Image-Guided Radiation Therapy: Benefits and Risks, Certainties and Uncertainties

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Hotlanta (sometimes Hot’Lanta):

I don’t know how hot it is outside, but two hobbits just walked up and tossed a golden ring on my front lawn.
Introduction and overview
How do we define IGRT?

- “Image-guided radiotherapy (IGRT) makes use of many different imaging techniques, using modalities ranging from portal imaging to fluoroscopy to megavoltage cone-beam CT and following regimens as simple as a single setup image or as complex as intrafraction tumor tracking.”¹

AAPM TG-75 (2007)
How do we define IGRT?

- TG-75 continues:
  
  ➢ “...the primary goal of this task group report is to collect into one place enough data to allow the clinical practitioner to make an informed estimate of the total imaging dose delivered to the patient during the complete treatment process.”

  ➢ “…we consider that the data in this report are adequate for about a factor of 2 estimate of air kerma and effective dose.”
How do we define IGRT?

- “IGRT involves the use of imaging technology to localize the intended target volume immediately prior to the administration of radiation therapy.”

  ASTRO Health Policy Coding Guidance (Jan 2013)
How do we define IGRT?

- The ASTRO defines **scope of supervision**: 
  - Compare IGRT images to planning scans to precisely adjust table position and/or patient orientation
  - “IGRT must be performed by the radiation oncologist, medical physicist or trained radiation oncologist under the supervision of the radiation oncologist.”
  - “The physician must supervise and review the procedure…”
  - “IGRT is considered to be an inherent part of the SRS and SBRT procedure; for that reason, IGRT guidance should not be billed with SRS and SBRT treatments.”
How do we define IGRT?

The ASTRO document defines IGRT indications:

- Absence of rigid immobilization in SRS or SBRT
- Target volume directly adjacent to critical structures
- The volume of interest is covered by narrow margins (to protect a PRV)
- Previous radiation was delivered near the target, requiring high precision to avoid/define overlap
- Dose escalation beyond conventional fractionation
- Target volume inter- and/or intra-fraction motion
How do we define IGRT?

- The ASTRO document defines IGRT indications:
  
  ➢ “...where conventional means of targeting are deemed inadequate.”
Two common approaches to presentations dealing generally with IGRT:

1. Review commercial and/or customized solutions currently in clinical use
2. Identify different problems and review possible solutions within the framework of IGRT

We’ll focus mainly on option 2
Difficult IGRT situations:

- LINAC-based SRT
  - 3DOF head-adjuster set up with real-time motion tracking
  - After initial setup CBCT, further adjustments require 3 more CBCT acquisitions
  
  - What is the magnitude of uncertainty, considering we’re treating a 5 mm metastatic lesion?
  
  - What dose distributions are we delivering with frequent image acquisition?
Difficult IGRT situations:

- SBRT for lung lesion
  - Vac-Lok immobilization system and compression plate
  - After initial setup CBCT, further adjustments require 3 more CBCT acquisitions
  - Physician aligns visible target to middle of contoured \( \text{GTV}_{\text{MIP}} \)
    - What dose distributions are we delivering with frequent image acquisition?
    - What is the effect of aligning to visible target with peripheral body misalignment?
Difficult IGRT situations:

- Left eComp breast tangents and sclav
  - Scheduled for MV weekly
  - Upon expanding the MV imaging port it is discovered that the patient has an implanted cardiac pacemaker
    - Should this observation change your imaging approach and precautions?
    - What dose might the CIED receive through imaging, and what is the potential impact?
Test of Audience Participation:

How do you like the talk so far?

1. Strangely tolerable; are you sure he’s a physicist?

2. Meh

3. How long is this session again?

4. I’m actually asleep: my neighbor is holding up my arm
Estimation of IGRT geometric uncertainty
...OR

Shoot first, and whatever you hit, call it the target...
Errors potentially mitigated by IGRT:

- **Systematic error**
  - Affects all fractions identically
  - Dataset registration, contouring complications, consistent immobilization issues

- **Random error**
  - Inter- and intra-fraction variability
  - Organ movement, random setup uncertainty, etc.

- Typically, systematic errors dominate, but *not always*:
  - Large movements in lung or prostate targets
  - Large, pendulous anatomical issues
Errors potentially mitigated by IGRT:

**Systematic Error:**
- Inaccurate
- Reproducible
- Definite cause
Errors potentially mitigated by IGRT:

- **Systematic Error:**
  - Inaccurate
  - Reproducible
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- **Random Error:**
  - Imprecise
  - Singular
Errors *potentially* mitigated by IGRT:

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- Inaccurate
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**What we want:**
- Accuracy
- Precision
Errors *potentially* mitigated by IGRT:
Errors *potentially* mitigated by IGRT:

How accurately and reproducibly can we zoom in on any target?
Quiz Question #1

How would you categorize the following error: a fiducial marker that was poorly delineated in the planning structure set.

1. Random error
2. Systematic error
3. Connectivity error
4. Grammatical error
Better accuracy with better technology

- Setup error for prostate treatments
- Derived from Soete, et al. (IJROBP 2002)

  “...positioning based on room lasers, infrared tracking, automated image fusion of bony structures from DRRs and X-ray images, or matching of implanted markers respectively.”
Better accuracy with better technology

Systematic and random residual error for prostate treatments

- Conventional
- IR
- DRR
- Markers

(mm)
Sources of IGRT uncertainty

- **Geometric (mechanical) uncertainty**
  - e.g. imaging-radiation isocenter, flex of imager arms, SDD accuracy (scaling), couch movements, etc.

- **Image-quality uncertainty**
  - e.g. scaling, distortion, contrast/noise/uniformity, artifacts, etc.

- **Quality-assurance must be rigorous, following accepted standards and vendor guidance**
  - e.g. TG-66, TG-142, TG-179 from the AAPM
Sources of IGRT uncertainty

- Multiple studies have demonstrated mechanical accuracies of *approximately*:
  - 2 mm for kV-kV, MV-MV, or kV-MV 2D match
  - 1 mm for CBCT and even better

- REMEMBER: these values are for *phantom* studies
“Both the ExacTrac and the OBI CBCT systems showed approximately 1 mm isocenter localization accuracies. The angular discrepancy of two systems was minimal, and the robotic couch angle correction was accurate. These positioning uncertainties should be taken as a lower bound because the results were based on a rigid dosimetry phantom.”

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- \textbf{REMEMBER:} these values are for \textit{phantom} studies

- \textbf{Must carefully examine patient/target movement when considering uncertainty approximations!}
CBCT vs. 4DCT

- Register images to the peripheral static landmarks or to the (moving) target structure itself?
  - Philosophies differ, and the literature does too
  - One *case study* indicates possible error by a factor of 1.6 when evaluating tumor motion based on 3DCT

- Tumor motion, patient mobility, degree of soft-tissue matching all reduce IGRT accuracy and should indicate the need for more generous margins.
CBCT vs. 4DCT

4DCBCT

3DCBCT
IGRT-induced dose burden by modality and anatomical site
Haven’t we already treated the tumor with CBCT at this point??
IGRT radiation dose: not straightforward

- Different imaging modalities distribute radiation dose in fundamentally different ways
  - kV photon energies stack dose toward the surface
IGRT radiation dose: not straightforward
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Single beam incident from right

6 MV

120 kVp
IGRT radiation dose: not straightforward

- Different imaging modalities distribute radiation dose in fundamentally different ways
  - kV photon energies stack dose toward the surface
  - 3D-kV imaging (e.g. CBCT) tends to spread dose uniformly throughout the volume
  - kV energies yield dose enhancement in bone
Quiz Question #2

What physical process causes dose enhancement in bony anatomy for kV-range photons?

1. Time-flux capacitance
2. Compton scattering
3. Photoelectric effect
4. Brownian motion
Quiz Question #2

“An additional estimation methodology for kV-CBCT imaging dose was also discussed by Ding et al. (Ding, Duggan et al. 2008). They have also found that the dose to the bone due to the photoelectric effect can be as much as 25 cGy, about three times the dose to the soft tissue.”¹
IGRT radiation dose: not straightforward

- Different imaging modalities distribute radiation dose in fundamentally different ways
  - kV photon energies stack dose toward the surface
  - 3D-kV imaging (e.g. CBCT) tends to spread dose uniformly throughout the volume
  - kV energies yield dose enhancement in bone
  - MV imaging is typically performed with the therapeutic beam, and so better characterized by standard measurements

- Vendors are continually improving algorithms and techniques to reduce imaging dose burden
Disclaimers:

- Published reports include a wide array of measurement types and dosimetric quantities.
- In order to estimate risk (i.e. risk to populations), we really should consider effective equivalent dose\(^1\).
- Delivered dose indicators reported by scanning software (e.g. CTDI) are measured for standard phantoms not actual patient anatomies.
- Delivered imaging doses vary extensively between vendors, scan protocols, and software versions.
IGRT radiation dose: definitions

- **Absorbed dose**: amount of energy absorbed by a unit mass of tissue (Gy)
- **Air Kerma**: kinetic energy released in the material by indirectly ionizing radiation (J/kg)
  - Virtually the same as dose for kV energy levels
- **Equivalent dose**: utilizes quality factors to compare biological effects of different types of radiation (Sv)
  - Quality factor is unity for photons and electrons
- **Effective dose**: estimates degree of harmful effects on the human body (Sv)
  - Each type of tissue is assigned a weighting factor, then all organ doses are summed to produce effective dose
IGRT radiation dose: approximations

- MV imaging pair\(^1\): 2-8 cGy (effective 2-20 mSv\(^2\))
IGRT radiation dose: approximations
IGRT radiation dose: approximations

- **MV imaging pair**: 2-8 cGy (effective 2-20 mSv²)
- **kV planar image**: 0.03-3 cGy
- **kV CBCT**: Skin dose of 8-10 cGy *
  - Mean dose of 5-7 cGy *
  - * Might be a factor of two to ten less...
- **MV CBCT**: 5-20 cGy
Straight comparison to *therapeutic* dose is flawed:

- Imaging dose is often highly distributed to normal tissues, not the intended target
- Imaging dose also has the capability of exceeding OAR tolerances if optimized to max out the tolerances with the therapeutic dose delivery
“Deterministic” effects have an onset threshold and severity increases with increasing dose

- Think QUANTEC here...
- Erythema (early) → 200 cGy (2-24 h)
- Temporary epilation → 300 cGy (1.5 wks)
- Erythema (main) → 600 cGy (3 wks)
- Permanent epilation → 700 cGy (3 wks)
- Skin necrosis → 1500 cGy (1 yr)
- Lens opacity → 100 cGy (5 yr)
- Cataract → 500 cGy (5 yr)
IGRT dose: risk of future cancers

- “Projected cancer risks from computed tomographic scans performed in the United States in 2007”\(^1\)
  - 29,000 future cancers from 72 million annual CT scans
  - 30% of future cancers for ages 35-54 when scanned
  - 15% of future cancers for ages <18 when scanned
  - 66% of future cancers were among females
  - Mostly lung cancers and leukemia (also, colon, bladder, oral)
  - Modeled on BEIR VII and LNT model
IGRT dose: risk of future cancers

- “Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer”\(^1\)
  - Large variation in delivered dose between scan types
  - Median effective doses from 2 mSv to 31 mSv
  - Women are twice as susceptible compared to men
  - Risks doubled for 20 year olds, and halved above 60 years
  - Calculations based upon CTDI\textsubscript{VOL} (and DLP) to estimate effective dose, assuming “ideal” patient anatomy universally
Methods of IGRT dose reduction

- Consider every imaging choice on a case-by-case basis (age, sex, severity of disease, etc.)
- Choose scan parameters (i.e. protocols) based upon anatomical site and necessary soft tissue contrast
- Choose imaging modality based upon the \textit{minimum necessary} image quality\textsuperscript{1,2}
- Adjust field-of-view to minimize exposure
- Apply correct CBCT filter and use limited arcs
The influence of bowtie filtration on CBCT imaging dose and quality
What the piddles is a bowtie filter and how do I tie one?

...OR

What the piddles is a bowtie filter and how do I tie one?
Bowtie filtration

- Use of a bowtie filter in CBCT produces uniformity in image quality across the FOV and simultaneously reduces peripheral dose$^{1,2}$

Half-scan, full bowtie filter

Full-scan, half bowtie filter
Sources for IGRT planning and safety

- AAPM Task Group 75:
  - 6 steps that should be considered for each case during planning
The task group recommends that practitioners of IGRT use this survey information to do the following six things:

(1) In all IGRT treatments, compile a complete picture of all of the imaging procedures to be used before, during, and after treatment;

(2) Identify those image-guidance steps that can potentially be accomplished without the use of ionizing radiation;

(3) Configure the image acquisition systems to eliminate dose outside the required FOVs;

(4) Plan the imaging technique to be consistent with the image quality and information needed for the treatment decision being made;

(5) After arriving at an IGRT imaging scenario that eliminates un-needed dose and optimizes the required exposure, use the resources of this report to estimate the total effective imaging dose, from all sources, that the patient will receive;

(6) Evaluate the total dose patient-by-patient using guidelines for estimating stochastic and deterministic risk, with the understanding that the diagnostic imaging community relies on judgment rather than prescription in assessing individual exposure risk.
Sources for IGRT planning and safety

- AAPM Task Group 75:
  - 6 steps that should be considered for each case during planning

  - 10 guidelines for enhancing quality/safety of IGRT program
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<tr>
<th>Recommendation</th>
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<td>1. Establish a multi-professional team responsible for IGRT activities.</td>
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<td>2. Establish and monitor a program of daily, monthly, and annual QA for all new or existing IGRT sub-systems.</td>
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<td>3. Provide device- and process-specific training for all staff operating IGRT systems or responsible for IGRT delivery.</td>
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<td>4. Perform ‘end-to-end’ testing for all new IGRT procedures (from simulation to dose delivery) and document performance prior to clinical release.</td>
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<td>5. Establish process-specific documentation and procedures for IGRT.</td>
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<td>6. Clearly identify who is responsible for approval of IGRT correction decision and the process whereby this decision is made and documented.</td>
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<td>7. Establish and document site-specific planning procedures; specifically, the procedure for defining PTV margins. Link these planning procedures to IGRT procedures.</td>
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<td>9. Verify proper creation and transfer of IGRT reference data (PTV, OARs, DRRs, etc) to IGRT system.</td>
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<td>10. Establish a reporting mechanism for IGRT-related variances in the radiation treatment process.</td>
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GTV/CTV, gross tumor volume/clinical target volume; IGRT, image guided radiation therapy; PTV, planning target volume; OARs, organs at risk; QA, quality assurance; ROs, radiation oncologists.
Available in notes section: email for copy of presentation!
Questions?

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How do you know *when* to image?
Motion management: AlignRT

- No radiation dose and real-time tracking
“Barn owl”
Arie van’t Riet
“Chameleon”
Arie van’t Riet
“Frog”
Arie van’t Riet