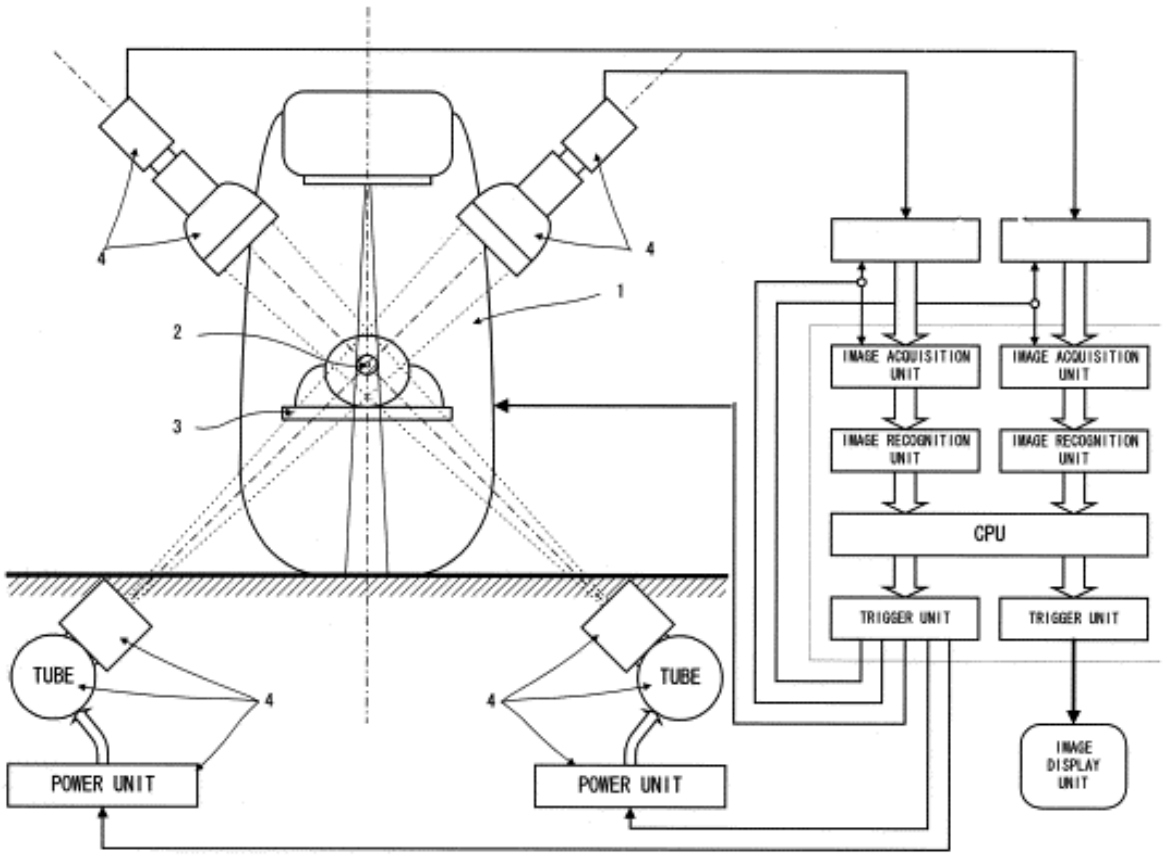
CyberKnife imaging dose

Site	kV	mAs	mGy
Cranium and C-spine	105-125	10	0.25
T-spine	120-125	10-20	0.25 – 0.50
L-spine	120-125	10-30	0.25 – 0.75
Sacrum	120-125	10-90	0.25 – 2.00
Synchrony	120-125	5-22.5	0.10 – 0.50

BrainLab ExacTrac

- Add picture

In-room fluoroscopy at Hokkaido University Hospital (Shirato, IJROBP 48, 2000)



Hokkaido fluoroscopic dose

kV	mA	ms	Dose @ patient (mGy)
			60 s
60	80	2	1.11
		4	2.07
80	80	2	2.45
		4	4.28
100	80	2	4.35
		4	7.41
120	80	2	6.69
		4	10.90

Computed tomography dose index (CTDI)

- Theory

$$CTDI = (1 / h) \int_{-\infty}^{\infty} D(z)\, dz$$

- Practice (measured with an ionization chamber in a phantom, including scatter)

$$CTDI_{100} = (1 / h) \int_{-50}^{50} K_{air}(z)\, dz$$

CTDI in air

- If the dose measurement is made with an ionization chamber on the central axis without a phantom one obtains the axial dose free-in-air, or CTDI(air).
- This is directly comparable to entrance air kerma.

Typical CTDI(air)

Examination	Scan Length	Pitch	$CTDI_{air}$
Head	12.0 cm	1.0	81 mGy
C-spine	18.0	1.2	55
Chest	27.0	1.3	47
Abdomen	42.0	1.3	54
L-spine	6.0	1.1	100
Pelvis (male)	24	1.2	60

Summing doses

- Because of the differing qualities of kV, planar, CT, and MV exposures the doses should only be compared and summed in units of “effective dose”, which represents the approximate stochastic risk associated with a given integral dose

Effective dose

- From Jacobi (Radiat Environ Biophys 12, 1975)

  “the mean absorbed dose from a uniform whole-body irradiation that results in the same total radiation detriment as from the non-uniform, partial-body irradiation in question.”

Effective dose

- $E = \sum_T w_T H_T$

  where the H_T are the average organ doses to tissue T for a particular exam and the w_T are tissue weighting factors that represent the relative radiation sensitivities of the organs.

Effective dose

- Practical conversion of imaging dose to effective dose
- Conversion coefficients from local to effective dose have been calculated for most imaging scenarios

$$E = D \bullet F[\, mSv / mGy]$$

Conversion of local to effective dose

- For planar imaging, multiply the local dose by the exposed area (dose-area product) and then by the conversion factor F(mSv/mGy cm^2)
- For axial imaging, multiply the CTDI by the scan length (dose-length product) and then by the conversion factor F (mSv/mGy cm)
- In some axial effective dose conversion tables the conversion factor already includes the scan length, for specfied exams.
- For CT be sure to distinguish CTDI(air) from CTDI in a phantom

Example of effective dose conversion factor F (mSv per mGy cm^2): kV planar imaging/ AP view

kVp	Filter (mmAl)	Chest (10^{-5})	Lumbar Spine(10^{-5})	Pelvis (10^{-5})
80	2	21.5	18.9	20.0
	4	26.9	24.9	25.2
100	2	25.5	24.0	24.3
	4	31.0	30.2	29.6
120	2	28.9	28.0	27.7
	4	33.9	33.8	32.6

Elekta cone-beam CT effective dose

Parameter	Head	Chest
Mean dose at center (mGy)	29	16
Mean skin dose (mGy)	30	23
Effective dose (mSv)	3.0	8.1
Conversion factor (mSv/mGy cm^2)	6.0×10^{-5}	16.0×10^{-5}

Effective dose from portal imaging

Port View	Gender	Effective dose (mSv/MU)
AP pelvis	Male	0.34
	Female	0.52
Lat pelvis	Male	0.32
	Female	0.7
AP chest	Male	1.74
	Female	1.8
Lat chest	Male	2.56
	Female	2.23

Evaluation of risk

- Deterministic risk is evaluated at the entrance using units of Gy, assuming air kerma/absorbed dose equivalence; hence it is hard to fold in the contribution from MV radiation.
- Stochastic risk is measured in Sv.

Deterministic risks

Effects	Threshold	Time of onset
• early transient erythema	2000 mGy	2 – 24 hours
• temporary epilation	3000 mGy	1.5 weeks
• main erythema	6000 mGy	3 weeks
• permanent epilation	7000 mGy	3 weeks
• dermal necrosis	15,000 mGy	> 52 weeks
• eye lens opacity (detectable)	> 1000 mGy	> 5 years
• cataract (debilitating)	> 5000 mGy	> 5 years

Stochastic risk

- The most recent ICRP coefficient for estimating the probability of inducing a fatal cancer from a single radiographic exposure is 5×10^{-5} per mSv of effective dose (ICRP-60 1991). This coefficient is based on the linear no-threshold model of radiation risk and is derived primarily from studies of atomic bomb survivors.

Example of risk estimation

- 70 male with prostate cancer
  - CT for planning (8.2 mSv)
  - 30 daily portal image pairs (30x1.3 mSv)
  - 0.2% risk of secondary cancer
- 30 year old female patient w/ cervical cancer
  - 30 daily CTs for positioning (30x8.2 mSv)
  - 1.2% risk of secondary cancer

Evaluating imaging dose by comparison to therapeutic dose

- Effective dose is an established way to measure and compare imaging dose in terms of its stochastic risk
- Imaging dose is delivered in standard formats
- Therapeutic dose is delivered in highly variable patient-specific scenarios
- There has not yet been much done to calculate effective dose for therapy
- Therefore it is not yet feasible to make precise quantitative comparisons of imaging versus therapy dose

Management of dose

- Reduce local dose via more efficient imaging - e.g., pulsed fluoroscopy
- Reduce effective imaging dose via smaller fields of view
- Optimize imaging duty cycles to trade off increased imaging dose with reduced therapeutic dose to normal tissue
- Calculate effective doses for the therapeutic beam