Image-Guided Radiation Therapy (IGRT)

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Imaging in radiation oncology

<table>
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<th>ANATOMICAL</th>
<th>IGRT</th>
<th>MOLECULAR</th>
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<tr>
<th>BEFORE</th>
<th>DURING</th>
<th>AFTER THERAPY</th>
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DIAGNOSIS and STAGING
TARGET DEFINITION
EARLY TREATMENT ASSESSMENT
LATE
Tumor localization

- Multiple approaches for tumor or organ localization
  - Radiographic imaging
  - Fluoroscopic imaging
  - Tomographic imaging
  - Functional/molecular imaging
- Each method has its own strength and weakness
- Which one should be used?

Are radiographs enough?
Tumor in upper lobe can be seen on the radiograph

Courtesy of Vanderbilt-Ingram Cancer Center, Nashville, TN
Are radiographs enough?
Tumor in upper lobe hard to see on the radiograph

Courtesy of Vanderbilt-Ingram Cancer Center, Nashville, TN

Are radiographs enough?
Tumor in upper lobe hard to see on the EPID

Courtesy of Vanderbilt-Ingram Cancer Center, Nashville, TN
**Image guidance for IMRT**

- **Cone beam (non-rotational) IMRT**
  - Treating cone by cone (port by port)
  - Using dynamic MLC
  - Techniques:
    - Step-and-shoot (multiple static field) technique
    - Sliding window (dynamic MLC) technique
    - Modulated arc therapy (e.g., VMAT, RapidArc)

- **Image guidance** enabled by **cone beam CT** imaging systems
  - Varian – CBCT
  - Electa – CBCT
Image guidance for IMRT

- **Fan beam (rotational) IMRT**
  - Treating slice by slice
  - Using binary MLC
  - Techniques:
    - Serial tomotherapy
    - Helical tomotherapy
- **Image guidance** enabled by **spiral CT** imaging systems
  - Accuray (Tomotherapy) - MVCT

MVCT vs CBCT

- **Density Plugs**
- **Water**
- **+3% Contrast**
- **-6% Contrast**

**UW Tomotherapy Unit** vs **UW Trilogy Unit**
Dose of different techniques

- **Radiographic mode**
  - kV radiographs: 0.1 – 0.3 cGy
  - MV portal image: 3 cGy (or 6 cGy double exposure)

- **Fluoroscopic mode**
  - Depends on the time, but can be several 10 cGy

- **CT mode**
  - kV CBCT: 3 cGy (depends on the object size and settings)
  - MV CT: 3 cGy (depends on the object)

Imaging guidance and tumor coverage

Courtesy of Lei Dong, Scripps Proton Therapy Center, San Diego, CA
### Types of image-guidance

<table>
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<tr>
<th>System Configuration</th>
<th>Floor Mounted System</th>
<th>Room Mounted Systems</th>
<th>Gantry Mounted Systems</th>
<th>Integrated Systems</th>
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<tbody>
<tr>
<td>Manufacturers</td>
<td>Varian-GE Siemens</td>
<td>BrainLab Accuray</td>
<td>Elekta Varian</td>
<td>Accuray/TomoTherapy</td>
</tr>
<tr>
<td>Radiography</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Imaging Capabilities</td>
<td>Fluoroscopy</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Tomography</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Floor-mounted systems

GE/Varian system
**Room-mounted systems**

Accuray Cyberknife

BrainLab Novalis

**Gantry-mounted systems**

Trilogy™ (Courtesy Varian Medical Systems)
Integrated system

Inter-fraction motion
(A/P prostate motion – from lateral EPID)
Intra-fraction motion
(A/P prostate motion – from lateral EPID)

- Non-periodic:
  - Patient movement
  - Physiological factors
    - Peristalses
    - Bladder and rectal filling

- Periodic:
  - Respiration
  - Cardiac
Intra-fraction motion: non-periodic

Significant shifts of ~3 mm (1σ) over 20 minutes

Intra-fraction motion: periodic

Heterogeneity  Motion  Combined

Patient B

Patient A

Rosu et al, Med Phys 34(4), 2007, 1462
Intra-fraction motion: periodic

- **Main approaches:**
  - Breath-hold (not image-guided)
  - Gating
  - 4D

- **Management:**
  - Imaging
  - Planning
  - Delivery

**Imaging: Gated CBCT**

- CT
- CBCT Free breathing
- CBCT Breath hold
**Imaging: 4D CT**

Conventional vs. 4D CT imaging of a tumor.

*Courtesy of Paul Keall, University of Sydney, AU*

**Imaging: 4D CT artifacts**

Regular breathing vs. Irregular breathing artifacts.

*Courtesy of Bill Loo, Stanford University, CA*
Imaging: 4D CBCT

CBC T

CT

7.1 cGy, 125 kV, 50 mA, 20 ms, 2730 projections

5 cGy, 120 kV, 100 mA, 500 ms

Courtesy of Tinsu Pan, UT MD Anderson, TX

Inter-fraction motion

- Van Herk & Remeijer modeled population based setup margins requirement \( \approx 2.5 \Sigma + 0.7 \sigma \)
  
  - **Systematic error** (\(\Sigma\)): average displacement of a target position relative to its position at simulation.
  
  - **Random error** (\(\sigma\)): variation of target position about its mean value.

\[
\Sigma \to 0 \quad \sigma \to 0
\]
Ways to reduce geometric error

- Precise initial set up and immobilization $\sigma$
- Image the target and shift (adapt) $\sigma$
- Offline patient review after multiple fractions (trend analysis) $\Sigma$
- IGRT QA $\Sigma$

Residual errors for image-guidance

Zeidan et al., Int J Rad Oncol Biol Phys 67, 2007, 670
IGRT workflow

- **Prior to therapy:**
  - Patient is scanned in the treatment position defining a **reference CT**.

- **Every IGRT fraction:**
  - The patient is positioned on the treatment couch in the treatment room and aligned to the laser positions.
  - A **daily CT** (i.e., CBCT) is performed
  - Daily CT scan is registered to the reference CT to determine discrepancies.
  - The adjustments are sent to the treatment unit and the couch shifts automatically to compensate for the differences

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Tumor shrinkage - replanning

![Graphs showing tumor shrinkage over time for different patients](Kupelian et al, Int J Rad Oncol Biol Phys 63, 2005, 1024)
Conclusions

- **Deviations from static anatomy:**
  - Intra-fractional (motion, physiological)
  - Inter-fractional (set-up errors, anatomical changes)

- IGRT aims at reducing this by employing imaging during the treatment process:
  - Radiography
  - Fluoroscopy
  - Tomography

- **Choice of appropriate IGRT technique** is very complex and non-trivial
Conclusions

- **Intra-fraction motion management:**
  - Gating: easier, less efficient, present
  - 4D: more complex, more efficient, future

- **Inter-fraction error management:**
  - Determination of individual institution statistical and systematic errors
  - Complex workflow
  - Several issues: inaccuracy, changed anatomy

- **Adaptive radiotherapy**