APPLICATION OF OPTICAL AND INFRARED IMAGING SYSTEMS FOR RESPIRATORY MOTION MANAGEMENT

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AAPM 63\textsuperscript{RD} ANNUAL MEETING
2021
DISCLOSURE

• I have no conflicts

• Prior motion management experience:
  • Varian RPM™ for 4DCT and DIBH CT simulation
  • Varian RPM™ and Respiratory Gating for treatment delivery with respiratory gating and voluntary inspiratory breath hold
  • VisionRT AlignRT® for treatment delivery with voluntary inspiratory breath hold

• Relevant prior treatment system experience:
  • Varian C-series and TrueBeam® accelerators

• References by name to commercially available products are for informational purposes only and do not constitute an endorsement by the speaker or the AAPM
OBJECTIVES

• Review methods to account for respiratory motion

• Review optical and infrared imaging technologies

• Discuss procedural considerations for the application of select imaging technologies for respiratory motion management
RESPIRATION

• Facilitates exchange of O\textsubscript{2} and CO\textsubscript{2} between blood and air

• Inspiration
  • Diaphragm contracts, moving inferiorly and anteriorly
  • Intercostal muscles contract, pulling ribs superiorly and anteriorly

• Expiration
  • Passive process
  • Diaphragm and intercostal muscles relax to resting position

• Hysteresis
  • Lung volume at given transpulmonary pressure is less during inhalation than during exhalation

RESPIRATORY MOTION

• 10-25% change in lung volume during respiration\(^1\)

• Approximately 3x-4x change in lung volume at DIBH\(^2\)

• Chest vs abdominal breathing
  • Abdominal breathing when expansion of abdominal circumference exceeds that of the chest by e.g., 10 mm\(^3\)


## ORGAN MOTION DURING RESPIRATION

### Table 2. Lung tumor–motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each cohort of subjects. The motion is in three dimensions (SI, AP, LR).

<table>
<thead>
<tr>
<th>Observer</th>
<th>Direction</th>
<th>SI</th>
<th>AP</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnes et al.</td>
<td>SI</td>
<td>18.5 (9–32)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Middle, upper lobe</td>
<td>SI</td>
<td>7.5 (2–11)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chen et al.</td>
<td>SI</td>
<td>(0–50)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Ekberg et al.</td>
<td>SI</td>
<td>3.9 (0–12)</td>
<td>2.4 (0–5)</td>
<td>2.4 (0–5)</td>
</tr>
<tr>
<td>Engelsman et al.</td>
<td>SI</td>
<td>(2–6)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Middle/upper lobe</td>
<td>SI</td>
<td>(2–9)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Lower lobe</td>
<td>SI</td>
<td>12.5 (6–34)</td>
<td>9.4 (5–22)</td>
<td>7.3 (3–12)</td>
</tr>
<tr>
<td>Ross et al.</td>
<td>SI</td>
<td>--</td>
<td>1 (0–5)</td>
<td>1 (0–3)</td>
</tr>
<tr>
<td>Middle lobe</td>
<td>SI</td>
<td>--</td>
<td>0 (0–16)</td>
<td>9 (0–13)</td>
</tr>
<tr>
<td>Lower lobe</td>
<td>SI</td>
<td>--</td>
<td>1 (0–4)</td>
<td>10 (0–13)</td>
</tr>
<tr>
<td>Grills et al.</td>
<td>SI</td>
<td>(2–30)</td>
<td>(0–10)</td>
<td>(0–6)</td>
</tr>
<tr>
<td>Hanley et al.</td>
<td>SI</td>
<td>12 (1–20)</td>
<td>5 (0–13)</td>
<td>1 (0–1)</td>
</tr>
<tr>
<td>Murphy et al.</td>
<td>SI</td>
<td>7 (2–15)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Plathow et al.</td>
<td>SI</td>
<td>9.5 (4.5–16.4)</td>
<td>6.1 (2.5–9.8)</td>
<td>6.0 (2.9–9.8)</td>
</tr>
<tr>
<td>Middle lobe</td>
<td>SI</td>
<td>7.2 (4.3–10.2)</td>
<td>4.3 (1.9–7.5)</td>
<td>4.3 (1.5–7.1)</td>
</tr>
<tr>
<td>Upper lobe</td>
<td>SI</td>
<td>4.3 (2.6–7.1)</td>
<td>2.8 (1.2–5.1)</td>
<td>3.4 (1.3–5.3)</td>
</tr>
<tr>
<td>Seppenwoolde et al.</td>
<td>SI</td>
<td>5.8 (0–25)</td>
<td>2.5 (0–8)</td>
<td>1.5 (0–3)</td>
</tr>
<tr>
<td>Shimizu et al.</td>
<td>SI</td>
<td>--</td>
<td>6.4 (2–24)</td>
<td>--</td>
</tr>
<tr>
<td>Sixel et al.</td>
<td>SI</td>
<td>(0–13)</td>
<td>(0–5)</td>
<td>(0–4)</td>
</tr>
<tr>
<td>Stevens et al.</td>
<td>SI</td>
<td>4.5 (0–22)</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>


### Table 3. Abdominal motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior–inferior (SI) direction.

<table>
<thead>
<tr>
<th>Site</th>
<th>Observer</th>
<th>Breathing mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shallow</td>
<td>Deep</td>
</tr>
<tr>
<td>Pancreas</td>
<td>Suramo et al.</td>
<td>20 (10–30)</td>
</tr>
<tr>
<td></td>
<td>Bryan et al.</td>
<td>20 (0–35)</td>
</tr>
<tr>
<td>Liver</td>
<td>Weiss et al. 80</td>
<td>13 +/- 5</td>
</tr>
<tr>
<td></td>
<td>Harauz et al. 90</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Suramo et al. 74</td>
<td>25 (10–40)</td>
</tr>
<tr>
<td></td>
<td>Davies et al. 64</td>
<td>10 (5–17)</td>
</tr>
<tr>
<td>Kidney</td>
<td>Suramo et al. 74</td>
<td>19 (10–40)</td>
</tr>
<tr>
<td></td>
<td>Davies et al. 64</td>
<td>11 (5–16)</td>
</tr>
<tr>
<td>Diaphragm</td>
<td>Wade 80</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Korin et al. 79</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Davies et al. 64</td>
<td>12 (7–28)</td>
</tr>
<tr>
<td></td>
<td>Weiss et al. 80</td>
<td>13 +/- 5</td>
</tr>
<tr>
<td></td>
<td>Giraud et al. 78</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Ford et al. 66</td>
<td>20 (13–31)</td>
</tr>
</tbody>
</table>

RESPIRATORY MOTION MANAGEMENT METHODS: MOTION ENCOMPASSING

- Slow CT
- Inhale/Exhale CT
- 4DCT
- Compression to restrict motion

4DCT

- Oversampled CT dataset with full 3D data at multiple respiratory phases
- Scan parameters dependent on patient respiratory pattern
- Identify free-breathing motion envelope of gross disease (ITV)

RESPIRATORY MOTION MANAGEMENT METHODS: RESPIRATORY GATING

- Delivery of radiation during imaging and treatment synchronized with patient’s breathing

- Planar radiographic imaging for prostate fiducial tracking, Gig Mageras

RESPIRATORY MOTION MANAGEMENT METHODS: BREATH HOLD

- Compared with free breathing technique for left breast RT, DIBH\textsuperscript{1}
  - ↓ heart V20, V40 and Dmean
  - ↓ lung V20
  - ↑ target coverage

- Compared with free breathing technique for lung SBRT, DIBH\textsuperscript{2}
  - ↓ lung V20, Dmean
  - ↓ PTV volume

- Compared with free breathing technique for RT of advanced lung disease, DIBH was clinically correlated with\textsuperscript{3}
  - ↓ acute pulmonary toxicity
  - ↓ late pulmonary, cardiac, and esophageal toxicity

RESPIRATORY MOTION MANAGEMENT METHODS: REAL-TIME TUMOR TRACKING

- Field-defining aperture tracks tumor motion during treatment delivery
- MLC tracking for motion management, Emma Colvill
- Motion tracking with MLC and jaw during tomotherapy delivery, X. Allen Li
TG-76 RECOMMENDATIONS

• Respiratory motion management should be used:
  • When motion exceeds 5 mm due to potential for imaging artifacts
  • When significant normal tissue sparing can be gained

• Consider possible future treatment when evaluating reduction in normal tissue toxicity

• PTV margins should consider:
  • Motion-induced imaging artifacts
  • Variability in respiratory pattern, breath-hold position, and residual motion
  • Uncertainty in relationship between tumor and surrogate position

## OPTICAL AND INFRARED IMAGING TECHNOLOGIES

<table>
<thead>
<tr>
<th>Infrared</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian RPM™</td>
<td>VisionRT AlignRT®</td>
</tr>
<tr>
<td>Varian Respiratory Gating/RGSC</td>
<td>C-RAD Catalyst™</td>
</tr>
<tr>
<td>BrainLab ExacTrac®</td>
<td>Varian Identify™</td>
</tr>
<tr>
<td>Accuray Synchrony®</td>
<td>BrainLab ExacTrac® Dynamic</td>
</tr>
</tbody>
</table>

INFRARED TECHNOLOGIES

• Reflectors placed on patient surface tracked during treatment

• Fast refresh rate

• Submillimeter spatial accuracy

• Reflectors must be visible throughout treatment
  • Verify visibility for treatment with couch kicks

• Motion tracking only available at location(s) of reflector(s)
RPM™/RESPIRATORY GATING

• Marker block

• Camera
  • Monitors respiration-induced motion of block
  • 30 Hz frame rate

• Control software
  • Extracts motion data from images of marker block
  • Distance calibration based on apparent separation between reflectors
  • Threshold motion amplitude to initiate tracking
  • Defines reference (i.e., baseline) position
  • Beam control

Images courtesy Varian
OPTICAL TECHNOLOGIES

- Structured light pattern or scanned laser light projected onto patient
- Cameras image reflected pattern
- Image of patient surface is registered to reference surface, and required transformations are reported
- ~5 fps
- Imaged surface must be sufficiently reflective
- Multicamera installations may have visibility impacted by treatment head or on-board imaging arms
ALIGNRT® SYSTEM COMPONENTS

• Cameras
  • Three pods, each with two stereoscopic cameras and projector

• Control software
  • Surface capture
  • ROI definition
  • Tolerance setting
  • Beam control

Images courtesy VisionRT
TG-76 QUALITY PRACTICE RECOMMENDATIONS

• Coaching and evaluation of patients (e.g., breathing regularity, breath-hold duration and consistency)

• Sanitization of devices that contact patients

• Backup planning scan at simulation if patient may not comply with motion management techniques

• Allow patient to practice breathing technique at start of treatment

• Daily imaging verification of correlation between surrogate and target to start treatment
  • No less than weekly imaging over course of treatment

4DCT SIMULATION WITH OPTICAL/IR IMAGING SYSTEM

• Displacement of patient surface used as surrogate for respiratory phase

• Installation of camera on couch allows camera to move with patient
  • Mounting camera to room wall or ceiling requires separation of couch motion from respiratory motion

• Be mindful of superposition of other motion patterns (e.g., cardiac motion)

• Provide patient instruction and evaluate breathing
  • Coaching can be used to improve regularity of breathing, but must be consistent with treatment
Fig. 3. Example of a respiratory trace for free breathing, audio instruction, and audio-visual biofeedback. A constant y-offset value has been added to the displacement values of each these traces to improve the clarity of the figure.
RESPIRATORY GATED TREATMENT WITH IR SYSTEM

• Set gating window to limit residual motion as determined from 4DCT

• Reproducible marker block position to limit changes to phase shift or correlation between respiratory signal and position of internal anatomy

• Daily imaging to verify correlation between respiratory signal and position of internal anatomy
  • 4DCBCT
  • Gated CBCT
  • Fluoroscopy

• Verify and monitor stability of exhale breathing position
DIBH SIMULATION

• Educate patient and evaluate compliance with DIBH technique

• Position IR marker box to maximize AP motion

• IR marker box should be level with couch surface for accurate displacement measurement
  • May require adjustment of box position or patient-specific shim

• Box position should be marked for reproduction during treatment
  • Additionally document in patient’s chart

DIBH SIMULATION

- Evaluate patient compliance
  - Breath-hold duration and stability
  - Reproducibility of breath-hold amplitude
  - Stability of exhale

- Evaluate anatomical reproducibility over repeated breath holds for margin determination
  - Use variable breath-hold delay to evaluate motion during breath hold
  - Select mid-position scan for treatment planning

BREATH-HOLD TREATMENT

Infrared

- Be mindful of monitored position if marker block differs from simulation
- Verify stability of exhale breathing position

Optical

- Use ROI robust to setup uncertainty and camera blockage
- Verify alignment of patient to free-breathing and DIBH surfaces

- Coach patients to encourage chest breathing
- Daily imaging to verify correlation of surrogate and internal anatomy
QA: TG-142

• Monthly
  • Output constancy with gated delivery
  • Beam control
  • Gating interlock
  • Functionality of in-room system

• Annual
  • Energy constancy with gated delivery
  • Temporal accuracy
  • Calibration of surrogate
  • Interlock testing


<table>
<thead>
<tr>
<th>Frequency</th>
<th>Test</th>
<th>Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily</td>
<td>Safety</td>
<td>Check interlocks and clear field of view for all mounted cameras</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>Static localization</td>
<td>Daily QA phantom positioned at isocenter and can track movement to isocenter from offset</td>
<td>2 mm</td>
</tr>
<tr>
<td>Monthly (in addition to daily tests):</td>
<td>Safety</td>
<td>Machine interface: Gating termination, couch motion communication</td>
<td>Functional</td>
</tr>
<tr>
<td></td>
<td>Static localization</td>
<td>Localization test based on radiographic analysis (i.e., hidden target)</td>
<td>2 mm/(1 mm SRS/SBRT)</td>
</tr>
<tr>
<td></td>
<td>Dynamic localization</td>
<td>Motion table or manual couch motion of monthly phantom by known distances</td>
<td>2 mm or less if manufacturer spec. Pass</td>
</tr>
<tr>
<td>Annually (in addition to all monthly tests)</td>
<td>Safety</td>
<td>Test/reset buttons, backup power supply, and emergency-off switches</td>
<td>Unchanged from previous &lt;2 mm over one hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System mounting brackets (all cameras are secure)</td>
<td>&lt;1 mm after stabilizing &lt;2 mm of isocenter (1 mm SRS/SBRT)</td>
</tr>
<tr>
<td></td>
<td>Integrity</td>
<td>Check camera settings if available</td>
<td>&lt;2 mm of isocenter</td>
</tr>
<tr>
<td></td>
<td>Stability (drift/reproducibility)</td>
<td>Drift Measurement (over at least 1 hour)</td>
<td>Functional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reproducibility (localization repeated several times)</td>
<td>&lt;1% change in localization Per spec.</td>
</tr>
<tr>
<td></td>
<td>Static localization (extensive)</td>
<td>Full end-to-end tests (with data transfer check of localization accuracy, etc.)</td>
<td>Functional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Translation and rotation auto correct over a clinical range of motion</td>
<td>&lt;1% change in expected dose Per spec.</td>
</tr>
<tr>
<td></td>
<td>Dynamic (gating system)</td>
<td>Using a motion phantom / check of gating system radiation dosimetry accuracy.</td>
<td>Functional</td>
</tr>
<tr>
<td>Commissioning:</td>
<td>Data transfer</td>
<td>From all systems in use</td>
<td>Functional</td>
</tr>
<tr>
<td></td>
<td>Safety (integration)</td>
<td>Communications with EMRs/other systems</td>
<td>&lt;1 mm change in localization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integration with Linac (radiation and interference)</td>
<td>Establish warm-up time</td>
</tr>
<tr>
<td></td>
<td>Stability (drift/reproducibility)</td>
<td>Drift measurement (over at least 1 hour)</td>
<td>Per spec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reproducibility (localization repeated several times)</td>
<td>&lt;1 mm after stabilizing</td>
</tr>
<tr>
<td></td>
<td>Dynamic localization</td>
<td>Latency test and update rates</td>
<td>Per spec.</td>
</tr>
</tbody>
</table>
SUMMARY

• Respiratory motion impacts positioning of target and critical volumes in the thorax and abdomen

• Amplitude of motion and critical organ sparing should be considered when evaluating use of motion management

• IR and optical system monitoring of patient surface can be used as surrogate for position of volumes moving with respiration