Adaptive Proton Therapy with CBCT

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Sensitivity of Proton Dose Distribution

- Protons have finite range
- Change in material composition along beam path → Shift in position of dose deposition

![Graph showing sensitivity of proton dose distribution]

- Repeat CT imaging or in-room CBCT needed throughout treatment course to monitor anatomic change

Impact of Anatomic Change

- Less optimal dose distribution degrades with time
- OAR doses may increase eg oral cavity
- Worse with IMPT compared with single field uniform dose technique

![Graph showing impact of anatomic change]
**Lung Anatomic Change**

Impact on dose distribution to target and organs at risk needs to be assessed

**Lung: Pleural Effusion, Atelectasis, Tumor Regression**

Anatomic change will impact proton range, periodic assessment during treatment is necessary

**Limitations of CBCT for Dose Calculation**

- Proton dose calculation is more sensitive to HU accuracy than photon therapy
- CBCT cannot be used directly for dose calculation unless HU accuracy is verified

If CT number is off by 100 HU, stopping power is different by 5%. For a 10cm range, error is 5 mm. Need error in water equivalent depth << Range uncertainty up to 3%.
Limitations of CBCT for Dose Calculation

- Inaccurate HUs
- Beam hardening and scatter artifacts (dark streaks between high density structures, cupping artifacts)

Motion artifacts (streaming)

Improving Accuracy of CBCT HUs for Dose Calculation

1) Histogram matching method

2) A priori CT based scatter correction – More accurate correction (CBCT_{corr})

3) Deformable Image Registration (DIR) approach - Deform planning CT to geometry of CBCT (virtual CT)
C. Veiga et al. IJROBP 95 3 (2016)
C. Veiga et al. IJROBP 95 3 (2016)
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Use one or combination of above methods

(1) Histogram Matching Method

- Replace cumulative value of CBCT HU histogram with SAME cumulative value of pCT histogram
- Apply rigid registration or DIR prior to histogram matching
- Scatter effects in CBCT as well as image artifacts may impact accuracy
(2) A priori CT Scatter Correction Method

\[ I_{\text{cor}} = I_{\text{raw}} - I_{\text{pred}} \]

From forward projection of prior image (eg pCT)

Subtraction of primary signal (no scatter) from raw projection with scatter

\[ I_{\text{cor}} = CF \times I_{\text{raw}} - I_{\text{sc}} \]  

Scatter corrected projection

CBCT with uniform scatter correction (traditional method)

CBCT\textsubscript{cor} with a priori CT based scatter correction

(3) Deformable Image Registration Method:

Virtual CT (vCT)

Deform planning CT to geometry of CBCT

Method works in most cases

Limitations:
1. Complex anatomical change not handled correctly by deformable image registration (DIR) software
2. Subtle changes in lung/tumor density not accounted for

Veiga et al, IJROBP 95 549 (2016)

Correction for Large Tumor Regression

Identify gross DIR errors between CBCT and vCT and replace HU with lung or tissue density

CBCT  vCT  Corrected vCT

Large tumor regression
Dose Analysis with vCT

Feasible to replace evaluation CTs with CBCT
IJROBP Veiga et al 2016

Impact to Organ at Risk

Mean heart dose 16.8Gy (pCT) vs 20.0 Gy (vCT)
Identify change in OAR dose

Comparison of Virtual CT with Rescan CT

WET: Water Equivalent Thickness from entrance of beam to target

Results of 20 patient study:

<table>
<thead>
<tr>
<th>Region of interest</th>
<th>WET_{max} (mm)</th>
<th>WET_{min} (mm)</th>
<th>WET_{50%} (mm)</th>
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</thead>
<tbody>
<tr>
<td>Distal surface</td>
<td>0.5±2.2</td>
<td>3.7±1.9</td>
<td>8±4</td>
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<tr>
<td>Proximal surface</td>
<td>1.1±3.9</td>
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<tr>
<td>PTV</td>
<td>0.4±2.1</td>
<td>3.4±2.0</td>
<td>7±4</td>
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- Mean difference in WET is about 1mm
- Possible to estimate shifts in range with 2 to 3 mm accuracy

C Veiga et al, IJROBP 95 549 (2016)
Head and Neck vCT

- vCT works well for head and neck
- Evaluated with a number of deformable image registration (DIR) algorithms (ANTS, Morphons, B-spline variants)

Comparison of vCT and CBCT Correction Dose Calculation

- High agreement of vCT and CBCT correction for proton range calculation for head and neck and prostate
- Between 95% and 100% of dose profiles agree to 3mm

Comparison of vCT and CBCT Correction

Anatomical inconsistencies between vCT and CBCT
Comparison of vCT and CBCT cor

<table>
<thead>
<tr>
<th></th>
<th>vCT</th>
<th>vCT with correction</th>
<th>CBCT cor</th>
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<tbody>
<tr>
<td>Head and Neck</td>
<td>✔️</td>
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Contours and HU
May have some local inaccuracies
Better than vCT
Best in accuracy

Dose
May have some local inaccuracies
Fairly accurate
Fairly accurate

On-Line or Off-Line Adaptive Therapy?

- Most anatomical change especially (weight, tumor response) is gradual → offline adaptation
- In some cases, on-line adaptation would be needed but is not practical (yet)

Summary:
- Periodic monitoring of anatomy using CBCT, evaluation CT is needed for proton therapy
- Virtual CTs (deformable image registration) can be used to estimate dose
- vCTs may have local errors for large anatomical change
- Offline adaptation triggered by CBCT