Dealing With Intra-Fraction Motion an IMPRACTICAL Evaluation

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Thank you Gig and Marcel!
- Took care of most of practical intrafraction motion management issues
This is a Physics Conference
- Lets have some physics and math!
- Impractical issues
Breathing Motion Modeling
ViewRay
If you want the practical stuff, read the chapter in the book…
Radiotherapy Time Scales

Intra-fractional time scale
- respiratory, cardiac motion
- digestive system motion
- bowel/bladder filling

Inter-fractional time scale
- random/systematic setup errors
- weight gain and loss
- tumor growth and shrinkage

Adaptive Radiotherapy
- Motion Management
- Registration

Thanks Rock!
The Clinical Challenge

Accurately deliver ionizing radiation to the dynamic patient
Breathing

- Understand breathing motion, understand breathing patterns

Breathing

- Quasi-voluntary function
- Breath hold possible
- Modification of breathing pattern possible
- Multiple “sources” of breathing
  - Diaphragm
  - Chest Wall
  - Mixing of these motions complicates breathing characterization
Motivation

- Image Artifacts
  - Clinical Consequences
  - Dose Consequences
- Dose Artifacts
- Margin Considerations
- Geographical Misses
Why is Quantitation Important?
Breathing motion increases the apparent size of the tumor
- Increases portal sizes
- Increases normal organ irradiation
Tomotherapy Example

- Measured beam profiles
- Convolve breathing motion + couch with dose profile
- Model breathing motion as product tidal volume $\times$ conversion factor (mm/ml)
- Vary conversion factor from 0 (no breathing) to 20 mm
- Subtleties in breathing pattern profoundly affect dose!
Profile Example (1 cm field)

- No Breathing Motion
- 15 mm Breathing Motion
- 0-15 mm Breathing Motion
Max Dose Errors (52 patients)

Drift!

Breathing Magnitude
Measuring the Breathing Cycle

- Surrogates
  - Chest Height
  - Abdomen Distension
Breathing Cycle

- How do we define the “breathing” cycle?
- Quasi-periodic
- 2 Basic Methods
  - Amplitude
  - Phase Angle

Veedam, et al
Phase vs. Amplitude

Select mid-inspiration

Mid-inspiration defined by percentile tidal volumes

Mid-inspiration defined by time between exhalation and inhalation peaks

Lu et al
Characterization of Amplitude

- Amplitude allows for irregular breathing and baseline drift
- Can we characterize amplitudes to allow more quantitative use of the information?
- e.g. Can we use amplitude information to allow for extrapolation to deeper breaths?
$v_x$ = Volume at which patient had $v$ or less volume $x\%$ of the time
Irregular Breather
$V_{98}$ (93% of time) vs $V_{85}$ (80% of time)

Amount of Motion We Want to Know

Available 3D Image Datasets

Ratio 1.38 ± 0.19
Breathing Motion Characterization

- Have descriptions of breathing
- Tie into breathing *motion*
- 1) Observations
- 2) Model
- Model: What should it look like? What are the variables?
Tumor Trajectories: What The Model Has To Be Able To Do

Fig. 4. Orthogonal projections of the trajectories of the 21 tumors on (left) the coronal (LR-CC) and (right) the sagittal (AP-CC) plane. The tumors are displayed at the approximate position, based on the localization mentioned in the treatment chart. Tumors that were attached to bony structures are circled.

Breathing Motion Model

- Time is not an appropriate independent variable
- Describe one component of motion by inhalation depth – tidal volume $v$
- Pressure imbalances cause hysteresis
  - Pressure proportional to airflow
  - Airflow $f$ is second variable
- Assume tidal volume and airflow biophysics are separable
- Equation?
Mathematical “5D” Model

\[ \vec{X}(v, f) = \vec{X}_0 + \vec{\alpha}(\vec{X}_0)v + \vec{\beta}(\vec{X}_0)f \]

position of tissue at volume \( v \) and flow \( f \)
position at reference \( v \)
\( \alpha = \) ratio motion to tidal volume \( v \)
\( \beta = \) ratio motion to air flow \( f \)
a 0.62 mm, 1.50 mm  
b 0.70 mm, 1.11 mm  
c 0.72 mm, 1.05 mm  
d 0.66 mm, 1.19 mm  
e 0.66 mm, 1.32 mm  
f 0.42 mm, 0.82 mm
Examples of $\alpha$
Examples of $\beta$

Coronal

Sagittal
“All models are wrong, some models are useful” (George Box).

- Models are used to describe nature
- Models need to provide testable predictions
Predictions of Model Equation

- Apply continuity equation (mass conservation) to the model and see what happens

\[ \bar{X} = \bar{X}_0 + \bar{\alpha} \nu + \bar{\beta} f \]

where \( \nu \) is the tidal volume and \( f \) is the airflow

This equation, plus the “continuity equation” below

Divergence:
Amount quantity spreads out from a point

\[ \nabla \cdot \rho \bar{U} = -\frac{\partial \rho}{\partial t} \]

lungen tissue density velocity field
\[ \mathbf{\nabla} \cdot \rho \mathbf{U} = -\frac{\partial \rho}{\partial t} \]

\[ \rho \mathbf{\nabla} \cdot \mathbf{U} + \mathbf{\nabla} \rho \cdot \mathbf{U} = -\frac{\partial \rho}{\partial t} \]

\[ \rho \mathbf{\nabla} \cdot \mathbf{U} = -\frac{d\rho}{dt} \]
Replace time with Volume

\[ \rho \mathbf{\nabla} \cdot \mathbf{U} = -\frac{d\rho}{dt} \quad \mathbf{U} = \frac{d\mathbf{X}}{dt} \]

Time is not our dependent variable, but tidal volume is, so replace time with volume.

\[ \rho \frac{dv}{dt} \left\{ \frac{\partial}{\partial x} \frac{\partial x}{\partial v} + \frac{\partial}{\partial y} \frac{\partial y}{\partial v} + \frac{\partial}{\partial z} \frac{\partial z}{\partial v} \right\} = -\frac{\partial \rho}{\partial v} \frac{dv}{dt} \]

\[ \mathbf{X} = \mathbf{X}_0 + \alpha v + \beta f \]

All terms are constant wrt \( v \) except for \( \alpha v \)
Therefore

\[ \nabla \cdot \mathbf{\alpha} = -\frac{1}{\rho} \frac{d\rho}{dv} \]

Divergence of \( \alpha \) field is the relative change in density as a function of tidal volume

- We hypothesize that this will be sensitive to radiation damage

While hysteresis complicates the actual motion (and therefore the analysis of that motion), this approach removes the hysteresis effect even though the patient was free breathing.
Models Require Prediction

- We have the equation

\[ \nabla \cdot \vec{\alpha} = -\frac{1}{\rho} \frac{d\rho}{dv} \]

What if we add up all of the divergence (integrate) over lungs? Gauss’ law states:

\[ \int_{V} \nabla \cdot \vec{\alpha} \, dV = \int_{S} \vec{\alpha} \cdot d\vec{s} \]
Gauss’ Law

\[ \int_{V} \nabla \cdot \vec{\alpha} \, dV = \int_{S} \vec{\alpha} \cdot d\vec{s} \]

summation of all divergences

surface summation of alpha

\[ \alpha \]
Interpretation of Right Side: What does it mean to add alphas?

- Surface integral of the $\alpha$ vector:
  $$\oint_{s} \vec{\alpha} \cdot d\vec{s}$$

- Use geometric case to examine and provide insight as to what it means

Cylinder: Piston
Cylinder and Piston model

\[ Z = \frac{v}{A} \]

\[ \alpha = \text{piston shift } Z \]

\[ \alpha = 0 \]

\[ \int \vec{\alpha} \cdot d\vec{s} \]

\[ s \]

\[ \alpha = \text{ratio of motion to tidal volume} \]

\[ Z = \text{Volume change } v / \text{piston area } A \]
\[ \int \vec{\alpha} \cdot d\vec{s} = \alpha \int ds = \alpha \ A \]

\[ = \frac{1}{A} \ A = 1 \]

\( \alpha = 1/\text{area} \) (constant, pull out of integral)
Actually, Alpha is shift per Tidal volume (higher density)
So Surface integral = 1.11
This prediction is for all patients, scans, days, disease states, etc. Does this pan out? If we add all of the divergences of our alpha maps, is it 1.11?
Is it 1.11?

- Computed divergence of $\alpha$ for 35 patients and integrate:

$$\int_{V} \nabla \cdot \tilde{\alpha} \, dV = 1.06 \pm 0.14$$
What about $\beta$?

- Look at the ratio of “expansion” between $\alpha$ and $\beta$:

$$\frac{\int \beta f_{max} \cdot d\vec{s}}{\int \alpha v_{max} \cdot d\vec{s}} \equiv R$$

- Based on relationship between $\alpha$ and volume, and assumed independence of hysteresis to filling, hypothesize that $R = 0$.
\[ \frac{\int \vec{\beta} f_{\text{max}} \cdot d\vec{s}}{\int \vec{\alpha} v_{\text{max}} \cdot d\vec{s}} \equiv R \]

\[ \frac{f_{\text{max}}}{v_{\text{max}}} \frac{\int \vec{\beta} \cdot d\vec{s}}{\int \vec{\alpha} \cdot d\vec{s}} \equiv R \]

\[ \frac{f_{\text{max}}}{v_{\text{max}}} \frac{\int \vec{\beta} \cdot d\vec{s}}{1.11} \equiv R \]

\[ \frac{f_{\text{max}}}{v_{\text{max}}} \frac{\int \nabla \cdot \vec{\beta} dV}{1.11} \equiv R \]

\[ \frac{f_{\text{max}}}{v_{\text{max}}} \approx 1 \text{s}^{-1} \]
\[ \int \nabla \cdot \vec{\beta} \, dV \equiv R = 0? \]

\[
\frac{1.11}{\text{Mean} = 0.02!}
\]
Breathing Patterns
Breathing Patterns

Type 1

Type 2
### Breathing Patterns

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>FBVM</th>
<th>Amplitude (ml)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>36</td>
<td>1.35±0.09</td>
<td>285±147</td>
<td>5.0±1.9</td>
</tr>
<tr>
<td>II</td>
<td>13</td>
<td>1.33±0.14</td>
<td>208±70</td>
<td>3.4±1.0</td>
</tr>
</tbody>
</table>

FBVM = Free Breathing Variability Metric

\[
FBVM = \left( \frac{v_{98} - v_5}{v_{85} - v_5} \right)
\]
Hysteresis

- How big is hysteresis?
- What if we ignored hysteresis?
  - Amplitude-based models work perfectly
- Used 5D model to evaluate hysteresis magnitude

\[ \zeta = \frac{\text{Height}}{\text{Width}} \]
Intrafraction Real-Time Management?

- What modality can provide real-time motion management
  - In 3D
  - With no dose (e.g. unlimited)
  - No distortion or implant required
- MRI!
ViewRay

I am on their SAB
Switch to movie
0.35T MRI

3-Head Cobalt IMRT
Cobalt: REALLY?!
Cobalt, REALLY?

- 6 MV 71 beams
- Co60 71 beams
- 6 MV 7 beams
- Co60 7 beams
Prostate plans

- **6 MV, 71 beams**
- **Co60, 71 beams**
- **6 MV, 7 beams**
- **Co60, 7 beams**
Prostate DVHs

6 MV (solid), vs. Co60 (dashed)
7 beams

6 MV 71 (solid), 9 (dashed),
5 (dotted) beams
Sharp penumbra: For IMRT, Co60 penumbra is equivalent to linac

- Penumbra ~ 4.5 mm 80–20% @ 1 m
- 2-cm diameter cobalt source
- 100 cm SSD
- 1x1 cm² divergent Cerrobend block at 50 cm
- Cobalt beamlet from cylinder ~cosine dist.
- Radiochromic film measurement
Sharp penumbra: For IMRT, Co60 penumbra is equivalent to linac

Varian: 4.2 mm at isocenter projecting to 5.5 mm at 30 cm depth

Elekta and Siemens: 5 to 6 mm penumbra range

Co60 + low-field MRI at 0.3 Tesla in tissue (1g/cc)

MC shows essentially no distortion in tissue or water.
MFP for large angle collisions of secondary electrons much shorter than radius of gyration.
Co60 + low-field MRI at 0.3 Tesla in lung (0.2 g/cc)

MC shows very small distortion in lung density material
Co60 + low-field MRI at 0.3 Tesla in air (0.002 g/cc)

MC shows sizable distortion only in air cavities
Hot spots at interface are greatly diminished
Breathing Motion is complicated by irregular breathing cycles
- Two breathing patterns 1 (73%) and 2 (27%), impact gating efficiency

Characterize breathing motion requires a model

Hysteresis is typically small (<20%) of amplitude-based motion (e.g. a few mm)

MR-Guided RT shows great promise to monitor and control impact of intrafraction motion