In-room Use of Volume Alignment
(Online Volumetric IGRT)

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Acknowledgement

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Learning Objectives:

• Learn about the rationales and procedures for in-room CT-guided radiotherapy.
• Suggest the design of computer-aided image processing algorithms.
• Demonstrate workflow and clinical applications.
Outline

• Rationale of soft-tissue volumetric imaging
• Workflow
• Manual alignment
• Automatic alignment
• Other factors for on-line applications
What is “Volumetric” Imaging?

- 3D representation of patient’s anatomy
  - Voxel-by-voxel
  - Both tumor target and critical normal structures
  - Potential for radiation dose calculation
- Equivalent to “CT simulation in a treatment room”
- Examples
  - CT-on-rails
  - Mega-voltage CT (tomotherapy)
  - Cone-beam CT (KV and MV)
  - MRI
  - US (?)
  - PET/SPECT
  - Digital Tomosynthesis
Ideal IGRT System?

  - 3D volumetric representations of soft tissue organs and tumors
  - Efficient acquisition and comparison of 3D volumetrics
  - An efficacious process for clinically meaningful intervention.
What are the main differences for 2D/3D alignments

• Direct soft-tissue target imaging
  – Alternatives: surrogates of the target:
    • Implanted fiducials
    • Bony alignment

• Unique identification of a 3D object
Example

- Traditional alignment assumes rigid-body for the entire H&N region
- Can you combine multiple 2D ROI for a 3D ROI?
  - $2 \times 2D = 3D$?

*Definition of individual Regions Of Interest (ROIs)*
Correlation of Setup Shifts between C2 and C6/PPM

Workflow
Online vs. Offline

- **On-line approach** makes treatment interventions based upon data acquired during the current treatment session
  - Speed
    - Simple image guidance: couch shifts
- **Off-line approach** is to determine treatment interventions from an accumulation of information that may be drawn from previous treatment sessions.
  - Predictable models
  - More comprehensive but infrequent corrections
    - Replanning etc.
A workflow diagram for in-room CT-guided adaptive radiotherapy
Expectations for Online Applications

• Speed
  – Patient is on the treatment couch
  – ~ seconds
  – Rigid-body alignment
  – Image guidance for patient setup

• Accuracy
  – Low alignment error
    • Fighting for every mm

• Robustness
  – High reliability and successfully rate
Manual Alignment

- The most reliable and intuitive approach for volume alignment
- Required for confirming the result of automatic alignment
- Subject to inter-observer subjectivity/variations
Methods for Manual Alignment

- **Image-based**
  - Direct comparison of two images
    - Side-by-side
    - Transparent color blending
    - Split view
    - Checkerboard

- **Feature-based**
  - Features (contours, fiducial points etc.) are extracted from the reference image and overlaid onto the daily image
Split View

A more accurate alignment  
Inaccurate alignment
Figure 1. A checkerboard method is often used for visual evaluation of image registration. In this example, the tomotherapy megavoltage CT image (MVCT) and the conventional kilovoltage planning CT image (kVCT) are shown in each checkerboard window. Image alignment is verified if the anatomy can extend smoothly from one window into another. Picture courtesy of Katja Langen, Ph.D., M.D. Anderson Cancer Center at Orlando, Orlando, FL.
Anatomy-based megavoltage CT (yellow) and kilovoltage CT (gray) registration. The soft-tissue interface between the prostate and its surrounding tissues was used for image registration.
An example of soft tissue target (prostate) alignment
The reference (planning) CT image is shown in (a); the initial alignment (using skin marks) is shown in (b)
The final aligned image is shown in (c).
Uncertainties in Manual Alignment

• Differences in Image Interpretation
  – Inter-observer variations
    • Differences in the interpretation of the same anatomy
    • Differences in the interpretation of features extracted from the same anatomy
    • Therapist’s alignment may not agree with physician’s contour

• Day-to-day variations
  – Organ deformation
    • What is the best compromise?
  – Intra-observer variations

• Techniques
  – The use of other viewing planes (sagittal, coronal, and axial) for 3D alignment

- 28 CTs evaluated by 7 observers
- Variations 0.8mm (RL), 2.0mm(AP), and 2.2mm(SI)
- Using a reference CT side-by-side
  - 0.7mm (RL), 1.0mm (AP), and 1.6mm (SI)

Intra-user variability
- 0.5mm (RL), 0.7mm (AP), 0.5mm(SI)
Different users consistently shift the contours anterior (e.g. □) or posterior (e.g. ●) to the mean.

Prostate Position Relative to Skin Marks

Systematic 1SD = 3.7 mm
Random 1SD = 3.3 mm
Prostate Position Relative to Skin Marks

Systematic 1SD = 3.3 mm
Random 1SD = 2.0 mm
Prostate Position Relative to Skin Marks

Systematic 1SD = 2.4 mm
Random 1SD = 2.8 mm
Reducing Inter-observer Variation By Using Direct Image Comparison

  – Comparison of image-based and contour-based alignment methods
    • Agreement is better in image-based alignments
    • 3mm accuracy can be achieved in 97% (RL), 52% (AP), and 76% (SI).
  – Fiducial markers (3) are more consistent for alignment
Automatic Alignment

- Direct image-based comparison
  - Soft-tissue target alignment
- More consistent
- Good image quality in volumetric CTs
- Good pixel accuracy or consistency
- 3D representation of an object
- Fast alignment (~ seconds)
Alignment Process

Planning CT

- Planning Contours
- Planning Isocenter

Treatment CT

- Treatment Image
- Treatment Isocenter
- Move Iso
- Move Couch
- $\Delta r$
- $-\Delta r$
Main Components in An Automated Alignment Process

- **Room coordinate system**
  - Where is the beam?
  - Isocenter (or reference point)
- **Alignment target**
  - ROI
    - Treatment target itself: prostate
  - Target surrogates
    - Bony structures: lung cancer
- **Cost function**
A diagram showing the volumetric CT-to-CT automatic registration process
Figure 3. A target ROI can be obtained from the contoured target in the treatment planning CT. The black line represents the delineated contours of the prostate and the seminal vesicles in one CT slice and the gray line represents an additional 5-mm expansion for the alignment ROI. The picture was originally published by Smitsmans et al (2004). "Automatic localization of the prostate for on-line or off-line image-guided radiotherapy." Int. J. Radiat. Oncol. Biol. Phys. 60(2): 623-635.
Example of Alignment Target

Cone-beam CT

Planning CT
Cost Function = Similarity Measure

• Feature based
  – Automatic feature extraction:
    • fiducial points, bony patterns etc.
    • The distance between features, such as points, curves, or surfaces of corresponding anatomical structure.

• Intensity based
  – Intensity differences or ratios
  – Cross correlation
  – Mutual information
The Role of Image Filter

- Image filter is a pre-alignment image processing step
  - Image enhancement
    - Window/level adjustment etc.
  - Image processing with prior knowledge
    - Gas removal filter
    - Gas-fill filter
- Main goals for image filter
  - Improve the behavior of the cost function
    - Smooth surface
    - Well-defined minimum
    - Large attraction range
Image Filter For Prostate Alignment

- **Gas-removal filter** (Court and Dong 2003)
  - Remove pixels corresponding to the area of gas pocket
- **Gas-fill filter** (Smitsmans et al. 2004)
  - Fill gas with tissue-equivalent pixels
Correlation method

Unfiltered

Gas-removal filter

Ref

Daily

A

A

B

B

L

L

R

R
Mutual Information Filtered

CAT (Filtered)

Mutual Information

Pixel Intensity Difference
Filtered

Correlation Method

Pixel Intensity Difference

Pat01, CT23
Alignment Evaluation

- Daily Bladder as image
- Bladder in planning CT as contour overlay
- Prostate target is aligned with the CT image
- Bony Structure is off
- Variable rectal filling observed
Figure 5. An example of soft tissue target (prostate) alignment using a fully automatic image registration technique. The reference (planning) CT image is shown in (a); the initial alignment (using skin marks) is shown in (b); the final alignment after the automatic image registration is shown in (c). In this example, significant inter-fractional prostate movement exists, which caused severe offset for the bony anatomy after the prostate is aligned in (c).
Figure 6. The reference prostate and contour are shown in (a). Due to rectal gas filling, the computer automatic image registration aligned the anterior boundary of the prostate better after the “gas removal” filter in (b). However, a radiation oncologist believes that a better alignment of the prostate-rectum interface is more clinically important. Therefore, he manually adjusted the prostate position to his preference.
Prostate alignment example with large gas filling. Final shifts: posterior: 2.44cm; inferior: 0.8cm; left: 0.84cm.
### Results of Soft Tissue Target Localization (366 prostate alignments)

#### Table 3: Evaluation of CAT automatic soft tissue registration (differences in mm)

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Superior/Inferior</th>
<th>Right/Left</th>
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<tr>
<td></td>
<td>Ave</td>
<td>1SD</td>
<td>% =&gt; 3m</td>
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<tr>
<td>Pat01</td>
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<td>0.0</td>
<td>0.0%</td>
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<td>0.0</td>
<td>0.0%</td>
</tr>
<tr>
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<td>4.0%</td>
</tr>
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</tr>
<tr>
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<td>0.0%</td>
</tr>
<tr>
<td>Pat09</td>
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<td>0.0%</td>
</tr>
<tr>
<td>Pat10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Pat11</td>
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</tr>
<tr>
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</tr>
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<td>Pat14</td>
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<tr>
<td>Pat15</td>
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<tr>
<td>Total</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3%</td>
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</table>
Results of Bony Registration (366 pelvic bone alignments)

Table 4: Evaluation of bony alignment using CAT software (difference in mm)

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Superior/Inferior</th>
<th>Right/Left</th>
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<tbody>
<tr>
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<td>Mean</td>
<td>1SD</td>
<td>%&gt;3mm</td>
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<tr>
<td>Total</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0%</td>
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</tbody>
</table>
Successful Rate

- Success: defined as <= 3 mm between calculation and experienced human evaluation
  - 97.9% for soft tissue target (prostate)
  - 98.4% for bony registration (pelvic bone)

- 32 patients 332 CBCT alignments
- Importance of image quality
  - Collimated CBCT
    - 65% successful rate to 84%
  - Streaky artifacts due to prostate/rectum motion during CBCT acquisition
    - Alignment error (1SD)
      - 1.0 mm (RL)
      - 2.0-2.4 mm (SI)
      - 1.7-2.3 mm (AP)
Head & Neck Study

Significant daily setup variation was observed using 3D analysis
An example of increasing room inside a thermoplastic facemask due to tumor shrinkage as treatment progressing. Near the end of treatment, the lower neck was not centered on the headrest, presumably due to patient’s self-adjustment to the relatively “roomier” mask.
Head & Neck Cancers: Best ROI: C2

Palatine Process of Maxilla (PPM)
CT-to-CT Auto-Registration
(ROI image-based bony registration)

Result – Margins and Residual Errors

Reference

Daily after C2 align

Daily after C6 align

Daily after PPM align
PPM did not match after C2 alignment

Daily Treatment CT

Planning CT
C6 did not match after C2 alignment

Daily Treatment CT

Planning CT
Effect of Rotations

Pitch

Roll Example

Yaw Example

Planning

Daily

Planning

Daily

Planning

Daily
Summary of Head & Neck Study

1. A true 3D analysis of setup uncertainties was performed using CAT software.

2. Relative shifts among multiple ROIs are significant due to non-rigid movements of different bony parts and rotations.

3. A simple couch translation is impossible to correct all shifts in the H & N area, but C2 bony alignment is the best compromise.

4. Positioning mouthpiece is found effective in reducing SI motion for PPM.

5. No significant benefit is found when using S-board for reducing C6 motion (neck immobilization).

Zhang et al. 2006
Other Factors in Volume Alignment

- Correction for rotations
  - Small target
  - Large target
- Deformation
- Intra-fractional organ motion
Anatomic and Dosimetric Analysis of Intra-fractional Motion during an IMRT Treatment Fraction

A Melancon*, R de Crevoisier, L Zhang, J O'Daniel, D Kuban, R Cheung, A Lee, R Mohan, L Dong,

Univ. of Texas M. D. Anderson Cancer Center, Houston, TX
Before Treatment

After Treatment (20 minutes)

Contours overlaid from before treatment
CT images after bony registration

Before Treatment

After Treatment (20 minutes)
### Results

**Statistics of 45 patients**

<table>
<thead>
<tr>
<th>measurement</th>
<th>Mean</th>
<th>SD</th>
<th>p-value</th>
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<tbody>
<tr>
<td>Fraction Duration (min)</td>
<td>21.4</td>
<td>4.25</td>
<td>N/A</td>
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<tr>
<td>Rectal Volume Change (cc)</td>
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<td>18.32</td>
<td>0.02</td>
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<tr>
<td>Bladder Volume Change</td>
<td>124.9</td>
<td>78.87</td>
<td>0.00</td>
</tr>
<tr>
<td>Anterior Prostate Displacement (cm)</td>
<td>0.13</td>
<td>0.29</td>
<td>0.00</td>
</tr>
<tr>
<td>Anterior SV Displacement</td>
<td>0.12</td>
<td>0.41</td>
<td>0.03</td>
</tr>
<tr>
<td>Inferior Prostate Displacement</td>
<td>-0.07</td>
<td>0.26</td>
<td>0.04</td>
</tr>
<tr>
<td>Inferior SV Displacement</td>
<td>-0.15</td>
<td>0.29</td>
<td>0.00</td>
</tr>
</tbody>
</table>

- All measurements significantly different from zero with one-sided z test.
Volume Change of the Rectum for 45 patients

Gaseous Build-up

Patient #

Volume Change of Rectum in cc
Residual Error

- Do you reduce margins (to zero) for online CT-guided treatment?
  - Suggest 3-mm margin minimum for prostate target alignment
Summary of Learning Objectives:

• Learn about the rationales and procedures for in-room CT-guided radiotherapy.
• Suggest the design of computer-aided image processing algorithms.
• Demonstrate workflow and clinical applications.