Managing the imaging dose during image-guided radiation therapy

Martin J Murphy PhD
Department of Radiation Oncology
Virginia Commonwealth University
Richmond VA
Radiographic image guidance has emerged as the new paradigm for patient positioning, target localization, and external beam alignment in radiotherapy.

Outline

- Imaging procedures for radiotherapy
- Measuring dose
- Dose summation
- Dose evaluation
- Dose reduction
- Summary
Uses of radiographic imaging in Image-guided radiation therapy (IGRT)

- Precise daily positioning of the patient before treatment
  - MV portal imaging
  - dual kV planar imaging
  - in-room fan-beam and cone-beam CT
- Intra-fraction motion monitoring
  - kV radiography and fluoroscopy
- Daily plan adaptation
  - fan-beam and cone-beam CT
BrainLab Exactrac x-ray
Varian On-board Imager (OBI)
CT on rails
Cone-beam CT
Measuring dose

- 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.
Difficulties in determining 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.
Diversity in imaging dosimetry

We distinguish

- Air kerma from absorbed dose
- Local dose from integral dose
- 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).
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!
Computed tomography dose index (CTDI)

- **Theory**
  \[
  CTDI = \frac{1}{h} \int_{-\infty}^{\infty} D(z) \, dz
  \]

- **Practice (measured with an ionization chamber in a phantom, including scatter)**
  \[
  CTDI_{100} = \frac{1}{h} \int_{-50}^{50} K_{air}(z) \, dz
  \]
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).
- There is no scatter.
- This is directly comparable to entrance air kerma.
Typical CTDI (air)
(from HD Nagel, Radiation Exposure in Computed Tomography)

<table>
<thead>
<tr>
<th>Examination</th>
<th>Scan Length</th>
<th>Pitch</th>
<th>CTDI&lt;sub&gt;air&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>12.0 cm</td>
<td>1.0</td>
<td>81 mGy</td>
</tr>
<tr>
<td>C-spine</td>
<td>18.0</td>
<td>1.2</td>
<td>55</td>
</tr>
<tr>
<td>Chest</td>
<td>27.0</td>
<td>1.3</td>
<td>47</td>
</tr>
<tr>
<td>Abdomen</td>
<td>42.0</td>
<td>1.3</td>
<td>54</td>
</tr>
<tr>
<td>L-spine</td>
<td>6.0</td>
<td>1.1</td>
<td>100</td>
</tr>
<tr>
<td>Pelvis (male)</td>
<td>24</td>
<td>1.2</td>
<td>60</td>
</tr>
</tbody>
</table>
### 2D planar example: CyberKnife imaging dose

<table>
<thead>
<tr>
<th>Site</th>
<th>kV</th>
<th>mAs</th>
<th>mGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranium and C-spine</td>
<td>105-125</td>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>T-spine</td>
<td>120-125</td>
<td>10-20</td>
<td>0.25 – 0.50</td>
</tr>
<tr>
<td>L-spine</td>
<td>120-125</td>
<td>10-30</td>
<td>0.25 – 0.75</td>
</tr>
<tr>
<td>Sacrum</td>
<td>120-125</td>
<td>10-90</td>
<td>0.25 – 2.00</td>
</tr>
<tr>
<td>Synchrony</td>
<td>120-125</td>
<td>5-22.5</td>
<td>0.10 – 0.50</td>
</tr>
</tbody>
</table>
Summing the imaging dose during IGRT
Issues in summing the doses from different modalities

- different imaging scenarios distribute dose in fundamentally different ways, making it difficult to sum dose in a radio-biologically consistent manner:
  - e.g., planar kV imaging dose attenuates rapidly along the line of sight; CT dose is uniformly distributed through the patient
- planar kV dose is evaluated as entrance (skin) dose in air kerma, without scattering; axial kV dose (CT) is evaluated as computed tomography dose index (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).
- kV surface dose buildup layer is very thin; MV surface buildup layer is much deeper; thus skin doses are very different
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 biological detriment associated with a given integral dose.
Effective dose

- The concept of “effective dose” (or effective dose equivalent) was introduced to provide a common framework for evaluating the biological detriment of exposure to ionizing radiation via any means.

- 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

- \( E = \sum_T w_T H_T \text{milliSieverts (mSv)} \)
  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.

- Unlike local absorbed dose, effective dose is a volume integral and thus depends on both the beam fluence and imaging area.
## Elekta cone-beam CT effective dose
(from Islam et al, Med Phys 33, 1573-1582, 2006)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Head</th>
<th>Chest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean dose at center (mGy)</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>Mean skin dose (mGy)</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>3.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Conversion factor (mSv/mGy cm²)</td>
<td>$6.0 \times 10^{-5}$</td>
<td>$16.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Effective dose from portal imaging

<table>
<thead>
<tr>
<th>Port View</th>
<th>Gender</th>
<th>Effective dose (mSv/MU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP pelvis</td>
<td>Male</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>0.52</td>
</tr>
<tr>
<td>Lat pelvis</td>
<td>Male</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>0.7</td>
</tr>
<tr>
<td>AP chest</td>
<td>Male</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1.8</td>
</tr>
<tr>
<td>Lat chest</td>
<td>Male</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>2.23</td>
</tr>
</tbody>
</table>
Some IGRT scenarios

- daily pre-treatment CTs for 30 fractions: 60 - 400 mSv
- two pairs of MV portal images daily for 30 fractions: 40 - 400 mSv
- two minutes of daily kV fluoroscopy for 30 fractions: 40 - 120 mSv
- 100 dual kV planar images daily for 5 fractions: 10 - 100 mSv
Evaluating the imaging dose
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.
    - Stochastic risk is estimated from the total effective dose
Examples of deterministic risk

<table>
<thead>
<tr>
<th>Effects</th>
<th>Threshold</th>
<th>Time of onset</th>
</tr>
</thead>
<tbody>
<tr>
<td>early transient erythema</td>
<td>2000 mGy</td>
<td>2 – 24 hours</td>
</tr>
<tr>
<td>Temporary epilation</td>
<td>3000 mGy</td>
<td>1.5 weeks</td>
</tr>
<tr>
<td>main erythema</td>
<td>6000 mGy</td>
<td>3 weeks</td>
</tr>
<tr>
<td>permanent epilation</td>
<td>7000 mGy</td>
<td>3 weeks</td>
</tr>
<tr>
<td>dermal necrosis</td>
<td>15,000 mGy</td>
<td>&gt; 52 weeks</td>
</tr>
<tr>
<td>eye lens opacity</td>
<td>&gt; 1000 mGy</td>
<td>&gt; 5 years</td>
</tr>
<tr>
<td>cataract (debilitating)</td>
<td>&gt; 5000 mGy</td>
<td>&gt; 5 years</td>
</tr>
</tbody>
</table>
Stochastic risk

- The ICRP coefficient for estimating the probability of inducing a fatal cancer from a single radiographic exposure is $5 \times 10^{-5}$ 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.
Examples of stochastic risk from IGRT concomitant dose

- 70 year old 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
  - Planning CT (8.2 mSv)
  - 30 daily CTs for positioning (30x8.2 mSv)
  - 1.25% risk of secondary cancer
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 concomitant 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.
Comparing imaging and therapeutic effective doses

- In addition to the primary therapeutic dose deposited in the target volume we have
  - Primary concomitant dose from beams transiting normal tissue
  - Secondary concomitant dose from internal and external scatter, linac leakage, etc
Evaluating imaging dose by comparison to therapeutic dose

- Effective dose is the established way to measure and compare radiation 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 doses for therapy.
- Therefore it is not yet feasible to make precise quantitative comparisons of imaging versus therapy dose.
Example dose comparison

- Estimate of 854 mSv effective dose from scattered internal beam and external leakage and scatter for a 70 Gy prostate treatment
  

- Compare to 350 mSv from 35 daily diagnostic quality pelvic CT scans for image-guided adaptive radiotherapy
Reducing the imaging dose
Dose reduction

- In general, for imaging during IGRT one should not assume that diagnostic quality procedures and images are necessary in all applications
Dose reduction

- Effective dose is a volume integral, so reducing fluence and/or area helps
  - Planar imaging FOV for patient setup can be collimated down to the region of interest
  - CT scan length can be reduced to the region of interest
  - Digital tomosynthesis - CT acquired over a limited angular arc reduces CTDI
Temporal dose reduction

- Fluoroscopy for target tracking doesn’t always require video frame rates (30 frames/second) or a continuous exposure
  - e.g., respiration monitoring can be done at 2 - 4 frames per second via pulsed fluoroscopy
Fluence reduction

- Image registration for patient setup, contour transfer, and dose summing can be fairly insensitive to noise, so the technique can be reduced below diagnostic quality.
Reduction by modality change

- Intra-fraction monitoring via kV fluoroscopy can be replaced by cine-mode MV portal imaging using the treatment beam
  - This can work for 3D conformal therapy, where the beam aperture is fixed for each field
  - Cannot work for dynamic IMRT, where the beam aperture is constantly changing
Summary

- Imaging systems and procedures for IGRT are often configured differently than for diagnostic exams, resulting in different doses.
- IGRT can combine several different imaging procedures for a particular patient.
- Estimation of the total concomitant dose must recognize the variations in dose deposition by using effective dose as the common measure.
- Risk evaluation in IGRT is fundamentally different than in diagnostic radiology because the imaging dose is added to a high therapeutic dose.
- There is a need for estimates of effective dose for the treatment procedures to enable evaluation of imaging dose in context.
- IGRT procedures do not always require diagnostic quality images and thus allow a variety of dose reduction strategies.