Clinical Implementation of Image Guided Radiation Therapy using Cone Beam CT

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Acknowledgements

- Vivek Mehta, MD
- Jin-song Ye, MS DABR
- Kent McCune, CMD
- Daliang Cao, PhD
Outline

- IGRT and benefits
- Elekta Synergy KV CBCT (XVI) platform
- KV CBCT patient dose
- CBCT Data transfer – Elekta XVI / CMS Xio
- IGRT clinical application
- Treatment / correction strategies
Image-Guided Radiation Therapy

Frequent imaging during a course of treatment as used to guide radiation therapy

(It is *distinct* from the imaging using different modalities to enhance target and organ delineation in the planning of radiation therapy)
Sources of Treatment Uncertainties

- **Setup uncertainty**
  - Patient position

- **Internal organ motion**
  - Target and/or normal tissues may change relative to skeletal anatomy

- **Organ deformation**
  - Variation in size and shape of the target and normal tissues
Benefits of IGRT

**Improve precision and accuracy**
- Optimize PTV margins and verification of target location
- Reduce treatment complication
- Improve tumor control with minimal toxicity

**Adaptation**
- Correct and moderate setup errors
- Assess anatomical changes / adaptive correction

**Can also...**
- Broaden application of RT
- Alter treatment scheme (dose escalation, hypo-fractionation... )
Elekta Synergy CBCT Platform

- **Small FOV = 27 cm**
  - Center of panel in line with KV isocenter
  - All the object is in the image; can do half revolution

- **Medium FOV = 41 cm**
  - Panel offset 11.5 cm from iso
  - Image quality better in center than the outside
  - Require full 360 degree revolution

- **Large FOV = 50 cm**
  - Edge of panel in line with iso
  - Half of object in each image
  - Require full 360 degree revolution
## CBCT Scan Geometry

<table>
<thead>
<tr>
<th>Collimator Label</th>
<th>FOV</th>
<th>Nominal Axial Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S20</td>
<td>Small</td>
<td>26.0</td>
</tr>
<tr>
<td>M2</td>
<td>Medium</td>
<td>2.5</td>
</tr>
<tr>
<td>M10</td>
<td>Medium</td>
<td>12.0</td>
</tr>
<tr>
<td>M20</td>
<td>Medium</td>
<td>26.0</td>
</tr>
<tr>
<td>L2</td>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>L10</td>
<td>Large</td>
<td>12.5</td>
</tr>
<tr>
<td>L20</td>
<td>Large</td>
<td>26.0</td>
</tr>
</tbody>
</table>
# KVp, mA and ms

<table>
<thead>
<tr>
<th>KVp</th>
<th>70 - 150</th>
</tr>
</thead>
</table>
| mA  | ms 10 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 12 - 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 16 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 20 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 25 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 32 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100
     | ms 40 – 10, 12, 16, 20, 25, 32, 40, 50, 64, 80, 100, 125, 160, 200, 250
     | ms 160 - 100, 125, 160, 200, 250, 320, 400, 500 |
| ms  | 10, 12, 16, 20, 25, 32, 40, 160 |
CBCT Acquisition Geometry

- Full scan - 360 degree gantry rotation (Also allows half scan)
- ~ 5 frames per second
- ~ 2 min / gantry rotation (3.18°/s)
- Typical Exposure
  - 120 KVp
  - 25-100 mA
  - 10-40 ms
- 41 x 41 cm² FP image
  - 1024 x 1024 at 400 μm pixel pitch

Offset detector allows larger FOV
Grantry Mounted Cone-Beam CT

**Features**
- Soft tissue contrast
- Patient imaged in the treatment position
- Calibrated to machine MV isocenter
- 3D isotropic spatial resolution ($\geq 7$ lp/cm)
- Geometrically precise ($\leq 1$ mm)

**Limitations**
- Relative slow acquisition - about 2 minutes for a full scan
- Not diagnostic quality
  - Ring, streak, ghost & radar artifacts
  - Cupping
  - Outline reduction effect

* Elekta Synergy System
3D Spatial Resolution $\geq 7$ lp/cm

Low contrast visibility $\leq 2\%$

Transverse geometric accuracy $\leq 1$ mm
KV / MV Calibration

- MV images of a ball bearing are acquired at 4 gantry angles
- Adjust BB to MV isocenter
- KV images of BB are acquired (for $360^\circ$ gantry angles)
- KV “Flex Map” generated / stored
- Apply “Flex Map” table for CBCT
- KV/MV Isocenter: essential for CBCT imaging
Long Term Stability: FlexMap

12 calibrations over 9 mo.

Sharpe et al, Med Phys 33(1), 2006
Daily “End-to-End” QA for CBCT

- KV/MV coincidence
- Setup parameters: isocenter, lasers…etc
- Automatic image registration accuracy (< 2 mm & 1 deg)
- Automatic couch shifts accuracy (< 2 mm)
Image Registration (RCT/CBCT)

- Automatic Registration
  - Bone
  - Grey value

- Manual Registration
KV CBCT Patient Dose

Patient dose depends on

- **Beam quality**: HVL (KVp, filtration)
- **Tube output**: Reference (mR / mAs)
- **Scanning geometry**: SAD, FOV, # of projection
- **Technique setting**: mAs
- **Patient size** (Head, Pelvis...)
**CBCT Dose at Isocenter**

*Dose in cGy/ 640 mAs; FOV\(_x\) = 26 cm*

<table>
<thead>
<tr>
<th>Phantom Size: dia.</th>
<th>FOV(_z)</th>
<th>100 kVp</th>
<th>120 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm</td>
<td>10 cm</td>
<td>0.58</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>26 cm</td>
<td>0.80</td>
<td>1.5</td>
</tr>
<tr>
<td>16 cm</td>
<td>10 cm</td>
<td>1.52</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td>26 cm</td>
<td>1.9</td>
<td>3.2</td>
</tr>
</tbody>
</table>

D. Jaffray - PMH
# CBCT Dose in Rando® Phantom

(For 125 KVp, 80 mA, 25 ms – Varian standard settings)*

Total 26 organs measured

<table>
<thead>
<tr>
<th>Organ</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>H/N:</td>
<td>(Dose in cGy)</td>
</tr>
<tr>
<td>Skin (irradiated site)</td>
<td>6.7 ± 1.2</td>
</tr>
<tr>
<td>Bone marrow (is)</td>
<td>5.9 ± 0.8</td>
</tr>
<tr>
<td>Thyroid</td>
<td>11.1 ± 1.2</td>
</tr>
<tr>
<td>Esophagus</td>
<td>3.8 ± 4.4</td>
</tr>
<tr>
<td>Spinal cord</td>
<td>4.1 ± 3.6</td>
</tr>
<tr>
<td>Lens</td>
<td>6.2 ± 0.5</td>
</tr>
<tr>
<td>Thymus</td>
<td>11.1 ± 1.2</td>
</tr>
</tbody>
</table>

Effective dose: 10.3 ± 0.5 mSv

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* 1320 mAs (660 projections, 2 mAs per projection). 330 proj. typically for Elekta

Kan et al (2008), IJROBP, 70(1), 272-279
(CBCT dose for 125 KVp, 80 mA, 25 ms)

Chest: (Dose in cGy)
- Skin (irradiated site) : 6.4 ± 1.0
- Bone marrow (is) : 6.9 ± 0.5
- Breast : 4.7 ± 0.2
- Esophagus : 3.6 ± 2.6
- Spinal cord : 3.6 ± 3.2
- Heart : 6.7 ± 0.6

Effective dose : 23.6 ± 0.4 mSv

Kan et al (2008), IJROBP, 70(1), 272-279
(CBCT dose for 125 KVP, 80 mA, 25 ms)

Pelvis: (Dose in cGy)
- Skin (irradiated site) : 5.4 ± 1.4
- Bone marrow (is) : 4.2 ± 0.3
- Bladder : 5.3 ± 0.9
- Rectum : 4.0 ± 0.3
- Small intestine : 6.3 ± 0.3

Effective dose : 22.7 ± 0.3 mSv

Daily CBCT potentially increase secondary cancer risk by up to 2 – 4% (based on probability of 5 x 10^{-5} per mSv – ICRP 60)

Reduced mAs setting (40 mA, 10 ms) reduces doses to 1/5th

Kan et al (2008), IJROBP, 70(1), 272-279
CBCT Data Transfer - Xio to XVI

Need DICOM export setup
- Port number
- Application Entity Title
- Host Name ... etc

3D Reference data required for CBCT
- RT plan
- Structure contours
- CT data
CBCT Data Transfer - Xio to XVI

Export DICOM

Export To: FH_XVI
Host: fhxvi Port: 104
Application Entity Title: FH_XVI

WARNING! This export can transfer data to many applications. For all clinical uses, the user must verify correct transfer and interpretation. See the DICOM Conformance Statement in 'On-line-help' for more information on CMS data export.

OK CANCEL
Importing 3D Reference Data from the DIVT (in XVI)

DICOM 3D Import

DICOM Import Validation Tool

RT plan / structure / CT set are OK
No RT plan - hence no green tick before patient ID

Patient Details:
- Patient ID: 5
- Patient Name: 

RT Plan Details:
- No Plan

RT Structure Set Details:
- UID: 2.16
- Label: CT Plan
- Date: 10/2/2005
- Time: 06:48
- Instance number: 1
- Field: 1

CT Series Details:
- UID: 2.16
- Number: 1
- Description: 

Number of slices: 125
Cautions in Reference Data Import

- Correctly associate reference images and plan data with the correct treatment site?
  - Check the imported data are correct
  - Check the RT plan
  - Wrong plan (wrong isocenter in particular) could result in wrong treatment correction

- Optimize image registration and verify
  - Define appropriate alignment clipbox for image registration (“Bone” or “Grey value” registration)
  - Need to verify the registration quality
IGRT Clinical Application

Goals
Workflow
Correction Strategies
Margin Design
IMRT H/N
70/63/56 Gy in
35 fx

Shift caused by patient wearing a thick sweater

Table Correction (cm)
- Lateral: 0.02
- Longitudinal: 0.25
- Vertical: 0.09
Rectum

50.4 Gy in 28 fx
3 Flds

Table Correction (base on bone)
Lat:  -0.13 cm
Long: -0.24 cm
Vert: -0.13 cm
NSCLC

3DRT (64.8 Gy) + Chemo

Change in target volume after 45 Gy
Geometric Uncertainties

Population Based

Patient Specific

SI

Lat

Random Error (Blur dose)

Residual Error (Shift/blur dose)

Systematic Error (Shift dose)
• Reduction of setup errors (Σ, σ, non-stationary etc)
• Optimize treatment scheme (dose escalation, hypofractionation)

Goals

• Estimation
• Standard deviation multiple
• Bounding volume
• Margin recipes (van Herk’s 2.5Σ+0.7σ)
• Adaptive RT

Workflow

• Off-line
• On-line
• Adaptive

IGRT Clinical Application

Margin Design

Correction Strategies

Action level
Hybrid Off-line Correction Strategies
(Two Strategies – NAL and Running-Mean (RM))

Data from 4 Consecutive CBCTs are Analyzed.
Systematic Error Identified, and Corrections Implemented.
Action Level is typically 3 mm.

### NAL: CBCT 1 – 4 Fx

<table>
<thead>
<tr>
<th>Fraction Number</th>
<th>Imaging Method</th>
<th>Image Reg. Method</th>
<th>Setup Error (cm)</th>
<th>Systematic</th>
<th>Random</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>X Shift (+/-)</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y Shift (+/-)</td>
<td>-0.26</td>
<td>-0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z Shift (+/-)</td>
<td>0.36</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Repeated Imaging? (Y/N)</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2nd CBCT</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Residual Error (cm)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### RM: CBCT 1- 4, 5, 10…Fx

<table>
<thead>
<tr>
<th>Fraction Number</th>
<th>CBCT 1</th>
<th>CBCT 2</th>
<th>CBCT 3</th>
<th>CBCT 4</th>
<th>CBCT 5</th>
<th>CBCT 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic</td>
<td>0.1</td>
<td>0.2</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Random</td>
<td>0.12</td>
<td>0.07</td>
<td>0.26</td>
<td>0.04</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

Call Physics if random error exceeds 0.3 cm

### Notes
- CBCT 1-4 for NAL
- CBCT 1-4, 5, 10… for RM
- Systematic error greater than 0.3 cm triggers physics review.
- Action level typically 3 mm.
“equivalent” to NAL in this case
Motion-encompassing Treatment Strategy for Lung

Start with treatment planning using 4D-CT
Reconstructed Images from 4D-CT

A) Separate phases of tumor during respiration
B) Maximum intensity projection (MiP)
C) Minimum intensity projection (Min-iP)
D) Average intensity projection (Ave-iP)

4D-CT for Internal Target Volume

Use MiP for ITV delineation
5 mm expansion for PTV
Ave-iP for dose calculation
CBCT for setup verification

- Tumor “clipping” the PTV
- Setup correction based on bone registration
Additional “manual” shift to improve precision
Set-up Errors for Lung

- 22 NSCLC patients had daily CBCT IGRT
- Setup shifted when errors exceeded 3 mm
- Systematic & random errors and 3D displacement vector (DV) were analyzed retrospectively

<table>
<thead>
<tr>
<th>Direction</th>
<th>Errors (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>5.2 ± 3.2</td>
</tr>
<tr>
<td>ML</td>
<td>4.4 ± 2.7</td>
</tr>
<tr>
<td>SI</td>
<td>4.4 ± 3.4</td>
</tr>
</tbody>
</table>

DV = 9.9 ± 4.7 mm
Residual Setup Errors for Lung (NAL Strategy)

61% (for 5 mm error)

\[ DV = \sqrt{AP^2 + ML^2 + SI^2} \]
References

- Underberg et al, IJROBP, 63(1): 253-260, 2005
- Rietzel et al, IJROBP, 61(5): 1535-1550, 2005
Thank you for your attention