Implementing New Technologies with quality and safety

3rd Annual Stereotactic Radiosurgery and Stereotactic Body Radiotherapy Symposium
17-18 October 2014
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Disclosures

- Dartmouth-Hitchcock Medical Center and Varian Medical Systems are parties to an evaluation agreement of the Varian 6DoF couch.
- No specific products are endorsed by Dartmouth-Hitchcock Medical Center.
- All human studies were approved by the Dartmouth IRB.
- No off label use.
- No animal studies.
Dartmouth-Hitchcock Medical Center
Are the outcomes of new technologies always positive?

- 1940’s – 1970’s Nasopharyngeal Radium Irradiation
- 1980’s Hyperthermia
- 1990’s Monoclonal antibodies (magic bullets)
- 1990’s BMT for breast cancer
- 2000’s Mamosite
- 2010 Radiation therapy accidents reported (IMRT, SRS, NYT)
Implementing new technologies with quality and safety

Or improve quality and safety of existing technologies.
Treatment sites

- Intracranial SRS as boost
- Intracranial SRS post surgical setting
- SBRT – Spine
- SBRT – Lung
Techniques

- Surgical frame SRS
- GTC frame SRS / SRT
- Open face mask
- Circular collimators
- Conformal Arc / VMAT
- Image guidance (IGRT)
- 4D delivery (gating)

**Intra-cranial**

**SBRT**
Systems at Dartmouth

- Planning
  - Varian Eclipse – VMAT
  - Philips Pinnacle – Cones

- Localization
  - BRW – intracranial
  - Vision RT – surface
  - CBCT – internal anatomy

- Delivery
  - Trilogy - Vision
  - TrueBeam 2.0; 6DOF couch; Vision

Aria R&V
Targets

- GTV - gross tumor volume
- CTV - clinical target volume
- ITV - internal target volume
- PTV - planning target volume
GTV defined by various image modalities
Image fusion for GTV definition

CT → Automated Fusion Software → MRI
Radiosurgery for brain metastases
Timing of cavity SRS

- Allow time for healing after surgery
- Allow time for cavity to collapse in order to treat the minimum volume
  - Note- toxicity is related to treatment volume
- Balanced against the risk of tumor growth in the interval- radiation most effective when minimal tumor burden
Cavities collapse

Post-op d1

Post-op d5

T2

T1 pre-Gd

T1 post-Gd

6.6cm³

2.5cm³
Cavities Expand

Post-op d1

Post-op d14

T2  T1 pre-Gd  T1 post-Gd

26.5cm³  11.5cm³
<table>
<thead>
<tr>
<th>Patients</th>
<th>41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resected brain metastases</td>
<td>43</td>
</tr>
<tr>
<td>Average age (y)</td>
<td>63 (range = 24-78)</td>
</tr>
<tr>
<td><strong>Histology</strong></td>
<td></td>
</tr>
<tr>
<td>NSCLC</td>
<td>18</td>
</tr>
<tr>
<td>Melanoma</td>
<td>7</td>
</tr>
<tr>
<td>breast cancer</td>
<td>5</td>
</tr>
<tr>
<td>rectal cancer</td>
<td>3</td>
</tr>
<tr>
<td>renal cell cancer</td>
<td>2</td>
</tr>
<tr>
<td>unknown primary</td>
<td>2</td>
</tr>
<tr>
<td>prostate cancer</td>
<td>1</td>
</tr>
<tr>
<td>small cell lung cancer</td>
<td>1</td>
</tr>
<tr>
<td>head and neck cancer</td>
<td>1</td>
</tr>
<tr>
<td>bladder sarcoma</td>
<td>1</td>
</tr>
<tr>
<td><strong>Average time between (d)</strong></td>
<td></td>
</tr>
<tr>
<td>MRI-2 and MRI-3</td>
<td>23.9 days (range 2-104 days)</td>
</tr>
<tr>
<td>MRI-3 and SRS treatment</td>
<td>5.5 days (range 1-18 days)</td>
</tr>
<tr>
<td>Surgery to SRS treatment</td>
<td>29.8 days (range 8-111 days)</td>
</tr>
<tr>
<td><strong>Surgical resections</strong></td>
<td></td>
</tr>
<tr>
<td>GTR</td>
<td>35</td>
</tr>
<tr>
<td>STR</td>
<td>8</td>
</tr>
</tbody>
</table>
Summary of cavity dynamics

- 20 cavities (46.5%) were stable in size as defined as a change of $\leq 2 \text{ cm}^3$
- 10 cavities (23.3%) collapsed by $> 2 \text{ cm}^3$
- 13 cavities (30.2%) increased by $> 2 \text{ cm}^3$
Cavity volume change depends on initial size

<table>
<thead>
<tr>
<th>Preop tumor size (largest diameter, cm)</th>
<th>Pre-op volume (cm³)</th>
<th>Post-op (cm³)</th>
<th>GTV(cm³)</th>
<th>PTV = GTV + 2mm (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 2.0 (n=8)</td>
<td>2.7 (1.5 – 5.0)</td>
<td>4.27(1.6 – 15.2)</td>
<td>5.0(0.8-12.2)</td>
<td>8.1(2.0-18.1)</td>
</tr>
<tr>
<td>&gt; 2.0–3.0 (n=13)</td>
<td>7.7 (2.4-16.3)</td>
<td>5.68(1.9– 4.6)</td>
<td>5.9(0.8-18.0)</td>
<td>9.5(2.1-25.5)</td>
</tr>
<tr>
<td>&gt; 3.0 (n=22)</td>
<td>22.3(10.5–52.7)</td>
<td>11.8(2.2 – 57.3)</td>
<td>11.8(1.2-42.8)</td>
<td>17.3(2.7-55.7)</td>
</tr>
</tbody>
</table>
Practice goals

- When medically appropriate, we will offer cavity SRS to patients immediately after surgical resection, during the same hospital stay
  - Eliminates the need for an additional MRI
  - Reduces outpatient clinic visits
  - Reduce the “lost to follow up” patients
  - Reduces the risk of tumor re-growth
    - Lead to the need for a second surgery
    - They may no longer be a candidate for SRS
SRS at Dartmouth (cones)

1990  
2006  
2013
SRS Immobilization

Surgical Frame
GTC frame (less frame)
Frameless
BRW coordinate system

\[ X_2 = D[1 - (q/Q)_2 \cos 60^\circ], \quad Y_2 = D(q/Q)_2 \sin 60^\circ, \]
\[ Z_2 = H[(q/Q)_2 - 0.5] + 8 \text{ mm}, \]
\[ X_5 = D\{[1 - (q/Q)_5]\cos 60^\circ - 1\}, \]
\[ Y_5 = D[1 - (q/Q)_5] \sin 60^\circ, \]
\[ Z_5 = H[(q/Q)_5 - 0.5] + 8 \text{ mm}, \]
\[ X_8 = D[(q/Q)_8 - 0.5], \quad Y_5 = -D \cos 30^\circ, \]
\[ Z_8 = H[(q/Q)_8 - 0.5] + 8 \text{ mm}. \]

\[ a_1 = [\frac{(y_2 - y_3)(X_2 - X_8) - (y_2 - y_8)(X_2 - X_5)}{T}], \]
\[ a_2 = [\frac{(y_2 - y_3)(Y_2 - Y_8) - (y_2 - y_8)(Y_2 - Y_5)}{T}], \]
\[ a_3 = [\frac{(y_2 - y_3)(Z_2 - Z_8) - (y_2 - y_8)(Z_2 - Z_5)}{T}], \]
\[ b_1 = [\frac{(x_2 - x_3)(X_2 - X_8) - (x_2 - x_8)(X_2 - X_5)}{T}], \]
\[ b_2 = [\frac{(x_2 - x_3)(Y_2 - Y_8) - (x_2 - x_8)(Y_2 - Y_5)}{T}], \]
\[ b_3 = [\frac{(x_2 - x_3)(Z_2 - Z_8) - (x_2 - x_8)(Z_2 - Z_5)}{T}], \]

where \( i', j', k' \) and \( i, j, k \) are the base vectors for the CT and

\[
\begin{pmatrix}
  j' \\
  k'
\end{pmatrix}
= 
\begin{pmatrix}
  a_1 & a_2 & a_3 \\
  b_1 & b_2 & b_3 \\
  c_1 & c_2 & c_3
\end{pmatrix}
\begin{pmatrix}
  j \\
  k
\end{pmatrix}.
\]
Pre-treatment QA
Isocenter check

0.8 mm
Patient specific localization QA

BRW Coordinates
Lateral (cm): −1.07
Ant–Post (cm): −2.93
Sup–Inf (cm): −3.58
Confirmation by imaging

Frame based: planar imaging | GTC or Mask: CBCT, 6DOF
GTC pre-treatment checks
Localization QA
Localization QA 2

Transversal - CT_SRS_BRW - 12/24/2013 09:52

<table>
<thead>
<tr>
<th>#</th>
<th>SRS X</th>
<th>SRS Y</th>
<th>SRS Z</th>
<th>Actual X</th>
<th>Actual Y</th>
<th>Actual Z</th>
<th>Dev. X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.29</td>
<td>-25.02</td>
<td>49.99</td>
<td>43.32</td>
<td>-25.02</td>
<td>49.59</td>
<td>-0.04</td>
</tr>
<tr>
<td>2</td>
<td>-43.32</td>
<td>-25.03</td>
<td>10.01</td>
<td>43.40</td>
<td>-25.03</td>
<td>9.55</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>49.98</td>
<td>30.00</td>
<td>0.09</td>
<td>50.02</td>
<td>29.53</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>-35.63</td>
<td>-50.02</td>
<td>-29.97</td>
<td>-66.80</td>
<td>-50.10</td>
<td>-30.43</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>86.59</td>
<td>-50.00</td>
<td>-49.95</td>
<td>85.59</td>
<td>-50.17</td>
<td>-50.42</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>-0.01</td>
<td>59.67</td>
<td>-9.98</td>
<td>0.16</td>
<td>99.97</td>
<td>-10.36</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

Sagittal - CT_SRS_BRW - 12/24/2013 09:52

Frontal - CT_SRS_BRW - 12/24/2013 09:52

Head First - Supine
Z: -1.00 cm

X: 0.00 cm

Y: 10.00 cm

Jump to Selected
Copy to Clipboard
Load Geometry from File
Close QA Mode

Dartmouth-Hitchcock
Norris Cotton Cancer Center

Geisel School of Medicine at Dartmouth
## Localization QA 3

<table>
<thead>
<tr>
<th>#</th>
<th>XPEV</th>
<th>YPEV</th>
<th>ZPEV</th>
<th>Actual X</th>
<th>Actual Y</th>
<th>Actual Z</th>
<th>Dev. X</th>
<th>Dev. Y</th>
<th>Dev. Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.20</td>
<td>-25.07</td>
<td>49.49</td>
<td>-0.20</td>
<td>-25.07</td>
<td>49.49</td>
<td>-0.06</td>
<td>0.06</td>
<td>0.29 mm</td>
</tr>
<tr>
<td>2</td>
<td>-3.32</td>
<td>2.93</td>
<td>30.01</td>
<td>-3.32</td>
<td>2.93</td>
<td>30.01</td>
<td>0.06</td>
<td>0.06</td>
<td>0.46 mm</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>45.81</td>
<td>30</td>
<td>0.09</td>
<td>50.02</td>
<td>30.53</td>
<td>0.08</td>
<td>0.08</td>
<td>0.46 mm</td>
</tr>
<tr>
<td>4</td>
<td>-26.85</td>
<td>-50.03</td>
<td>-25.07</td>
<td>-26.85</td>
<td>-50.03</td>
<td>-25.07</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.46 mm</td>
</tr>
<tr>
<td>5</td>
<td>4.53</td>
<td>-50</td>
<td>-30.01</td>
<td>4.53</td>
<td>-50</td>
<td>-30.01</td>
<td>0.06</td>
<td>0.06</td>
<td>0.46 mm</td>
</tr>
<tr>
<td>6</td>
<td>-0.02</td>
<td>55.97</td>
<td>-5.98</td>
<td>-0.02</td>
<td>55.97</td>
<td>-5.98</td>
<td>0.06</td>
<td>0.06</td>
<td>0.46 mm</td>
</tr>
</tbody>
</table>

**User:**
- **QA Phantom S/N:** 195
- **Analysis Date:** Tuesday, December 23, 2013 05:38:10 AM
- **Acquisition Date:** Tuesday, December 23, 2013 05:44:57 AM
- **Used Threshold:** 102
- **Version:** 3.2.13.0

**Statistics**

| Abs. pixel deviation (L, D) (Max, Avg) | 0.49 | 0.19 | mm |

**Phantom Fit:**

- **X [mm]:** -0.02
- **Y [mm]:** -0.03
- **Z [mm]:** -0.042
- **Roll [deg]:** 0.02
- **Pitch [deg]:** 0.01
- **Yaw [deg]:** 0.01
- **Bcrs [mm]:** 0.02

**Volume shearing X (corrected):** -0.02%

**Volume shearing Y (corrected):** 0.28%

**Original slice distance:** 1.25 mm

**Slew distance correction factor:** 1.003202

**Auto-Cut vote:**

<table>
<thead>
<tr>
<th>Avg. deviation (X, Y)</th>
<th>0.02</th>
<th>0.02</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. deviation (X, Y)</td>
<td>0.23</td>
<td>0.23</td>
<td>mm</td>
</tr>
</tbody>
</table>

**Predicted Statistics if using estimated pixel size**

<table>
<thead>
<tr>
<th>Original pixel size</th>
<th>0.039 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated pixel size</td>
<td>0.0394 mm</td>
</tr>
<tr>
<td>Estimated correction factor</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

| Abs. pixel deviation (L, D) (Max, Avg) | 0.48 | 0.18 | mm |

**Phantom Fit:**

- **X [mm]:** -0.06
- **Y [mm]:** -0.03
- **Z [mm]:** 0.01
- **Roll [deg]:** 0.01
- **Pitch [deg]:** 0.01
- **Yaw [deg]:** 0.01
- **Bcrs [mm]:** 0.06

**Transform:**
# Isocentricity - Trilogy

## Table Rotation Isocenter Test [Gantry Head Up and Collimator at Center Position]

Specification <= 0.75mm radius

<table>
<thead>
<tr>
<th>Table</th>
<th>Image</th>
<th>Deviation</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td><img src="image1.png" alt="Image" /></td>
<td>0.42&lt;br&gt;X: -0.41&lt;br&gt;Y: -0.11</td>
<td>Passed</td>
</tr>
<tr>
<td>135°</td>
<td><img src="image2.png" alt="Image" /></td>
<td>0.08&lt;br&gt;X: 0.05&lt;br&gt;Y: -0.06</td>
<td>Passed</td>
</tr>
<tr>
<td>225°</td>
<td><img src="image3.png" alt="Image" /></td>
<td>0.74&lt;br&gt;X: -0.23&lt;br&gt;Y: -0.70</td>
<td>Passed</td>
</tr>
</tbody>
</table>
### TrueBeam MPC

#### Beam Delivery
- **Value**
  - Isocenter: +0.34 mm
  - MV Imager Projection Offset: +0.21 mm
  - KV Imager Projection Offset: +0.29 mm

#### Processing
- **Value**
  - Output Change: +0.50 %
  - Uniformity Change: +0.66 %
  - Center Shift: +0.09 mm

#### Beam
- **Value**
  - MLC
  - Jaws
  - Rotation Offset: -0.27 °

#### Collimation
- **Value**
  - Gantry Absolute: -0.06 °
  - Gantry Relative: -0.08 °

#### Couch
- **Value**
  - Lateral: +0.10 mm
  - Longitudinal: +0.27 mm
  - Vertical: +0.08 mm

#### Display Scale:
IEC 61217 (Units shown are millimeters or degrees.)

---

**Dartmouth-Hitchcock Norris Cotton Cancer Center**

**Geisel School of Medicine at Dartmouth**
TrueBeam MPC 2

Trend-lines for all measured parameters
MPC 3

Induced failures
Uncorrelated errors add in quadrature

\[ \sqrt{BRW^2 + CT\ volume^2 + Gantry^2 + Couch^2 + OBI^2} \]

\[ \sqrt{0.19^2 + 0.3125^2 + 0.22^2 + 0.51^2 + 0.5^2} = 0.8\ mm\ (Trilogy) \]

\[ \sqrt{0.19^2 + 0.3125^2 + 0.31^2 + 0.2^2 + 0.3^2} = 0.6\ mm\ (TrueBeam) \]

Image matching uncertainty at treatment…
Frameless motivation

- Patient comfort
- Ability to plan ahead
  - IMRT/VMAT possible
  - Multiple lesions – single isocenter
- Image based setup VS mechanical / laser
6 DOF for frameless delivery systems

Trilogy with Vision 6DOF

TrueBeam with Varian 6DOF and Vision monitoring
Vision QA
Multiple lesions, single isocenter with RapidArc
RapidArc DVH
Shielding for fetus
# Fetal dose measurements

<table>
<thead>
<tr>
<th></th>
<th>Without lead</th>
<th>With Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Brain</td>
<td>6.5 mGy</td>
<td>4.4 mGy</td>
</tr>
<tr>
<td>3 Gy X 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RapidArc</td>
<td>6 mGy</td>
<td>2.2 mGy</td>
</tr>
<tr>
<td>12Gy – 18 Gy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Towards WYSIWYG in Rad Onc

• Can we devise a method to directly verify the correct dose is given to the correct place?
• Radiation is invisible
• Cherenkov emission is VISABLE
The Cherenkov effect – Physical origin

(a) Charged particle at rest

(b) Relativistic charged particle
The Cherenkov effect – light emission

\[ \cos \theta = \frac{AC}{AB} = c \]

\[ v_n = 1 \]

\[ \frac{dN}{dx} = 2\pi \alpha z^2 \left( 1 - \frac{1}{\beta^2 n^2} \right) \frac{1}{\lambda^2} \]

\[ \nu > \frac{c}{n} \]

Shock Wave

Probability

Wavelength (\( \lambda \))
The Cerenkov effect

Dose Production

\[ D = \frac{1}{\rho} \int \Phi \left( -\frac{dT}{dx} \right) dE \]

Cerenkov Production

\[ N = \frac{1}{\rho} \int \Phi \left( \frac{dN}{dx} \right) dE \]

*Strongest in the UV and blue*
Radiation induced Cherenkov Emission

Photograph of emission ring below water tank
Fluorescence randomizes emission direction.

Quinine sulphate (fluorophore)
Wavelength shifting

Quinine sulphate
(fluorophore)
Multiple Angle Beam Imaging

Images at different angles

Sinogram

Reconstructed 3D volume with FBP
3D Cherenkography of LINAC Beams

Square beam

Complex shaped beam
Parallel beam tomography

91 projections acquired every 2°
Exposure time: 18 sec.
Total scan time of < 30 min.
Resolution: 1 mm
Reconstructed volume: 10x10x10 cm³
IMRT and VMAT
Predicted versus measured
First imaging of Cherenkov emission from a human breast

- Whole breast radiotherapy with dynamic field.
- Real time monitoring and imaging (fps $\approx 2.5$).
First imaging of Cherenkov emission from a human breast

- Cherenkov emission shows correct beam field shape on body.
- Signal from entrance beam shows high superficial dose in axilla, where skin reactions are common.
- Signal from entrance and exit beams show high surface dose in inframammary fold and near the arm, where skin reactions are also common.
Stereotactic team

Alan Hartford, MD PhD
Lesley Jarvis, MD PhD
Phil Schaner, MD PhD
Benjamin Williams, PhD
Colleen Fox, PhD
Cherenkography Team

Adam Glaser
Rongxiao Zhang
Chad Kanick, PhD
Scott Davis, PhD
Whitney Hitchcock

Sergei Vinogradov, PhD
Brian Pogue, PhD
Colleen Fox, PhD
Lesley Jarvis, MD PhD

Audrey Prouty
Development Fund
“Sometimes you can get shown the light in the strangest of places if you look at it right.”

J. Garcia, R. Hunter
Spine Metastases

- Of cancer patients,
  - 40 – 85% with spinal mets at autopsy
  - 5% with MESCC (>20,000/year in U.S.)
- 95% extradural (mostly vertebral)
- Survival depends on histology, systemic disease, functional status
- Pain due to spine metastases is an important clinical problem
Traditional External Beam RT

- 2/3 patients have pain relief at 3 months
- Common fractionation schemes
  - 3Gy X 10
  - 2Gy X 20
  - 4Gy X 5
  - 8Gy X 1
- No difference in ambulatory rates, but local recurrences increased in short schedules
- Consider protracted schedules to avoid local recurrences given the consequences of a failure and difficulty with re-irradiation
- Common techniques
  - C spine: opposed laterals
  - T spine: PA or AP/PA
  - L/S spine: AP/PA
Traditional Tx field
Spine SRS plan
Spine SRS results

- From experience in brain - 85% local control
- Single day or few days of treatment
- Non-invasive
- Dose escalation while respecting spinal cord tolerance
- Decreased volume of treated bone marrow
- Improved pain control
  - Reported results of 80% pain control and 95% LC, compared to ~60% pain control with fractionated RT
Definition of target on CT

- 77 yo man, diagnosed with prostate cancer in 2003
- Initially treated with systemic therapy
- Disease became androgen resistant in 2008
- Received EBRT to prostate and pelvic LNs in 2008
- At initial consult: PSA 109, back pain, bone scan +T10 only, MRI showed involvement of anterior and posterior elements, and involvement of left foramina
RapidArc treatment plan
On board imaging prior to and during treatment
Spine treatment verification

**Trilogy**
- RapidArc delivered in three segments
- CBCT before each segment
- Out of plane rotations adjusted by patient setup
- Abort if motion detected
- 6 SRS
- Tx time ~45 min

**TrueBeam**
- Single RapidArc
- CBCT before treatment
- 6DOF couch used for setup adjustment
- Real-time marker detection during treatment.
- FFF
- Tx time ~20 min
Rotations of cervical vertebrae

<table>
<thead>
<tr>
<th></th>
<th>% vertebrae &lt; -3 degrees</th>
<th>% vertebrae &gt; +3 degrees</th>
<th>% vertebrae outside ± 3 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx rotation</td>
<td>0.6</td>
<td>3.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Ry rotation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rz rotation</td>
<td>1.0</td>
<td>0.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>
RPM used for lung SBRT

• Plan is prepared on gated scan
• Copied to non-gated scan to match CBCT
• Dose grid removed from non-gated scan to preserve intent
Gated treatment details

**Trilogy**
- RPM not integrated
- CBCT – normal mode
- SRS mode (1000) MU/min

**TrueBeam**
- RPM integrated
- CBCT (extra long)
- Gated fluoro
- Automated marker detection
- FFF (1400 – 2400 MU/min)