Image Registration for Radiation Therapy Applications: Part 2: In-room Volumetric Imaging

Peter Balter Ph.D
University of Texas M.D. Anderson Cancer Center
Houston, TX, USA
Disclosure Information
Peter Balter, Ph.D.

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Employee of
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I will **NOT** include discussion of investigational or off-label use of a product in my presentation.
QA: This is important, but I’m not going to talk about it.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Quality metric</th>
<th>Quality check</th>
<th>Tolerance</th>
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<tbody>
<tr>
<td>Daily</td>
<td>Safety</td>
<td>Collision and other interlocks</td>
<td>Functional</td>
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<tr>
<td></td>
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<td>Warning lights</td>
<td>Functional</td>
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<td></td>
<td>System operation and accuracy</td>
<td>Laser/image/treatment isocentre coincidence OR</td>
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<td></td>
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<td>Phantom localization and repositioning with couch shift</td>
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<td>Monthly or upon upgrade</td>
<td>Geometric</td>
<td>Geometric calibration maps OR</td>
<td>Replace/refresh</td>
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<td>kV/MV/laser alignment</td>
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<td>Couch shifts: accuracy of motions</td>
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<td>Image quality</td>
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<tr>
<td></td>
<td></td>
<td>Uniformity, noise OR</td>
<td>Baseline</td>
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<td>High contrast spatial resolution OR</td>
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<td></td>
<td>Low contrast detectability OR</td>
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<td>If used for dose calculation</td>
<td>Image quality</td>
<td>CT number accuracy and stability OR</td>
<td>Baseline</td>
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<tr>
<td>Annual</td>
<td>Dose</td>
<td>Imaging dose</td>
<td>Baseline</td>
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<tr>
<td></td>
<td>Imaging system performance</td>
<td>X-ray generator performance (kV systems only):</td>
<td>Baseline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tube potential, mA, ms accuracy, and linearity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geometric</td>
<td>Anteroposterior, mediolateral, and craniocaudal orientations are maintained</td>
<td>Accurate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(upon upgrade from CT to IGRT system)</td>
<td></td>
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<tr>
<td></td>
<td>System operation</td>
<td>Long and short term planning of resources (disk space, manpower, etc.)</td>
<td>Support clinical use and current imaging policies and procedures</td>
</tr>
</tbody>
</table>

Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

Jean-Pierre Bissonnette

Task Group 179, Department of Radiation Physics, Princess Margaret Hospital, University of Toronto, Toronto, Ontario, Canada, M5G 2M9
Learning Objectives

• Understand the registration between image guidance image set and treatment planning CT.
• Recognize the limitations and clinical applications of image guidance registration.
• Acknowledge the advantages and disadvantages for selection of ROI
  • Dose as an ROI
• Discuss requirements of communication and means of communication among the treatment team for IGRT.
In-room volumetric imaging

- Allows direct visualization of many type of tumors (but not all)
- CT-on Rails
- CBCT
- MVCBCT
- MVCT
Available technologies for in-room CT

<table>
<thead>
<tr>
<th>Make and model</th>
<th>Elekta XVI</th>
<th>Varian On-Board Imager</th>
<th>Siemens Artiste</th>
<th>TomoTherapy</th>
<th>Siemens Primatom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging configuration</td>
<td>kV-CBCT</td>
<td>kV-CBCT</td>
<td>MV-CBCT</td>
<td>MVCT</td>
<td>kVCT-on rails</td>
</tr>
<tr>
<td>Field of view</td>
<td>50 × 50 × 25.6</td>
<td>45 × 45 × 17</td>
<td>40 × 40 × 27.4</td>
<td>40 cm</td>
<td>50 cm</td>
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<tr>
<td>Correction method</td>
<td>Translation</td>
<td>Automatic couch motion</td>
<td>Automatic couch motion</td>
<td>Automatic in 2 directions</td>
<td>Manual couch motion</td>
</tr>
<tr>
<td></td>
<td>Rotation</td>
<td>Optional</td>
<td>None</td>
<td>Optional</td>
<td>Optional</td>
</tr>
<tr>
<td>Geometric accuracy</td>
<td>Submillimeter</td>
<td>Submillimeter</td>
<td>Submillimeter</td>
<td>Submillimeter</td>
<td>Submillimeter</td>
</tr>
<tr>
<td>Dose (cGy)</td>
<td>0.1–3.5</td>
<td>0.2–2.0</td>
<td>3–10</td>
<td>0.7–3.0</td>
<td>0.05–1</td>
</tr>
<tr>
<td>Image acquisition and reconstruction time</td>
<td>2 min</td>
<td>1.5 min</td>
<td>1.5 min</td>
<td>5 s per slice</td>
<td>3 s per sec</td>
</tr>
</tbody>
</table>

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In-room CT- Cone Beam CT

- X-ray tube and flat panel imager are mounted on the linac gantry
- In one rotation around the patient (1 min) 400 projection images can be acquired
- These can be reconstructed into a short CT volume
Acquisition – Head Scan

Physical aperture: 83 cm

Reconstructed Volume

17 cm

25 cm diameter
Cone Beam CT images
Acquisition – Body Scan

Physical aperture: 83 cm
14 cm
45 cm diameter

Reconstructed Volume
Cone Beam CT – Large GU patient (330 lbs)
Cone Beam CT can also be generated using MV x-rays (Example from a Siemens Machine)
In-room CT: CT-on Rails

- **CT-on-rails**
  - Diagnostic CT gantry
  - CT is modified to move the CT gantry rather than the patient.
  - Provides a diagnostic quality CT in treatment position
  - Ideal for low contrast (liver) tumors
  - Ideal for long tumors and/or breathhold
CT-on-rails vs. Cone Beam

< 5 min acquisition and reconstruction time

Patient is rotated into scanning position on treatment couch (lateral and vertical shifts required)

Isocenter not linked to images

Each slice is a 0.5 sec time average

50 cm FOV (full scan)

< 5 min acquisition and reconstruction time

Patient is imaged in treatment position (except for lateral shifts)

Isocenter defined in CT space

Each slice is a 60 sec time average

45 cm FOV half-scan
Breath-hold CBCT to improve image quality

• Some of the poor quality in current generation CBCT in the lung is due to breathing motion

• BH-CBCT can be used when performing SBRT on low contrast tumors or small tumors with large motion ranges
Localization of Images in space

• Current radiotherapy systems use DICOM-RT to define the location of images, isocenters, contours with respect to each other.

• Each radiotherapy plan has a “primary image set” that is used to define the coordinate system for all other objects.

• Other image sets can be used to assist in contouring
  • If these sets are from the imaging session they may share the DICOM coordinate set.
Data flow

- The reference CT for CT-CT matching needs to be chosen and communicated to the treatment console
- The reference structures as well
- The isocenter co-ordinates

Verification of all of these should be part of pre-treatment physics QA (Plan-Check)
Example data-flow in Pinnacle-MOSAIQ-Varian environment
Data Flow For IGRT at MDACC

Note: CAT is in-house 3D-3D match system
Localization of images in Space

- The CT is related to the treatment site via UID in the RT structure set.
- The localization of the CT to the isocenter is contained in 3 numbers that are easy to get wrong.
- CT setup should always be verified against some other system on the first day of treatment (we use MV ports are verification on our SBRT cases).
TPS DICOM export should send needed values to R&V system
CT coordinates can be looked up in the POI section of the planning window.

Plan checks in the IGRT world should (shall?) include checking isocenter coordinates and reference data set.
Localization of images in Space

• For patients with multiple isocenters there is more opportunity for error
Choice of Reference CT dataset

• If only 1 planning CT dataset – easy no choice
• If 4DCT
  • We use Average intensity projection since CBCT is nearly equivalent to an average CT due to the slow acquisition (1 breath cycle per 20 deg arc)
  • Mid-ventilation would be reasonable
  • MIP is good to provide contours but should not be used for planning or reference
• If breath-hold or gating
  • Should be reference image taken from BH or the central phase of the gating window
Clinical applications and Limitations of CT localization

Applications

- IGRT
  - Reduced margins
  - Soft tissue targeting
  - Verification of setup surrogates
  - Verification of anatomy vs plan
- SBRT
- Gating
- Adaptive planning
  - Dose calc on CBCT
  - Triggered re-sims

Limitations

- Low contrast objects
- Multiple targets
- Changing targets
- Dose vs Structures for setup
In-room CT use case: Verification of Daily Projection Imaging

- CBCT can be used to test the appropriateness of projection imaging for daily setup

- MDACC Protocol:
  - Daily orthogonal pair kVp Images
  - Weekly CBCT (setup to bone) to validate:
    - The use of kVp for daily
    - The appropriateness of the plan for the changing anatomy

- Other protocols
  - Daily CBCT
  - CBCT for several days to create patient specific margins
Monitoring of patient during the course of treatment

• Tumors can change during 6 weeks of radiotherapy
• This can cause the target to move outside of the target when the patient is aligned on bones (daily kVp imaging)
Rapidly Changing Patient: Comparison between CBCT and projection Imaging

Simulation

Treatment
Day 1
Day 5
Day 10
CBCT to adapt to daily anatomy changes

- CBCT can be used to adapt plan by shifting isocenter to cover target
- SBRT in lung is an ideal use-case
  - Targets don’t change in a few fractions
  - High contrast between lung and GTV
  - CBCT slow acquisition can be an asset (averages tumor motion)
CBCT used to trigger a new planning CT

- Obvious Geometric Miss
- Shifting Isocenter cannot restore coverage
- CBCT doesn't have enough range or quality to adequately replan
Re-planning (adaptive)

- Dose can be re-calced on Daily CT
  - CT-on-rails/Tomotherapy: Direct dose recalculation
- CBCT
  - HU values can be calibrated: Megavoltage Photons are not particularly sensitive to HU accuracy
  - Length and/or FOV is more of a limitation
  - Poor quality for re-contouring
    - Abdomen – poor contrast
A study on adaptive IMRT treatment planning using kv cone-beam CT

George X. Ding*, Dennis M. Duggan, Charles W. Coffey, Matthew Deeley, Dennis E. Hallahan, Anthony Cmetak, Arnold Malcolm

Department of Radiation Oncology, Vanderbilt University, Nashville, TN, USA

Fig. 2. A CBCT image slice of Calphalon phantom containing high and low density materials and four lines (a) and the comparison of Hounsfield Units determined between conventional CT and CBCT along these four different lines (b-e). The diameter of Calphalon phantom is 200 mm.

Fig. 3. Calculated dose distributions in an inhomogeneous phantom (GETPhan 60D shown on a CT slice (A) from a Picker 500 scanner and on a CBCT slice (b) from a Triology DB. Two target volumes, PTV-1 shown in green and PTV-2 shown in blue, were contoured on the CT images and then copied to the CBCT images. Calculated dose-volume histograms using CT and CBCT images for target volumes PTV-1 and PTV-2 are shown in (c). The solid and dash lines are for CT and CBCT respectively.
Fig. 4. Two 14 cm long CBCT acquisitions (upper) were combined into one head and neck CBCT volumetric image (middle) for dosimetric comparison between using CBCT and CT image (lower) in IMRT treatment planning.
Registration of Daily CT to Planning CT

- **Algorithm**
  - Varian – Mutual Information
  - Elekta
    - Soft tissue: Cross correlation
    - Bone: Chamfer matching

- **Region-of-Interest**
  - Clip Box
  - Structure from planning
  - HU value ranges
  - Combination of the above
A combination of manual and automatic tools will give the best results

Example:
Scanned with couch at zero

Manual shift should be done prior to auto-match

Manual fine-tuning if often done after auto-match

Note: we often leave the couch at lateral zero when we do CBCT to avoid a) an extra step for the therapist b) an error between MOSAIQ and VARIAN in SRO processing
Automatic tools should be chosen for each patient (not just the default)
Auto match can be restricted to an HU value range to emphasize different materials.
Auto match can be restricted to a geographical region (clipbox)
The best way to define a region for matching is by using an ROI.
These tools can be combined
If boney anatomy were used as a surrogate a larger PTV would be needed to cover the target.
Difference between bone and soft tissue

Planning CT

In room CT-on-Rails
Differences between Boney Anatomy Based Setup and Soft tissue (GTV) based setup

76 Lung SBRT patients treated at MDACC
Average differences: 0.1 ± 0.4 cm in anterior-posterior (AP)
  0.1 ± 0.4 cm in superior-inferior (SI)
  0.0 ± 0.3 cm

Maximum observed 1.5 cm in AP direction
  1.6 cm in SI
  1.3 cm laterally
Auto-registration with 3D imaging NOT accurate

- University of Florida study compared automatic gray value alignment to gold-fiducial marker alignment in 6 patients with and without fiducials

**FIGURE 4.** Histogram of superior-inferior difference between automatic gray-scale and manual fiducial alignment.

Remote 3D IGRT Review for RTOG Trials

- Int J Radiat Oncol Biol Phys 2012 Apr 27. [Epub ahead of print]
- Remote review carried out for 87 3D cases
- Average differences between reviewers and institutions 2 mm - 3 mm.
- Largest sup-inf for MVCT due low spatial resolution

<table>
<thead>
<tr>
<th>Imaging modality</th>
<th>No. of datasets</th>
<th>Absolute value of difference of shifts (mm), mean ± SD (range)</th>
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<tr>
<td></td>
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<td>Left-right</td>
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<tr>
<td>kV CBCT</td>
<td>96</td>
<td>1.7 ± 1.1 (0.0-6.7)</td>
<td></td>
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<tr>
<td>MVCT</td>
<td>37</td>
<td>1.5 ± 1.0 (0.1-5.1)</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>133</td>
<td>1.7 ± 1.0 (0.0-6.7)</td>
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<tr>
<td></td>
<td></td>
<td>Superior-inferior</td>
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<tr>
<td>kV CBCT</td>
<td>96</td>
<td>1.6 ± 0.9 (0.0-6.9)</td>
<td></td>
</tr>
<tr>
<td>MVCT</td>
<td>37</td>
<td>3.7 ± 1.7 (0.1-8.2)</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>133</td>
<td>2.2 ± 1.5 (0.0-8.2)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Anterior-posterior</td>
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</tr>
<tr>
<td>kV CBCT</td>
<td>96</td>
<td>1.7 ± 1.1 (0.0-5.0)</td>
<td></td>
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<tr>
<td>MVCT</td>
<td>37</td>
<td>1.9 ± 0.9 (0.0-7.3)</td>
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<tr>
<td>Overall</td>
<td>133</td>
<td>1.8 ± 1.0 (0.0-7.3)</td>
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</table>

Abbreviations: kV = kilovoltage; CBCT = cone-beam CT; MVCT = megavoltage CT.
Dose vs structure for setup

- We setup to structures (anatomy) but our goals are generally dose based
  - Ensure the target gets enough dose
  - Ensure the OARs don’t get too much dose
The shape of Megavoltage Dose Distributions are relatively insensitive to local anatomical changes.

Dose calc on CT taken during 1rst week of treatment

Dose calc on CT taken during last week of treatment
Study done at MDACC

- We recalculated the doses based on weekly CTs taken as part of an IRB protocol for another purpose
- We compared dose metrics from the recalculated doses vs those from assuming the dose distribution did not change
  - Bone based alignment
  - Deformed the contours to match the changing anatomy)
What we found

• Target coverage can be assessed by shifting the dose distributions

• Critical structure doses
  • In general accurate
  • Can have a higher uncertainty in areas of step dose gradients (suggesting PRVs are needed)
Compromise set ups

• Between different ROIs
• Treat the tumor or avoid the OAR
• Rotations
• Deformations

Which GTV should be used for setup
For Head and Neck you need to choose a set-up area if the head tilt can't be matched to simulation.
Is 3D imaging always better?

• Longer to acquire
• Longer to analyze
• Therapists are not trained to look at the information
  • Need discreet bits of data to analyze – decide what you are looking for, what you want therapists to looks for, what your thresholds for calling MD are
  • Slows down your practice
Standardization of IGRT instructions

• IGRT involves various choices and trade-offs
• There have multiple opportunities for the Attending and the RTT to have different interpretations of the IGRT goals
• There needs to be a standardized method to communicate the IGRT goals and results between the Attending and the RTTs
Never assume something is obvious

Real sign posted at a major Cancer Center
Communication

• Standardization of set-up volumes
  • Both targets and OARs

• Clear and consistent instructions to therapists on
  • What they are setting up to (ex. label a contour as “SS”)
  • When to call MD (ex shift bone and soft tissue)
  • Any avoidance rules
Training: Physicians

- IGRT allows for margin reduction (If done correctly)
- Use the right setup techniques for each patient
  - Daily kVP for conformal avoidance of cord
  - Daily CBCT for hypo-fractionated (SRT) body
  - Weekly CBCT to look for tumor changes and trigger a replan
- Understand the limitations of the technology
Example of Guidelines for Physicians

• The radiation prescription should include the IGRT instructions and should indicate
  • Type of IGRT
  • Frequency of IGRT
  • Setup Surrogate – or avoidance structure

• Example:
  • Daily kVp (Bone) Weekly CBCT (bone) notify Dr if “63 Gy” doesn’t cover GTV
  • Daily CBCT (GTV)
  • Daily CBCT (avoid major vessel then cover GTV)
  • Daily CBCT (GTV, notify Dr. if “45 Gy” crosses the cord)
Training: Dosimetrist

- New steps to prepare imaging fields/CBCT fields for treatment
- Labeling of contours and choosing which contours to send to the treatment console
- Creation of Isodose line contours
- PTV margins as a function of setup technique
Example Guidelines for Dosimetry

• Volumetric (CT) Imaging: The Prefix SS (Setup Structure) should be added to the contour indicating the alignment structure for CBCT
  • Add any isodose lines needed to evaluate setup to the CT structure set

• Transcribe the imaging instructions into the setup instructions section (same place as isoshift)

Setup Instructions
supine, orfit board/pad/mask, 9 degree wedge heel to pt, w. /NEW BLUE #2 headrest, wedge knees, arms down by sides, marks for alignment, see photos

**1 shim**
Tool developed at MDACC to help setup CBCT based IGRT

- We created a Pinnacle script to
  - Reduce Points (very important in Pinnacle Paintbrush created contours to reduce MOSAIQ/4DITC issues)
- Choose structures for export
- Create Isodose lies
- Label setup structure
Example Guidelines for Physics

• Initial chart reviews should include
  • Ensuring the IGRT instructions are consistent with the treatment
    • Is the correct setup structure (SS) being used
  • Ensuring that the imaging instructions match the labels in the CBCT structures and/or DRRs.
  • Ensure the reference images are of sufficient quality and little or no extraneous contours are sent to the treatment machine
Training: Therapists

• Operation of new systems
• How to take good images/what anatomy to include
• Interpretation of 3D images
• Dose management (don’t retake CT due to computer problems)
Example Guidelines for RTTs

• On the first day: Review the prescription for imaging instructions and ensure they understand what the goal is for the IGRT and that the CT structures and/or DRRs are labeled correctly to help them accomplish these goals.

• On each day of imaging ensure the correct setup surrogate is used.

• For Volumetric setup
  • Ensure there are no un-expected conflicts between various setup goals
    • If weekly CT ensure that setting up on the bony anatomy used in the daily projection X-ray CT does cause the tumor to be outside of the PTV. If it does contact the attending for further instructions.
  • Ensure avoidance structures are outside the high dose region.
Steps to Implement better communication

1. Identify various IGRT scenarios
2. Develop communications that would cover these scenarios
3. Create guidelines
4. Train staff (Physician, Physicist, Dosimetrist, RTT) on the guidelines
5. Implement the guidelines
6. Audit the staff on the usability of the guidelines and revise as necessary
Examples of IGRT scenarios

1. Daily kVp and weekly CBCT: Instructions need to enable the RTTs to know if using the boney anatomy as the setup surrogate is adequate for daily treatments 1) is the CTV still covered 2) Are the OARs still spared

2. Daily CT: Instructions need to indicate the setup surrogate and avoidance structures and give guidance on what to do if there is a conflict

3. Daily kVp projection X-rays setup on fiducials: Instructions need to indicate fiducials should be used and what do if there is a large disagreement between various fiducials and/or between the fiducials and boney anatomy.
Establish what happens at the machine

• How often does the MD look at the images? (real time? End of the day?)
• What does the therapist set up to?
• Clear and consistent action points
  • Shift vs treat
  • When to call MD
IGRT - steps

• Contouring – establish your department-specific PTV (what is your set-up error for each site, with and without daily imaging, and which type of imaging?)
• Which contours get transferred to machine
• Instructions to therapist - Set-up to what?
• Action point – when to call md
• Change in treatment over time with what you learn
Summary

Room CT has the potential to improve the quality of care

• Requires understanding of margins
• Requires an understanding of imaging
• Requires good communication
  • Simulation – Dosimetry - Treatment
• Requires comprehensive training
  • RTTS
  • Dosimetrists
  • Physicists
  • Attendings
Proper use of IGRT (especially in room volumetric Imaging) requires your most import asset: Time

TABLE III. Estimated human resources required for image guidance using CT-based IGRT technologies. Estimates are obtained from the collected experiences of the task group members. More time is required when performing commissioning and quality control testing of 2D functions on some platforms.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Responsibility</th>
<th>Time</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance testing and commissioning</td>
<td>Physicists</td>
<td>2.5 days</td>
<td>First install only</td>
</tr>
<tr>
<td>Education</td>
<td>Physicists</td>
<td>2 days</td>
<td>First install only</td>
</tr>
<tr>
<td></td>
<td>Therapists</td>
<td>2 days</td>
<td>First install only</td>
</tr>
<tr>
<td></td>
<td>Dosimetrist</td>
<td>2 days</td>
<td>First install only</td>
</tr>
<tr>
<td>Operation</td>
<td>Therapists</td>
<td>5 mins/patient</td>
<td>Each treatment with IGRT; includes image acquisition and evaluation</td>
</tr>
<tr>
<td></td>
<td>Dosimetrist</td>
<td>10 min/patient</td>
<td>Data transfers to imaging platform</td>
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<tr>
<td>Review of images</td>
<td>Physicians</td>
<td>5 min/scan</td>
<td>0 when performed by therapists</td>
</tr>
<tr>
<td>Daily quality control tests</td>
<td>Therapists</td>
<td>10 min</td>
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<td>Monthly quality control tests</td>
<td>Physicists</td>
<td>1–2 h</td>
<td></td>
</tr>
<tr>
<td>Annual quality control tests</td>
<td>Physicists</td>
<td>2–4 h</td>
<td></td>
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<tr>
<td>Continued clinical support</td>
<td>Physicists</td>
<td>0.05 full-time equivalent position</td>
<td>Ad hoc activity</td>
</tr>
</tbody>
</table>

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Task Group 179, Department of Radiation Physics, Princess Margaret Hospital, University of Toronto, Toronto, Ontario, Canada, MSG 2M9

These estimates are probably too low especially with the lack of manufacture’s tools to optimize setup and communication for 3D-3D matching.
Thank You

- Kara Bucci, M.D.
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- Karl Prado, Ph.D.
- Lei Dong, Ph.D.
- Patricia Lindsay, Ph.D (PMH)