PATIENT/ORGAN GEOMETRY VERIFICATION IN EXTERNAL BEAM TREATMENT DELIVERY

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One of major impediments to ensure the accuracy of radiation delivery and to achieve treatment optimization is the inherent variability of patient and organ geometry over the course of radiation dose delivery. To overcome this obstacle, advanced imaging technologies to facilitate patient/organ geometry detection during treatment delivery are being rapidly developed. These technologies include MV portal imaging for detecting daily patient setup error, and on board ultrasound and CT imaging for detecting internal soft tissue motion. In addition, embedded radiomarker displacement monitored via on-line kV radiographic imaging, as well as body surface motion monitored using a CCD camera, have been investigated as surrogates for measuring inter or intra-treatment organ motion respectively.

In tandem advanced imaging technology, computer algorithms and software tools for measuring patient/organ geometric variation relative to the radiation beam have been developed. These algorithms can be divided into two groups: Group I for determining the rigid body motion of patient bony structure or inserted radiomarkers, and Group II mainly for determining the non-rigid body motion of patient soft tissues. Temporal variation of patient/organ geometry during radiation treatment has been classified, based on its statistic behavior, as a systematic variation and a random variation. The effects of these two variations on treatment planning are quite different, and the systematic variation is dominant factor. One should carefully examine the effects in relation to the treatment goal and clinical resources before selecting a method to correct and compensate for them.

The major goal of measuring patient/organ geometric variation can be twofold. The first is for treatment quality assurance, where patient/organ geometric variation identified from image feedback is corrected to ensure that the treatment can be delivered as pre-planned. Various methods of off-line and on-line patient/organ position correction have been proposed and some of them have been clinically implemented. Additional study of output residuals is critical and required to validate these correction methods. The second purpose of using image feedback is more proactive, whereby the feedback images are systematically applied in designing an optimal dose distribution so that treatment planning and decisions can be fully adapted to patient/organ geometric variation. Few strategies have been proposed, so far, and only for limited treatment sites. The major challenges in implementing an adaptive control strategy include image-based organ registration, organ subvolume position estimation, and beam intensity optimization. In addition, practical issue has heavily influenced the new developments on this subject.
Patient/Organ Geometric Variation in Radiotherapy Process

There have been numerous steps in a radiotherapy process, which potentially cause geometric discrepancy on patient/organ position between treatment planning and actual treatment delivery. In treatment simulation & planning, starting from patient positioning and ending at transferring treatment plan to radiotherapy machine, each step will introduce uncertainties in patient/organ geometry. On the other hand, most of the positioning steps will be repeated during the treatment delivery introducing the systematic variation and random variation in the patient/organ treatment geometry.

Patient/organ geometric variation can be best quantified using subvolume displacement in an organ of interest. Subvolume of an organ of interest has its single position in treatment simulation, and multiple positions in actual treatment deliveries. The difference between the mean of the treatment positions and the simulation position has been defined as the systematic displacement of the subvolume, meanwhile the standard deviation of the treatment positions has been used to represent the random displacement.
Organ geometric variation can be quite heterogeneous. The color map on this figure shows the distribution of random displacement represented using the standard deviation along the AP direction for a typical patient prostate and seminal v. Therefore, eventually we should expect a non-uniform CTV-to-PTV margin.

Dose deviation caused by organ geometric displacement is also dependent on the dose distribution itself. The figure shows a curve of dose profile (along the patient RL direction) in a lung cancer treatment. In this case, dose profile closed to mediastinal region has sharper gradient compared to the lung side due to the electron transport. Depending also on the dose prescription point, the dose gradient (pink) and dose curvature (blue) around the target edges will be different.

Dose deviation caused by subvolume displacement is mainly dependent on the dose gradient with respect to the systematic displacement, and the dose curvature with respect to the random displacement. Therefore, in this specific treatment, we can expect a larger margin required at target edge in the mediastinal side than the one in the lung side.
This figure shows the corresponding margins required to compensating for the random displacement alone for both lung and mediastinal sides of target edge. The margin is calculated based on the dosimetric tolerance of 0.1%. The results indicate that CTV-to-PTV margins can be quite different even patient/organ geometric variations are identical. CTV-to-PTV margins are treatment site and treatment modality dependent.

The effect of patient/organ geometric variation on physical dose deviation can be well determined using the systematic and random displacements alone. The figure on left shows two displacement distributions. The top one is a Gaussian type, and the second one is formed from a respiratory motion. The two distributions have quite different shape, however as long as they have the same systematic displacement and same standard deviation of random displacement, the corresponding CTV-to-PTV margin required (left figure) will be very similar.
Summary

- Effect of patient/organ geometric variation on treatment dose in an organ subvolume can be appropriately studied using 4 parameters, $\left(\bar{\mu}, \bar{\sigma}\right)$; $\left(\nabla D, \frac{\partial^2 D}{\partial x^2}\right)$

- CTV-to-PTV margin is dominated by the systematic displacement
- It is also treatment site and treatment modality specific

Detection Methodologies

<table>
<thead>
<tr>
<th>Method</th>
<th>Patient Setup</th>
<th>Internal Organ Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Anatomy Marker</td>
<td>UA, LE</td>
<td>X X</td>
</tr>
<tr>
<td>MVI Marker</td>
<td>LA, LE</td>
<td>X</td>
</tr>
<tr>
<td>KVI Marker</td>
<td>LA, ME</td>
<td>X</td>
</tr>
<tr>
<td>Gating with CCD &amp; Skin Marker</td>
<td>LA, HE</td>
<td>X</td>
</tr>
<tr>
<td>Ultrasound Imaging</td>
<td>LA, ME</td>
<td></td>
</tr>
<tr>
<td>MVCT</td>
<td>UA, LE</td>
<td></td>
</tr>
<tr>
<td>KVCT</td>
<td>UA, HE</td>
<td></td>
</tr>
</tbody>
</table>

* UA - Universally Applicable; LA - Limited Applicability
* LE, ME, & HE - Low, Moderate, & High Efficacy

Correction Methodologies

<table>
<thead>
<tr>
<th>Method</th>
<th>Translational Motion</th>
<th>Rotational Motion</th>
<th>Non Rigid Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move Couch</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Move Couch, Collimator, Gantry</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Adjust Beam Aperture Static</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Adjust Beam Aperture Dynamic</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Adjust Beam Intensity fluence</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Correction Strategies

- Offline
  - Reduce CTV-to-PTV margin by reducing the systematic displacement and customize individual margin
    - Limited measurements
    - Estimate the systematic and random displacements
- Online
  - Reduce CTV-to-PTV margin by reducing daily displacements
    - Perform measurement and correction before treatment delivery

Residuals

- Residual ($R_1$) caused by the calibration between an imaging device and dose delivery device
  - Ultrasound
    - WA Tome, et al, (UWM), Medical Physics, 2002
  - KV
  - Gating Device
    - GMageras, et al (MSKCC)
  - KV (CB) CT
    - C. Rowbottom, et al, (WBH), IJROB 2002
- $R_1 \leq 1$ mm

Residuals

- Residual ($R_2$) introduced by an indirect measurement
  - Marker position vs ROI?
  - Skin motion (gating) vs tumor position?
- Need more validation study
  - Multiple CT scans with markers
  - Inserted markers in tumor with skin motion
Residuals

- Residual ($R_1$) introduced by a measurement method
  - Center of mass displacement
    - Effect of rotation and deformation
        - ~10 degree (95% confidence) => 4-5 mm residual in AP direction at prostate apex and base
      - Rigid body transformation (2D)
        - Effects of out-of-plane rotations
          - P Remeijer, et la: IJROBP, 46:5, 2000
          - ~4 mm residual (95% confidence)
  - Rigid body transformation (3D)
    - Effects of organ deformation?
      - Ultrasound Imaging
        - J Lattanzi, et la: IJROBP, 43:4, 1999
        - 3+1.8 mm (A/P), 2.4+1.8 mm (LAT), 4.6+2.8 mm (S/L)

- Residual ($R_2$) caused by an estimation (offline)
  - Estimate the systematic and random displacements
    - The residual is dependent on the number of measurements & random feature
Residuals

• Residual ($R_5$) due to the limit of a correction method
  – Adjust couch position alone?
  – Adjust couch and collimator alone?
• Residual ($R_6$) due to the inaccuracy of a dose delivery device
  – MLC position
  – Dose output

Summary

• Patient/organ geometric verification by means of image feedback has two major goals, (a) treatment QA and (b) treatment optimization by adapting treatment plan to the feedback information
• No matter which measurement and correction methods are applied, we should always perform an intensive study to determine the potential residuals for proper margin design

Acknowledgement

My colleagues in William Beaumont Hospital
Marcel van Herk & Joos Lebesque in Avl/NKI
Gig Mageras & Michael Lovelock in MSKCC
James Balter & Dale Litzenberg in U Michigan
Gustavo Olivera & Wolfquang Tome in UWM
Vincent Khoo in Christie Hospital, UK