**AAPM 2009 Continuing Education**

Therapy - Panel Session - The Management of Motion: Technologies and Practical Limitations

4D Treatment Planning: Rationale, Methods and Significance

Mihaela Rosu, VCU

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**4D treatment planning: rationale, methods and significance**

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**Conventional CT - The issue**

- Image data have artifacts because of respiratory-induced motion

- Chain process
  - Inaccurate anatomical information
    - inaccurate dose evaluations
    - inaccurate dose-treatment outcome correlations

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**The “4D” solution**

- Image acquisition process that includes a temporal dimension
  (on the time-scale of the breathing period)
- Multiple image datasets

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**Questions**

*(assuming accurate 4D image data is available)*

- How to factor the more complete / accurate image data into dose calculations?
- How much image data is needed?
- How does dose change in 4D compared to 3D?
- What are the end-points of all this?
Questions

How much image data is needed?

How does dose change in 4D compared to 3D?

What are the end-points of all this?

Dose Mapping

(anatomy-based summation of doses)

Planning dataset
(will be used to score cumulative dose)

Any other dataset

Planning dataset

Any other dataset

Simple interpolation

\[ D_{Cumulative} = w_C D_C + w_C' D_C' \]

Finer interpolation

* When deformations occur, particularly if they are large and over high dose gradient regions:
Finer interpolation

\[ D_C' = \text{average}(d_1 + d_2 + d_3 + d_4) \]

\[ D_{Cumul} = w_C D_C + w_C D_C' \]

Grid size effects

Inhale doses mapped on the reference (Exhale) dataset

Energy transfer method

\[ D_{Cumul} = \frac{wE + w'(E_a' + E_b')}{m} \]
Methods comparison

- Direct Voxel Tracking and Energy Deposition Method compared to interpolation-based methods.
- Differences exist (high dose gradient regions) but decrease as voxel size decreases.
- Interpolation works with any dose calculation algorithm.
- The other methods, potentially more accurate, but require Monte Carlo dose engine.

**Practical considerations**

- Huge amount of image data available that requires increased storage space and time to contour.
- Simplified approaches available – e.g.:
  - MIP function available for automated ITV generation
  - Automated contour propagation
- Image registration is time consuming and the errors introduced and their propagation are still active research topics.

**4D planning work flow**

1. Create deformation fields (image reg.)
2. Define anatomy on Reference datasets
3. Define anatomy on other datasets
4. Create plan on Reference datasets
5. Create plan on other datasets
6. Map doses on Reference dataset
7. Eval. tx. metrics on Reference dataset

Adapted from P. Keall et al., PMB, 2004

**4D planning work flow**

1. Create deformation fields (image reg.)
2. Define anatomy on Reference datasets
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6. Map doses on Reference dataset
7. Eval. tx. metrics on Reference dataset

Adapted from P. Keall et al., PMB, 2004

**Practical considerations**

- Dose computations on multiple datasets is also time consuming.
- Unless Monte Carlo is used (any number of dose computations will require the same amount of time as one calculation).
- However, one Monte Carlo calculation still takes longer than a dose calculation performed with any other algorithm.
- Computational power increases continuously, execution time may drop significantly in the future.
Practical considerations

- 4D dose calculations are not available yet in the commercial planning systems
- One vendor has this capability available in a research version

All things considered...

- A number of investigations have focused on finding methods to simplify 4D computations while preserving a level of accuracy comparable to that otherwise offered by a full 4D dose computation.

Questions

How much image data is needed?

How to factor the more complete/accurate image data into dose calculations?

How much image data is needed?

How does dose change in 4D compared to 3D?

What are the end-points of all this?

How many datasets are needed?

- How many datasets are needed?
  - 11 Phases - Exhale
  - 11 Phases - AVE Phase

- How many datasets are needed?
  - 11 Phases - 6 Phases
  - 11 Phases - 2 Phases

* M. Rosu et al., Univ. Michigan
How many datasets are needed?

- Exhale
- Inhale
- 15-State
- 6-State
- 2-State (Sobek)

Inhale

Exhale

MidV – CT dose calculation

- Compute dose on MidV-CT, assume same dose for all phases, accumulate using deformation fields.

AVG-CT dose calculation

- AVG-CT – a synthetic image set created by averaging CT density over the entire breathing cycle ("smears" the density).
- Compute dose on AVG-CT, assume same dose for all phases, accumulate using deformation fields.
Trade-offs

- MidV and AVE-CT approaches
  - represent a simplification from the full 4D dose computation (Dose computed on one dataset only)
  - somewhat improved accuracy compared to calculation on time-average dataset only
- They still require image registration
- Decide between:
  - Gain in dose accuracy
  - Unknown/unclear effect of registration errors and their propagation and increased processing time required for image registration

Targeting the average location

- These studies suggest that using some “average” anatomy/location for planning could ensure sufficiently accurate dose evaluation with the least amount of user intervention.
- The “average” patient configuration requires minimal margin to ensure appropriate target dose coverage (D. Yan, M. Engelsman).

Questions

How to factor the more complete/accurate image data into dose calculations?

How much image data is needed?

How does dose change in 4D compared to 3D?

What are the end-points of all this?

Motion effects

“Cumulative” – “Static” (at Exhale)
Questions

How to factor the more complete / accurate image data into dose calculations?

How much image data is needed?

How does dose change in 4D compared to 3D?

What are the end-points of all this?

3D vs. 4D – U. Mich. experience – Lung

Iso-NTCP: change in prescription dose from EXHALE

<table>
<thead>
<tr>
<th>Patient #</th>
<th>3D vs. 4D</th>
<th>Dose (Gy)</th>
<th>Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.5</td>
<td>0.00</td>
<td>59.0</td>
</tr>
<tr>
<td>2</td>
<td>67.2</td>
<td>0.7</td>
<td>64.5</td>
</tr>
<tr>
<td>3</td>
<td>66.5</td>
<td>1.5</td>
<td>61.5</td>
</tr>
<tr>
<td>4</td>
<td>66.2</td>
<td>3.0</td>
<td>66.5</td>
</tr>
<tr>
<td>5</td>
<td>69.5</td>
<td>5.0</td>
<td>66.5</td>
</tr>
<tr>
<td>6</td>
<td>65.0</td>
<td>7.0</td>
<td>66.5</td>
</tr>
<tr>
<td>7</td>
<td>73.6</td>
<td>9.0</td>
<td>66.5</td>
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<tr>
<td>8</td>
<td>66.5</td>
<td>11.0</td>
<td>66.5</td>
</tr>
<tr>
<td>9</td>
<td>70.0</td>
<td>13.0</td>
<td>66.5</td>
</tr>
<tr>
<td>10</td>
<td>66.5</td>
<td>15.0</td>
<td>66.5</td>
</tr>
</tbody>
</table>

Each patient's dose and volume are shown in the table above. The Iso-NTCP indicates changes in prescription dose from EXHALE.

3D vs. 4D – MDACC experience – Target

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>3D vs. 4D</th>
<th>D99 (CTV)</th>
<th>D99 (PTV)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>57.0</td>
<td>6.00</td>
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<td>2</td>
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</tbody>
</table>

Each patient's D99 for CTV and PTV are shown in the table above. The figures for D99 are displayed in the graph showing volume percentage change.

Serial organs – hot spots may be clinically important in certain cases

- Maximum prescription dose allowed by an upper 5% limit in the esophagus NTCP for late toxicity
- Cumulative dose indicates increased probability for esophagitis above the upper bound as a result of motion/deformation

Rosu et al., Univ. Michigan

- Starkschall et al., IJROBP, 2009

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3D vs. 4D – MDACC experience – NT

- Doses to lung (large parallel organs) less sensitive to changes in doses emerging from motion and deformation.
- Substantial changes in doses to cord (serial organ) in two cases.

Starkach et al., IJROBP, 2009

Final remarks

- The aim of this presentation was to:
  - Review current approaches of computing 4D doses (full calculations and simplified methods)
  - Present some results from photon RT studies that compared “static” and “cumulative” doses
- Overall, improvements in patient specific geometrical conformality are achievable, thus potentially minimizing the chances for in-field target misses.
- Improvements in the dose computation accuracy are expected as well.
- However, treatment plan evaluators appear less impacted by motion effects. Certain scenarios when 4D could be required have been highlighted.

A number of important aspects have been left out:

- Residual imaging errors/artifacts
- Registration errors
- Optimal margin definition
- Variations in patient model during treatment
- 4D in SBRT
- 4D in proton therapy
- ...

although these issues have already been addressed to a certain extent in studies in the recent years.

Future?

Has “4D research” reached a “plateau”?

- No -
  - … but, while we refine our way of managing breathing effects through 4D treatment planning, we should perhaps focus also on:
    - evaluating whether the clinical outcomes improve
    - better identifying those scenarios where the whole effort is truly justified.