Cone Beam CT guided Radiotherapy

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• CBCT Acquisition & Reconstruction
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CT Acquisition

Conventional CT
- ‘Fan’ beam
- 1D detector
- 1 rotation = 1 slice

Cone-beam CT
- ‘Cone’ beam
- 2D detector
- 1 rotation = volume (many slices)
kV image guidance: not a new idea!

First isocentric Co-60 machine in Netherlands at NKI (1960)
First Prototype CBCT Guided Linac


6.5 cm
Available Cone Beam Systems

- Elekta Synergy™
- Siemens Artiste™
- Varian Trilogy™

Bench Top

C-arms
Acquisition and Reconstruction
Elekta Synergy Research system at NKI

Frame Rate: 5.4 fps; Acquisition Time: 1 - 2 min
Cone beam reconstruction

\[ V(x, y, z) = \int_{0}^{2\pi} W_2 \cdot \left( (W_1 \cdot p(\beta, a(x, y, z, \beta), b(x, y, z, \beta))) \ast g(a) \right) d\beta \]

\[ \text{dim}_x \ast \text{dim}_y \ast \text{dim}_z \ast N_{\text{proj}} \text{ computations: } 5 \times 10^9 \text{ for } 256^3 \]
Imaging Field of View
Field of View

Central detector position

$180^\circ + \text{fan-angle}$
Field of View: Offset Detector

Partially displaced detector position
Offset Detector

Partially displaced detector position
Offset Detector

<table>
<thead>
<tr>
<th>Panel Position</th>
<th>FOV</th>
</tr>
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<tbody>
<tr>
<td>Central</td>
<td>25 cm</td>
</tr>
<tr>
<td>Partially displaced</td>
<td>40 cm</td>
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<tr>
<td>Fully displaced</td>
<td>50 cm</td>
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</tbody>
</table>
Geometric Calibration and QA
Geometry: Flex calibration

- Calculate center of ball bearing for all gantry angles
- Generate Lookup table for U & V displacements
- Lookup table includes Set-up error BB
Geometry: kV to MV Isoc Calibration

Gantry & Collimator Angle: -180, -90, 0, 90, 180

Determine COG field edge & BB

Calculate mean setup error
QA Phantom
QA Geometrical Accuracy

Planning CT  \[\xrightarrow{\text{Match 3D}}\]  CBCT CT

same?  \[\xrightarrow{\text{Match 2x 2D}}\]
3D Imaging Performance and Artifacts
Sources of cupping and streaks

- Missing data (truncation)
  - Detector field of view 25 cm

- Scattered radiation
  - Extra signal not from local anatomy
  - Adds noise!

- Beam hardening
  - Attenuation of patient smaller than expected

- Ghosting
  - High exposure signal gives residual extra signal later
Scatter-to-primary ratio (SPR) in excess of 300% occur in lateral pelvic projection data occur for CBCT geometry.
Strategies for Scatter Management

- **Select**
  - Minimize FOV$_{cc}$ to minimize SPR
  - Optimize Air gap $\rightarrow 0.5 - 0.6$ m
  - Compensators (e.g. BowTie filters)
- **Reject**
  - Anti-scatter grid
- **Correct**
  - Scatter correction algorithm

*Courtesy Jaffrey Siewerdsen*
Scatter correction algorithm

Assumption: scatter uniform and proportional to average image intensity where there is patient in the beam

Boellaard et al. Two-dimensional exit dosimetry using a liquid-filled electronic portal imaging device and a convolution model
*Radiother. Oncol.* **44** 149-157, 1997
CBCT versus Fan Beam CT
Motion
Moving Gas

Smitsmans et al. Med Phys. 2005
Image quality

- Diet, given by a dietician based on the patients own insight, starting 7 days before treatment

- Mild laxatives: Magnesium-oxide tablets (1 gram) 2 nights before CT scan and during treatments

- No scans/treatments before 10 am
Moving structures are blurred over their trajectory
4D CBCT

Retrospective sorting of the projections before reconstruction yields 4D data
3D versus 4D CBCT

- 4D Data set
- 8 x 84 projections

- 3D Data set
- 670 projections
The ‘Amsterdam Shroud’ (Lambert Zijp)

Breathing Signal automatically extracted from projection data
Clinical Implementation
Clinical Implementation CBCT @ NKI-AvL

- First clinical images on July 9th, 2003
- Special team of 4 radiotherapy technicians
- Normal patient program during the morning
- Patients with extra CBCT in the afternoon
- Close cooperation with the physicists
Clinical Implementation CBCT @ NKI-AvL

8 months of validation and improvement of image quality (waiting for CE marking for intervention):

• Over 150 scans made to compare with EPID:
  • prostate, head & neck, lung, bladder, sarcoma, stomach and breast patient
• Different scan protocols were tested
  • Position of the detector
  • Variation in kV and mA
  • Variation in number of frames, by reducing gantry rotation speed
Current situation @ NKI - AvL

- Patient set-up is monitored with CBCT for most of our patient groups, using a decision protocol based on bony anatomy match

- Radiotherapy technicians perform the acquisition, registration and evaluation (bony anatomy)

- Soft-tissue registrations performed by dedicated radiotherapy technicians in close cooperation with physicists and physicians
Current situation (AvL)

June 2006
We have acquired:

- > 6500 CBCT scans
- On 3 Synergy systems
- > 700 patients
Archiving
Scenario I

- Online Protocol
  → 30 scans per day per machine
- Storing projections at high resolution \((1024^2)\)
  → 650 * 2 MB per image
- Storing high resolution scans (0.5 mm voxel size)
  → 256 – 625 MB per scan
- ~225 GB per machine per week
Scenario II

- Offline Protocol
  \(\rightarrow\) 10 scans per day per machine
- Storing projections at medium resolution \((1024^2)\)
  \(\rightarrow\) 650 * 0.5 MB per image
- Storing medium resolution scans (1 mm voxel size)
  \(\rightarrow\) 32 MB per scan
- \(~17\) GB per machine per week
Scenario III

- Offline Protocol
  → 10 scans per day per machine
- Storing no projections
- Storing medium resolution scans (1 mm voxel size)
  → 32 MB per scan
- ~1.5 GB per machine per week
Set-up Error
Bony Anatomy
Registration
Image analysis: comparison with reference image

Reference image (planning CT)  Localization image (cone beam CT)  Mixed image (not matched)
Automatic matching on region of interest built-in in Synergy system

By zooming in on a region of interest, any target can be accurately localized even if the anatomy changes shape.

Tumor in top of neck
Required table shift:
(-3.2, -1.5, -0.6) mm

Tumor in lower part of neck
Required table shift:
(+1.5, -3.2, -6.1) mm
Matching cone beam to planning CT on bone is highly accurate - example for lung treatment series - 10 days matched

Vertebrae are perfectly still

Estimated match accuracy << 1 mm SD, much better as EPID for lung
Can cone beam CT replace EPID?

- As CBCT acquisition is slower but alignment is faster
- Cone beam CT is matched more accurately
- Imaging dose is similar or lower

- Cone beam CT can safely replace EPID for bony anatomy setup corrections

→ We replaced EPID with cone beam CT
→ The collected data is used to develop soft tissue protocols
Adaptive Radiation Therapy (ART)
Principle

Adaptive Radiation Therapy (ART *) uses imaging information of the first few treatment fractions to re-optimize the treatment plan

⇒ reduction systematic error
⇒ reduction treatment margins
⇒ reduction dose to the rectal wall
⇒ reduction of rectal toxicity **

* Yan et al., IJROBP 50 (2001)
** Peeters et al., IJROBP jan. (2006)
ART treatment scheme

Conventional plan, 10 mm

Average prostate & rectum adaptive plan, 7 mm**

CBCT first 6 days

weekly monitoring treatment

**unpublished data: Tonnis Nuver (NKI/AVL)
Average prostate

Grey-value registration ⇒
\[ T_{AP} / T_{CC} / T_{LR} / R_{AP} / R_{CC} / R_{LR} \]

** Smitsmans et al., IJROBP 60 (2004)
Automatic prostate localization in CBCT (30 s)

Cone beam CT

Planning CT contours placed automatically

10 CBCT scans: automatic bone match

10 CBCT scans: automatic prostate match

help line (GTV+3.6 mm)

Smitsmans et al., IJROBP 2004, 2005
Monitoring the treatment

Visual assessment if the prostate + SV were inside average prostate + 7 mm

(PTV volume ART plan)
Variability of 4D CT Patient Models
Repeat 4D cone beam CT

<table>
<thead>
<tr>
<th>Original scans</th>
<th>Fused scans</th>
<th>Linked scans</th>
<th>Orthogonal view</th>
<th>Render view</th>
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<td>July 26</td>
<td>14</td>
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Shows respiration, tumor shrinkage and baseline position variation
Base line shifts

Tumor motion is very similar but occurs at very different places. Verification is essential for accurate treatment.
Local Rigid Body Registration
Visual Validation

[Image of medical imaging software interface with various settings and data entries]

- **Reference preset**
  - Scan
  - Align plane
  - Align point
  - Load
  - Save

- **Alignment**
  - Convert to correction
  - Automatically
  - 4D mask

- **Translation (cm)**
  - L-R: 0.23
  - A-P: 0.37
  - C-C: 4.47

- **Rotation (dg)**
  - L-R: 0.0
  - A-P: 0.0
  - C-C: 0.0

- **Couch shift (cm)**
  - Height
  - Lateral
  - Longitudinal

- **Readout**
  - -

- **Computed**
  - -
Multiple Targets

Misalignment of the primary target
Multiple Targets

Correcting alignment of the primary target
Multiple Targets

Correct alignment of primary target might misalign the nodes
Conclusions

• Organ motion limits accuracy of radiotherapy
• Cone-beam CT provides soft tissue contrast, is efficient and does not require moving or touching the patient
• (4D) CBCT provides a wealth of information (and a huge amount of data!)
• Dose needed for CBCT scan is considerably smaller than for standard EPID localization fields
• Image quality sufficient for image guidance
Conclusions

- Several soft-tissue and bony anatomy based protocols in routine clinical use
- Substantial investment and support of vendors required to enable advanced image guided protocols
- Image Guidance is potentially dangerous. Do not underestimate the residual uncertainties!
Delineation variation: CT versus CT + PET

CT (T2N2)  
SD 7.5 mm

CT + PET (T2N1)  
SD 3.5 mm

The beams will be pointed to the target the physician draws!

Steenbakkers et al Radiother Oncol. 2005