Development of an Image-Guidance System Quality Assurance Program for the Gamma Knife® Icon™ Radiosurgery Treatment System

by

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Medical Physics Program
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"IN THE NAME OF GOD, THE MOST GRACIOUS, THE MOST MERCIFUL"

TO THE MEMORY OF MY BELOVED MOTHER, BAHYIA, WHOSE BELIEVE IN ME MADE THIS JOURNAL POSSIBLE;

TO MY BELOVED FATHER, ABDULMAJEED, WHO DREAMED OF THE DAY HIS SON HOLDS A PhD;

TO MY SOULMATE, FATIMA, WHO SHOWERED ME WITH HER INFINITE LOVE AND SUPPORT THROUGHOUT THESE YEARS;

TO MY ANGEL BABIES, SALMA & BASMA, WHO CAME TO MY LIFE FOR A REASON: YOU HAVE CHANGED OUR WORLD...

"AND SAY: O MY LORD! ADVANCE ME IN KNOWLEDGE"
(SURAH TAH: 20:114)
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Development of an Image-Guidance System Quality Assurance Program for the Gamma Knife® Icon™ Radiosurgery Treatment System

ABSTRACT

**Purpose:** The recently released Gamma Knife® Icon™ is equipped with an image-guidance system for tracking patient motion and correcting for inter- and intra-fractional shifts, mainly used with thermoplastic immobilization for fractionated and frameless stereotactic radiosurgery Intracranial treatments. This work aims to develop a comprehensive quality assurance (QA) program for Icon's image-guidance system covering the need in this important area. We have developed tools and methodologies to go together with the ones mandated by the manufacturer, and prepared procedures and documentations needed for such a program.

**Method and Materials:** The Icon comes with a cone-beam CT (CBCT) and an intrafraction motion management (IFMM) system used for image-guidance treatments. We first evaluated the few quality control tests already in place, as required or recommended by the manufacturer. These check some aspects of the image-guidance system, namely the CBCT system precision using the manufacturer-provided User tool (QA tool Plus), and image quality (uniformity, contrast to noise ratio (CNR), and spatial resolution) using a Catphan® 503 phantom. We also performed CT dose index measurements using a 10-cm pencil ionization chamber in a standard CTDI acrylic head phantom. The results are reported and analyzed for these tests over a 2-year period starting at the installation of the Icon in the Gamma Knife Center of Roswell Park Comprehensive Cancer Institute. We then investigated the long-term stability of CBCT-based stereotactic space definition and its agreement with the Frame-based stereotactic space definition. We used a tool developed in-house and procedure for performing such a test and reported the results of a 6-weeks long measurements and annual measurements. We also used a three-dimensional translation/rotation stage tool that we have developed to investigate the accuracy of several image-guidance components, namely the IFMM system, the co-registration algorithm, and the delivery-after-shift. Based on the experience gained throughout this work, we proposed the additional quality control tests we have developed to be combined with the
manufacturer tests in a comprehensive QA program for LGK Icon's image-guidance system.

**Results:** The CBCT precision check: $0.12 \pm 0.04$ mm (maximum deviations average). CBCT image quality: spatial resolution range: $[6,7]$ lp/cm (low-dose (Low) preset), and $[7,8]$ lp/cm (high-quality (High) preset); CNR: $1.07 \pm 0.08$ (Low), and $1.69 \pm 0.10$ (High); uniformity: $12.82 \pm 0.69\%$ (Low), and $13.01 \pm 0.69\%$ (High); $CTDI_w$: $2.3$ mGy (Low), and $5.7$ mGy (High). Agreement of CBCT-based with Frame-based stereotactic coordinates range: $[0.3, 0.7]$ mm. Accuracy of IFMM: $0.00 \pm 0.12$ mm (average) with $0.27$ mm (max.); image accuracy of co-registration: $0.03 \pm 0.06$ mm (average) with $0.23$ mm (max.); and accuracy of delivery-after-shift: $0.24 \pm 0.09$ mm (average) with $0.42$ mm (max.). Finally, our proposal for a comprehensive image-guidance QA program combining the manufacturer tests with our user-defined tests, including their frequencies, tolerance levels, documentations, and instructions was presented.

**Conclusion:** The manufacturer-required QA checks together with additional user-defined checks are an important combination for a robust quality assurance program. We have developed a comprehensive quality assurance program for LGK Icon's image-guidance system, together with procedures and documentation to be used with such a program, ensuring the safe use of Gamma Knife® Icon™'s image guidance and motion management features in treatments of frameless stereotactic radiosurgery.
Introduction

1.1 Overview of Stereotactic Radiosurgery

The use of radiation as a surgical tool, known as radiosurgery, was proposed and implemented by Dr. Lars Leksell - a neurosurgeon at the Karolinska Institute in Stockholm, Sweden. The intention was to mimic the lesions effects of a surgeon's knife using gamma radiation, hence the name "Gamma Knife Surgery" (GKS) given to the first gamma radiation unit that implemented radiosurgery. Dr. Leksell defined stereotactic radiosurgery (SRS) as "a technique for the non-invasive destruction of intracranial tissues or lesions that may be inaccessible or unsuitable for open surgery."[1] In 1949, Dr. Leksell developed the stereotactic frame and published it as a device used to implement the concept of "stereotaxy": a technique used for identifying and recording the three-dimensional coordinates of non-visualized anatomic structures within the brain used mainly by neurosurgeons at that time. Two years later, he published a work describing the use of his stereotactic device in targeting a beam of proton radiation into a brain.[2] He used a lightweight rigid frame screwed to the patient head under local anesthesia that works as a reference for identify the target within the brain in relationship to this external frame. In 1967, Dr. Leksell and his collaborator Dr. Börje Larsson, a radiobiologist/physicist from the Uppsala University in Sweden, constructed the first prototype of a Gamma Knife unit that uses the synthetic radioactive isotope of cobalt (Co-60) as the radiation source for SRS. Dr. Leksell went later on to commercialize his invention and founded his company "Elekta" that became a leading
global company in manufacturing Gamma Knife Radiosurgery systems, as well as medical linear accelerator devices and other radiotherapy-related products. By its 50th year anniversary in 2018, the Gamma Knife system has been used in treatments of over 1.1 million people around the globe. About 330 clinical Gamma Knife units across 54 countries collectively treat more than 80,000 new patients each year.³ The application of SRS is not restricted to the Gamma Knife systems, however. Medical linear accelerators equipped with radiation collimating devices (e.g. cones or multi-leave collimators) are also used for cranial radiosurgery. Of notably mentioning are the Truebeam medical accelerator (Varian Associates, Inc., Palo Alto, CA), Cyberknife (Accuray Inc., Sunnyvale, CA), Tomotherpay (Accuray Inc., Sunnyvale, CA), and VERO (BrainLAB AG Feldkirchen, Germany and Mitsubishi Heavy Industries, Tokyo, Japan). In SRS, a high dose of radiation is delivered to a small target within the brain, typically less than 3-4 cm, while sparing healthy structures. This mandates precise 3D localization and the expertise of a multidisciplinary team of neurosurgeons, radiation oncologists, physicists, and nurses. Single high dose is traditional and common, but multiple fractions are feasible for larger lesions or located at sensitive locations.⁴ SRS is used for the treatment of cranial tumors such as metastatic tumors to the brain, acoustic neuromas, meningiomas, pituitary adenomas, pineal tumors and glioblastoma; vascular disease such as arteriovenous malformations; and pain and movement disorders such as trigeminal neuralgia, essential tremor, and Parkinson's tremor.

1.2 THE LEKSELL GAMMA KNIFE® SYSTEMS

In early 1968, Dr. Leksell and his team were excited to use the first Gamma Knife unit prototype that they developed even before it left the Studsvik AB manufacturer site to the installation destination in the Sophiahemmet private Hospital in Stockholm. The first patient was a young boy with a Craniopharyngioma treated on November 2, 1967. The initial applications of the Gamma Knife unit were restricted to functional disease only, and thus its 179 beam channels had rectangular cross-sections generating disc-shaped dose distributions with 3 different sizes inner helmet collimator inserts deemed suitable for such an application. The original prototype from
1967 was later donated for 1 Swedish Krona to the neurosurgeon Robert Ran at UCLA (California, USA) for research work in 1979. A second Gamma Knife unit was developed by Leksell’s team with a larger helmet (145 mm radius vs. 125 mm in the first Gamma unit) and circular collimators that generate spherical dose distributions to be used for small tumor treatments. The whole helmet (> 100 Kg) would have to be changed if a different collimator size is needed, and thus a helmet changer and helmet supports had to be constructed for this task. This second unit was installed in Radiumhemmet, the oncology department of the academic Karolinska University Hospital in 1974. An interesting note is that the medical physicists at Radiumhemmet played an important role with their measurements and assessments of safety and accuracy of the use of this Gamma Knife unit for patient treatments. This was because the Swedish regulatory authority at that time, the Swedish Institute of Radiation Protection (SIRP), would only grant a license to equipment emitting therapeutic radiation on the condition that the department of Radiophysics had to approve every patient with regard to radiophysics suitability for treatment and dose planning.

In 1972, Lars Leksell with his son, Laurent, formed a company (Elekta) to commercially manufacture and distribute the Gamma Knife unit. The first Gamma Knife systems installed outside of Sweden were in Buenos Aires, Argentina in 1983, and in Sheffield, UK in 1985. There was a need for an improved third design of the Gamma unit for several reasons: to have a larger helmet allowing for treatments of lateral targets closer to skull base; to make the position of patient’s neck similar to that of the CT and MRI imaging (i.e. straight and not bent like in the previous Gamma units); and to make a unit that can accept source loading in the hospital instead of shipping pre-loaded units like in the first and second generation. As the design of the third generation of Gamma Knife progressed, several centers in the United States were interested in introducing the Gamma Knife in their practices. The US Food and Drug Administration (FDA), however, required rigorous technical and clinical testing of this new design. Elekta, being a small company at that time, elected to make a special design for their US customers that is similar to the first prototype which has had already been imported to the US and landed in UCLA before the FDA was established and became involved in regulating medical devices. By doing so, Elekta
avoided the expensive extra testings that would have been required by the FDA for a new design. This special design was installed only in the US at that time, and thus was called model U - the "U" standing for United States. The first clinical Gamma Knife Unit brought to United States was by neurosurgeon L. Dade Lunsford of Pittsburgh University to treat the first US patient in August 1987. With the model U, a hydraulic system moved the patient into the machine inward and upward into the radiation unit. While the other 3rd generation units sold in the rest of the world, under the name model B - with the letter "B" standing for the city of Bergen in Norway, had a simpler design where the patient moved in and out. Both models used 201 Co-60 sources, but unit U had a hemispherical distribution titled 55° from the horizontal plane to avoid having primary gamma beams penetrating the patient body as the head is bent into position inside the unit. Both the U and B models, similar to the original unit design, used external helmets containing collimators of different diameters to shape the radiation beams, but with a larger radius (165 mm) and collimators having a diameter of 4, 8, 14 mm, and also a 18 mm allowing treatment of larger targets with shorter delivery time. In 1999, model C was introduced with the first robotic patient positioning system in Gamma Knife for automatic and faster positioning. The delivery of stereotactic radiosurgery became more efficient by the addition of APS (automatic positioning system) in model C, as the Gamma Knife team would not need to manually change the patient position within the unit. This allowed for the treatment delivery to be performed much faster which in turn allowed for more shots to be planned for better optimized dose distributions.[5, 6]

In 2006, Elekta introduced the Leksell Gamma Knife® Perfexion™ with a complete re-design.[7, 8] The first installation was in Timone University Hospital of Marseille, France. The first Perfexion in the US was installed at Washington Hospital in California with clinical treatments commenced in mid-2007. The most critical change in the Perfexion is the new integrated collimator system, as it replaces the external multi-helmet collimator setup with a single integrated permanent collimator system of 4 mm, 8 mm, and 16 mm that can change beam size dynamically by sectors. The collimator is partitioned into 8 independently movable sectors, each delivering 24 beams of radiation using a total of 192 $1mm \times 20mm$ cobalt-60 sources.
encapsulated in bushings. Sectors can be blocked individually for shot shaping. The Perfexion positions the patient by moving the couch rather than moving the patient’s head within an APS like in the former model C. Fig. 1.2.1 shows the design of the Perfexion compared to model C. In a newly loaded unit, each source is about 30-36 curies (1.11-1.33 TBq), totaling about 6000-6600 curies, delivering a dose rate on the order of 3.5 Gy/min at the unit center. [9, 10]. In 2015, Elekta introduced the latest generation of Gamma Knife systems, the Icon model, with image-guidance add-ons. Fig. 1.2.2 shows the different generations of Leksell Gamma Knife systems that have been produced by Elekta.
1.2. THE LEKSELL GAMMA KNIFE® SYSTEMS

- Model U (~1987)
- Model B (~1988)
- Model C (~1999)
- Model Perfexion (~2006)
- Model Icon (~2015)

**Figure 1.2.2:** The different Leksell Gamma Knife models manufactured by Elekta, with the year they were introduced. (Images courtesy of Elekta AB, Stockholm).
1.3 The New Leksell Gamma Knife® Icon™ System

The Leksell Gamma Knife® systems have been designed by the manufacturer (Elekta Instruments, A.B., Stockholm, Sweden) to precisely deliver stereotactic treatments to intracranial targets. Its sixth generation model and latest design, the Leksell Gamma Knife® Icon™, is no exception. The Icon is based on a preliminary work at the University of Toronto in Canada that adapted an image-guidance system [11], supporting frameless and hypo-fractionated radiation treatments [12]. The Icon is identical in the core radiation unit to its predecessor the Perfexion, i.e., 192 Co-60 sources distributed over 8 sectors that can be moved independently to deliver an isocentric treatment. The Icon, however, comes with an integrated Cone-beam CT (CBCT) system for image-guidance and a couch-mounted stereoscopic infrared camera for intrafraction motion management, allowing the option of a "frameless" stereotactic radiosurgery and fractionated stereotactic radiotherapy treatments. In frameless-based SRS, a removable non-rigid thermoplastic mask that can be fixed to a head support is used for head immobilization instead of the traditional invasive rigid frame used in frame-based SRS. The Icon's CBCT system is composed of a rotating anode X-ray tube (RTM 75H, Industria Applicazioni Elettroniche, Cormano MI, Italy) and an a-Si/CsI flat-panel x-ray detector (Pixium CBCT 2630, Thales Electron Devices SAS, France) mounted on C-arm allowing a 210-degree rotation for scanning. CBCT can be used for obtaining reference images that define the Leksell stereotactic space coordinates, and also can be used prior to treatment delivery for verifying the actual skull position and determining translational and rotation shifts based on co-registration with the reference CBCT images [13] so that the shot positions are adapted to the target and plan dose distribution is recalculated [14]. The CBCT scan takes about 30 seconds to be completed. There are two available scanning presets: a CTDI 6.3 mGy (high-quality images) preset; and a CTDI 2.5 mGy (low-dose images) preset. Table 1.3.1 shows the geometrical characteristics of the Icon's CBCT system, while Table 1.3.2 compares the parameters of the two scanning presets [13, 15].

The intra-fraction motion management system (IFMM) is composed of a stereoscopic infrared camera (Polaris Vicra, Northern Digital Inc., Waterloo ON, Canada) mounted on the far end of
1.4 TRADITIONAL GAMMA KNIFE FRAME-BASED TREATMENT PROCESS

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<td>Source to axis distance (SAD)</td>
<td>790 mm</td>
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<tr>
<td>Source to detector distance (SDD)</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Magnification factor</td>
<td>1.27</td>
</tr>
<tr>
<td>Detector physical size</td>
<td>340 × 390 mm²</td>
</tr>
<tr>
<td>Reconstructed volume</td>
<td>224 × 224 × 224 mm³</td>
</tr>
<tr>
<td>Cone beam angle</td>
<td>15°</td>
</tr>
<tr>
<td>Fan angle</td>
<td>16°</td>
</tr>
</tbody>
</table>

Table 1.3.1: Geometrical characteristics of the Icon's CBCT system.[13, 19]

the patient couch and is used to monitor the movement of an infrared (IR) reflector marker placed on the patient nose tip with respect to four stationary reflector markers fixed to the patient head support when using the thermoplastic mask for immobilization. The system allows for automatic pausing of radiation delivery (in active mode) if the nose movement exceeded a threshold that can be set from 0.5 mm up to 3 mm.[16, 17]. In "Active" mode, the Co-60 sources move to the blocked sector position as soon as the IFMM threshold is exceeded and stay there unless the IR marker is back below threshold for at least 2 seconds. If the IFMM readout stayed out of tolerance for more than 30 seconds, a treatment pause sequence is initiated by the system stopping the irradiation delivery and retracting both the radiation sources and the patient couch to their corresponding home positions. The user have the option to select a "Passive" mode where the IFMM output is visible for monitoring without any automatic hold/pause actions by the system. The IFMM cannot be used when the patient is immobilized with the traditional rigid frame immobilization system. In earlier references, the IFMM may also be referred to as the High Definition Motion Management (HDMM) system.[18]

1.4 TRADITIONAL GAMMA KNIFE FRAME-based TREATMENT PROCESS

To achieve the high precision in localization, the Gamma Knife uses the concept of stereotaxy: defining the three-dimensional coordinates of non-visualized anatomic structures within the brain. Traditionally, this is achieved using a stereotactic frame (e.g. Leksell stereotactic
1.4. TRADITIONAL GAMMA KNIFE FRAME-BASED TREATMENT PROCESS

<table>
<thead>
<tr>
<th></th>
<th>CTDI 6.3 Preset</th>
<th>CTDI 2.5 Preset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal spot size</td>
<td>0.6 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>kVp</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>mAs/projection</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of projections</td>
<td>332</td>
<td>332</td>
</tr>
<tr>
<td>Voxel size</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Nominal Spatial Resolution</td>
<td>8 lp/cm</td>
<td>7 lp/cm</td>
</tr>
<tr>
<td>Nominal CNR</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Nominal CTDI</td>
<td>6.3 mGy</td>
<td>2.5 mGy</td>
</tr>
</tbody>
</table>

Table 1.3.2: Comparison of the Icon’s CBCT two scanning presets. The CTDI 6.3 is a high-quality image scanning preset, while the CTDI 2.5 is a low-dose scanning preset.[13, 19]

G-Frame) that defines a reference Cartesian coordinates system, known as the Leksell Coordinate System (LCS). The stereotactic frame is rigidly fixed to the patient’s skull with screws under local anesthesia. The origin of LCS is located at the most right lateral, superior, and posterior of the frame base ring, as shown in Fig. 1.4.1. In order for the Leksell GammaPlan\textsuperscript{®} (LGP) software to model the skull shape for calculating photon attenuation and for avoiding collision between the patient and the treatment unit, the collection of sampled skull measurement data using a skull scaling instrument (referred to as "Bubble") is traditionally required. However, the new version of LGP (Ver. 10.1.1 and above) has the capability to generate the skull surface contours from MRI or CT images directly in lieu of the physical measurements. After frame fixation, the next step is for the patient to be imaged (with diagnostic MRI, CT, or Angiography) with a fiducial indicator box attached securely to the frame. The fiducial box is filled with Copper-Sulfate (CuSO\(_4\)) solution that is visible in MRI images, or a radio-opaque material visible in CT/Angio images. This helps the planning software in defining and positioning the patient’s brain in the LCS by matching the fiducials visible in each image slice to a model of the fiducial system and stereotactic space. The stereotactic images are transferred to LGP and are co-registered with other non-stereotactic images if needed. The target(s) and critical structures are determined/contoured and shots of radiation are planned. The overall planned dose distribution is evaluated by the treating radiation oncologist and neurosurgeon. Once approved, the plan parameters (shots coordinates, collimator sizes, and
Figure 1.4.1: The Leksell coordinate system (LKS) defined by Leksell stereotactic G-Frame. (Image courtesy of Elekta AB, Stockholm)

Figure 1.4.2: A flowchart summarizing the Gamma Knife frame-based treatment process. (Images courtesy of Elekta AB, Stockholm)

delivery times) are exported to the clinical unit console. Prior to treatment delivery, the frame is docked to the treatment table end using a frame adapter for immobilization and precise delivery. Once the treatment is initiated, the treatment table moves automatically into the Gamma Knife Unit to align the planned shot coordinates to the radiation focal spot for treatment delivery. After the treatment is completed, the frame is undocked and removed.\[^4\] The process for frame-based treatment is summarized in Fig. 1.4.2.
1.5 Gamma Knife Icon Frameless Treatment Process

With its new added features, the CBCT and IFMM systems, the Icon is well equipped for frameless radiosurgery treatments. Icon’s CBCT images can be used for defining the Leksell stereotactic coordinates, eliminating the need for the invasive head frame. The IFMM system can be used to track patient any head movement during delivery (intra-fraction motion) resulting from the non-rigid thermoplastic mask immobilization used. Instead of the rigid frame used in frame-based SRS, a thermoplastic mask system (referred to as frameless fixation) can be used, making it easier for multiple fractionated dose delivery as opposed to a single high dose with the invasive frame. The CBCT also is used in case of fractionated treatments to co-register the daily setup CBCT with the reference CBCT that has treatment plan approved and correct for the inter-fraction shifts.

The process of frameless Gamma Knife treatment starts with preparing the patient immobilization: a customized cushion and thermoplastic mask (Nanor® mask, Art. No 1514925, Elekta Inc. Atlanta, GA) that holds the patient head tight and secured to the head/mask adapter attachment to table treatment. The mask material is made of a nanoparticle composite designed to provide molding at low temperatures (145 °F [62.8 °C]) with a short curing time (about 15-30 mins) and reduced shrinkage when fully cured.²⁰ The A “reference” CBCT image is taken next with the patient immobilized with the cured mask. The reference CBCT is then co-registered with the planning MRI/CT and this maps the images in the Leksell stereotactic coordinates. The treatment planning is carried next where the skull is defined using planning MRI/CT images, the targets and organs at risk are determined/contoured, and shots are placed for optimum dose distribution. Once the plan is evaluated and approved, the plan parameters (shots coordinates, collimator sizes, and delivery times) are exported to the clinical unit console. In preparation for treatment delivery, the patient head is immobilized with the custom mask to the treatment table, an infrared reflective marker is placed on the patient nose tip for IFMM tracking. A setup CBCT is then taken and is co-registered with the reference CBCT to verify head position. The translational and rotational shifts between the two CBCT are determined and an adapted plan
with updated dose distribution taken into account the head shifts is shown in Leksell GammaPlan (LGP) for re-evaluation and approval. Once approved, the system automatically applies the translation changes in table position and the treatment table moves into the unit to align the planned shot coordinates to the radiation focal spot for treatment delivery. The IFMM infrared camera tracks the patient nose marker and is capable of pausing the irradiation if a threshold (ranges between 0.5 to 3 mm) is exceeded (in Active mode). The irradiation can be stopped manually during treatment for a new setup CBCT to be taken for another round of plan adapting if deemed clinically necessary. Once the treatment is completed, the mask is removed. For fractionated cases, the process starting with a new setup CBCT is repeated for each fraction.[21] The process for frameless Gamma Knife treatment is summarized in Fig. 1.5.1. A detailed process tree of frameless treatment is presented in Fig.6.2.4.
1.6 Gamma Knife Stereotactic Radiosurgery at Roswell Park Comprehensive Center (Roswell Park)

The Gamma Knife Center opened at Roswell Park in November 1998 with a Leksell Gamma Knife Model B2. In 2005, the Gamma Knife Center was the second in the world to install the Gamma Knife Model 4C[22], and in 2009 the completely re-designed Gamma Knife Perfexion was introduced at Roswell Park. In March 2016, Roswell Park’s Leksell Gamma Knife Icon was the first one to be implemented clinically in an American cancer center. Fig.1.6.1 shows the upgrading installation of Perfexion to Icon. As of 2018, Roswell Park is the only center in western New York to offer cranial radiosurgery with Gamma Knife. The center has treated about 6000 patients in total since it was initiated in 1998, and is currently treating more than 500 patients per year. The Gamma Knife team at Roswell Park is comprised of a multidisciplinary team of full-time radiation oncologists, medical physicists, neurosurgeons, and nurses.[23, 24] Fig.1.6.2 shows the different treatment indications of cases treated with Gamma Knife Icon at Roswell Park between March 2016 - February 2018. Fig.1.6.3 shows the number of monthly frame- and CBCT-based treatment cases for the same period. About one-quarter of the cases received treatments with CBCT-based stereotactic definition, as shown in Fig.1.6.4. Brain metastasis is one of the larger application of hypofractionated radiosurgery using the thermoplastic mask system, with one-third of cases treated with the frameless stereotactic radiosurgery at Roswell Park. Fig.1.6.5 shows the distribution of the origin of brain metastasis treated with Icon during the March 2016 - February 2018 period.

1.7 Image-Guidance Quality Assurance

The aim of radiotherapy is to deliver a high dose of radiation to the malignant target while limiting the dose to the surrounding healthy tissues. With the advancement and rapid pace in
1.7. IMAGE-GUIDANCE QUALITY ASSURANCE

Figure 1.6.1: Upgrading of Leksell Gamma Knife Perfexion to Icon at Roswell Park.
Figure 1.6.2: Treatment indications of cases treated using the Gamma Knife Icon at Roswell Park for two years period (March 2016 - February 2018).

Figure 1.6.3: Gamma Knife Icon monthly treatment statistics at Roswell Park for two years period (March 2016 - February 2018).
Figure 1.6.4: Portion of CBCT- and Frame-based treatments using the Gamma Knife Icon at Roswell Park during the first two years (March 2016 - February 2018).

Figure 1.6.5: Origin of brain metastasis of cases treated using the Gamma Knife Icon at Roswell Park during the first two years (March 2016 - February 2018). Brain metastasis is one of the larger application of hypofractionated radiosurgery using the frameless thermoplastic mask system.
technology innovations applied in the field, it is possible nowadays to generate highly tolerated dose distributions with high conformality to the target. This mandates the need for accurate determination of target and normal structures during each radiation treatment fraction. Imaging and tracking systems technology have been integrated in treatment rooms and within treatment units to pursue such high level of localization precision. These imaging and tracking systems used to ensure the precise delivery of dose distribution within the patient are referred to image-guidance systems, and radiotherapy treatments that utilize such systems are often referred to as image-guided radiation therapy (IGRT). Geometric positioning errors that can occur between treatment planning and delivery can be reduced with IGRT techniques. These include the ‘systematic’ errors that would occur during the entire course of therapy, and also the ‘random’ errors that would occur from fraction-to-fraction. IGRT helps in reducing the geometric positioning errors by imaging the patient’s anatomy at the time of treatment, registering the image to a reference image where a radiation plan and dose distribution has been applied on, adjusting the machine or patient to assure the radiation is directed at the target while avoiding the normal structures.[25] Portal imaging with megavoltage (MV) beams and films/electronic portal imaging devices are probably the most commonly used form in basic IGRT. Newer technologies such as kilovoltage (KV) orthogonal, KV- and MV CT and Cone-beam CT, ultrasound imaging, MRI, and optical-guidance systems are becoming the norm in IGRT. With appropriate IGRT application, planning target volume (PTV), a concept used in traditional radiotherapy where a volumetric margin is added to account for uncertainties in target localization, planning and treatment delivery, can be reduced and one can have more confidence in the delivery of radiation dose to the target.[26] However, deploying IGRT robustly and safely in the clinic requires investing in quality assurance and testing, patient-specific preparation, and training for the radiation therapy staff for using these systems. Otherwise, failure to do so can result in a very complex treatment being ‘precisely wrong.’[25] Several protocols have been published providing guidance for establishing a quality assurance program to ensure the safe application of image-guidance radiation therapy, but none is specific to the new Gamma Knife Icon system. Recently, few articles were published reporting commissioning test results, and
measuring the performance of the different aspects of Icon's image guidance. The manufacturer, Elekta AB, has published several white papers evaluating and characterizing the Icon's CBCT and IFMM systems.\cite{13-17, 19, 27} Li et al. evaluated the intra-fraction motion monitoring for use with the thermoplastic mask system prior to being implemented in the Gamma Knife system.\cite{28} In her master thesis work, Krista Burton conducted end-to-end testings to ensure the correct calculations for positioning and accuracy of motion monitoring methods when treating with the Icon.\cite{29} Zeverino et al., in their commissioning of Icon, evaluated the agreement between CBCT isocenter and radiological focus; the CBCT image quality (spatial resolution, contrast-to-noise ratio, and uniformity); and the Computed Tomography Dose Index (CTDI).\cite{30} Blake et al. also published their experience with Icon's commissioning tests and results as a scientific poster.\cite{31} Most recently, Sarfehnia et al. evaluated the performance of the Icon's image-guidance system in terms of CBCT image quality; mechanical integrity; image co-registration fidelity; adaptive treatment delivery quality; and IFMM system performance.\cite{32} These few publications merely report the system performance results, and do not sufficiently cover the need for establishing a comprehensive quality assurance program for the image-guidance system used in Leksell Gamma Knife Icon.

1.8 DISSERTATION OUTLINE

This work aims to develop a comprehensive quality assurance program for Leksell Gamma Knife Icon image-guidance system covering the need in this important area. We have developed tools and methodologies to go together with the ones mandated by the manufacturer, and prepared the procedures and documentation needed for such a program. In Chapter 2, we start by going over the few quality control tests already in place, as required or recommended by the manufacturer. These check some aspects of the image-guidance system, namely the CBCT system precision and image quality. We report the results of these tests over a 2-year period starting at the installation of Icon in the Gamma Knife Center of Roswell Park Comprehensive Cancer Institute. The next chapter, Chapter 3, is a study of a long-term stability of CBCT-based
1.8. DISSERTATION OUTLINE

stereotactic space and its agreement with the Frame-based stereotactic space. We describe the tool developed and procedure for performing such a test as well as the results of a 6-week long measurements and bi-annual measurements. In Chapter 4, we report our accuracy test results of several image-guidance components, namely the IFMM system, the co-registration algorithm, and the delivery-after-shift using a 3D translation stage tool that we have developed. In Chapter 5, a comprehensive quality assurance program for LGK Icon’s image-guidance system based on the experience gained thorough this PhD work is presented, together with procedures and documentation to be used with such a program. Chapter 6 is a summary of our work with suggestions for future work to complement what has been accomplished in this study and ensure the safety and accuracy of using the image-guided treatment for delivery stereotactic radiosurgery with LGK Icon.
Current Quality Assurance Tests for Icon’s CBCT

This chapter describes the current image-guidance quality assurance tests of the LGK Icon at Roswell Park that are already in place and are performed according to the manufacturer requirements and methodology. These checks are the CBCT precision, image qualities, and CT dose index. The work described in this chapter has been published as part of a manuscript in the Journal of Applied Clinical Medical Physics. [33]

2.1 Introduction

Leksell Gamma Knife® Icon™, shown in Fig. 1.2.2e, allows the treatment of patients in a precise stereotactic environment using cone-beam computed tomography (CBCT) for positioning, a thermoplastic mask system for fixation, and an infrared-based motion management system for patient tracking during treatment. Using these novel options, Gamma Knife Icon enables the possibility to adaptive fractionated stereotactic radiosurgery. The quality assurance tests available for such new add-on are limited to the manufacturer required tests of CBCT precision and CBCT image quality. In this work, we report our results for these routine tests and for the CT dose index measurement that we perform at Roswell Park over a two-year period since the installation of the Icon.
2.2 MATERIAL AND METHODS

The manufacturer requires only two tests to be performed routinely by the user for the Icon’s CBCT system: 1) CBCT Precision Test, and 2) CBCT Image Quality Test. Additionally, an annual CT dose index (CTDI) measurement is also performed at Roswell Park following the manufacturer methodology[16] which is based on the commonly used formalism such as described by the AAPM Task Group 23 report.[34] These tests only focus on the CBCT part of Icon’s image-guidance system.

2.2.1 CBCT PRECISION QA TEST

The manufacturer provides a user QA tool (QA tool Plus) to enable testing the CBCT precision (FIG. 2.2.1). The QA tool Plus has four posts each with a steel ball-bearing (BB). The four steel ball-bearings are distributed such that they only have three distinguished coordinates in the lateral direction (X), three distinguished coordinates in the vertical direction (Y), and two distinguished coordinates in the longitudinal direction (Z). The pre-programmed CBCT precision test algorithm, loadable directly at the unit operator console, finds the location of the four ball-bearings from a CBCT scan of this tool and compares them with their baseline coordinates obtained during the calibration of the tool by the service engineer. The algorithm calculates and reports each of these four fiducial deviation to the user. The test algorithm also calculates the CBCT image volume and compares test points with baselines to report the maximum deviation in the reconstructed CBCT image volume.[15, 16] The test is considered “passed” if the maximum deviation is within the acceptable limits (< 0.4 mm). This test is required by the manufacturer to be performed once a month, but it is recommended to be carried out on a daily basis. We report our daily maximum deviation values for a two-year period in this work.
2.2. MATERIAL AND METHODS

Figure 2.2.1: The QA tool Plus attached to LGK couch in preparation for daily CBCT precision test. The yellow arrows point to the four steel ball-bearings

2.2.2 CBCT IMAGE QUALITY TESTS

The second test required by the manufacturer is to check image qualities for the two scanning presets available on the Icon: low-dose preset of a nominal CTDI = 2.5 mGy; and high-quality preset of a nominal CTDI = 6.3 mGy. The CBCT image quality test is required by the manufacturer to be performed on a semi-annual schedule, with the recommendations to be performed monthly. The Catphan® 503 Phantom (The Phantom Laboratory, Salem NY), shown in Fig.2.2.2 is scanned with CBCT for this test and different modules within the phantom are utilized to check for spatial resolution, contrast to noise ratio (CNR), and image uniformity. The spatial resolution was determined by an observer finding the highest number of line pair that can be seen in the CBCT image of the phantom. The CNR was calculated from an image of a polystyrene and LDPE inserts using the equation:

\[
\text{CNR} = \frac{I_{PS} - I_{LDPE}}{\sqrt{\sigma_{PS}^2 + \sigma_{LDPE}^2}}
\]  

(2.1)

where \(I_{PS}\) and \(I_{LDPE}\) indicate the mean pixel values using a 5-mm square image probe for the polystyrene and LDPE inserts, respectively; and \(\sigma_{PS}\) and \(\sigma_{LDPE}\) indicate the standard deviation values for the same inserts. For the uniformity test, five readings were taken at the center, 12, 3, 6, and 9 o'clock positions of an image of a homogenous section of the Catphan 503 phantom using
2.2. MATERIAL AND METHODS

Figure 2.2.2: Catphan 503 phantom setup on Icon’s couch in preparation for CBCT image quality test.

a 10-mm square image probe. The uniformity was calculated using the formula:

\[
\text{Uniformity} = 100 \% \times \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + 1000}
\]  

where \(I_{\text{max}}\) is the maximum mean pixel value, and \(I_{\text{min}}\) is the minimum mean pixel value of the five readings.\[16\] We report our two-year results of the manufacturer monthly image quality tests in this work.

2.2.3 CBCT DOSE CONSTANCY TEST

A weighted CT dose index measurement was performed for both CBCT low-dose and high-quality presets using a 10-cm pencil ionization chamber (Radcal Model 10X6-3CT, Radcal Corporation, Monrovia, CA) in a standard CTDI acrylic head phantom (16 cm diameter). The head phantom was placed on a Styrofoam spacer on the Icon’s patient head support to bring the phantom central in the CBCT field of view. Fig.2.2.3 shows a CTDI phantom setup, and the centering within the imaging volume. The weighted CTDI (\(\text{CTDI}_{w}\)) was derived from the weighted average of central and peripheral dose measurements values according to the formalism
described in AAPM Task Group 23 report: [34]

\[
CTDI_w = \frac{1}{3} \text{CTDI}_{center} + \frac{2}{3} \text{CTDI}_{periphery}
\]

We report the results obtained during commissioning and two annual \( CTDI_w \) measurements for both CBCT presets.

2.3 RESULTS AND DISCUSSION

2.3.1 CBCT PRECISION QA TEST

The plot in Fig. 2.3.1 shows the daily maximum deviation in the reconstructed CBCT image volume for the CBCT precision QA test for a two-year period (March 2016 - February 2018). The average was \( 0.12 \pm 0.04 \) mm with a maximum of \( 0.24 \) mm. Our results for this test were well within the acceptable limit (\( < 0.4 \) mm) as established by the manufacturer. The current practice at Roswell Park is to perform the CBCT precision test on clinical days (i.e. on days that we use the CBCT for patient treatments) as recommended by the manufacturer. [16]

2.3.2 CBCT IMAGE QUALITY TESTS

Table 2.3.1 summarizes our monthly CBCT image quality results over the two-year period for our Icon and the corresponding manufacturer acceptable limits. Our results meet the specifications for the image quality tests, with some exception in the spatial resolution of the low-dose preset. The results of the spatial resolution test were on the borderline in two nonsequential months (out of the 24 months reported). Considering that the spatial resolution test is a subjective test and the low-dose preset used, we find these minor deviations acceptable. The high-quality preset showed better image quality in terms of spatial resolution and CNR compared to low-dose preset. However, the uniformity was comparable using either of two presets. Zeverino et. al. reported a similar spatial resolution (7 lp/cm) for both presets, and
2.3. RESULTS AND DISCUSSION

Figure 2.2.3: (a) Setup for CTDI measurement with a calibrated pencil chamber in a CTDI head phantom. The head phantom was brought central in Leksell coordinate space by mounting it on a Styrofoam piece; and (b) Checking the centering of CTDI head phantom to be within the center of Leksell coordinate space (100,100,100).

The dosimetry equipment shown here is a 10-cm pencil ionization chamber (Victoreen 500-100 / SN 207) connected to an electrometer (Keithly Electrometer 35040 / SN 59171) that were previously cross-calibrated with a Radcal Model 10X6-3CT system.
2.3. RESULTS AND DISCUSSION

![Graph](image.png)

**Figure 2.3.1:** Results of the daily CBCT precision test (maximum deviation (mm) in image volume) over the two-year period. The red line represents the manufacturer limit for the test to pass (0.4 mm).

Better image qualities for the high-quality preset in terms of CNR: 0.8 vs. 1.2 (low/high presets, respectively); and uniformity: 9.3% vs. 8.8% (low/high presets, respectively).[30] Black et al. reported spatial resolutions of 7 lp/cm and 8 lp/cm (low/high presets, respectively); CNR of 1.1 and 1.8 (low/high presets, respectively); and image uniformity of 11% and 8% (low/high presets, respectively).[35] Sarfnehia et al. reported spatial resolutions of 9 lp/cm (both presets); CNR of 1.1 and 1.9 (low/high presets, respectively); and image uniformity similar to ours of 13.7% and 13.8% (low/high presets, respectively).[32] Dorenlot and Champoudry used a different software (MyQA, IBA Dosimetry, Schwarzenbruck, Germany) with the Catphan 503 phantom to evaluate the image qualities, and reported lower spatial resolution values than ours of 4.9 and 4.8 lp/cm (low/high presets, respectively); higher CNR values of 1.41 and 2.24 (low/high presets, respectively). As for the uniformity test, it seems they used different formalism as they reported values of 83.14 and 86.57 (low/high presets).[36] The current practice at Roswell Park is to perform the image quality tests on a monthly basis, as recommended by the manufacturer[16] and AAPM Task Groups 142[37] & 179[38], with adhering to the manufacturer specifications listed in Table 2.3.1. Furthermore, the U.S. Nuclear Regulatory Commission (NRC) requires a monthly check of the CBCT system to confirm that the CBCT image quality is "satisfactory".[18]
### 2.3. RESULTS AND DISCUSSION

<table>
<thead>
<tr>
<th>Test</th>
<th>[Range] or Average ± SD</th>
<th>Manufacturer Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTDI 2.5 mGy (Low-Dose Preset)</td>
<td>CTDI 6.3 mGy (High-Quality Preset)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>[6,7] lp/cm</td>
<td>[7,8] lp/cm</td>
</tr>
<tr>
<td>CNR</td>
<td>1.07 ± 0.08</td>
<td>1.69 ± 0.10</td>
</tr>
<tr>
<td>Uniformity</td>
<td>12.84% ± 0.70</td>
<td>13.01% ± 0.69</td>
</tr>
</tbody>
</table>

**Table 2.3.1:** Summary results of monthly image quality tests (spatial resolutions, CNR, and uniformity) with the manufacturer specification for each test.

#### 2.3.3 CBCT DOSE CONSTANCY TEST

Our $CTDI_w$ results have been consistent for the commissioning and two annual dose measurements as summarized in Table 2.3.2, and are within 10% of nominal values as specified by the manufacturer. Zeverino et. al. reported $CTDI_w$ values closer to the nominal (2.41 and 6.32 mGy for low/high presets, respectively),[30] while Dorenlot and Champoudry reported values similar to ours (2.23 and 5.9 mGy low/high presets, respectively).[36] Blake et. al. also reported values of 2.4 and 6.0 mGy low/high presets, respectively.[35] According to the manufacturer, less than ± 3% deviations from the nominal values of the Icon’s x-ray unit are expected, and the differences are dependent on the generator, tube output, and the manufacturing of the unit covers.[16] Although the manufacturer describes a methodology for CTDI measurement of Icon’s CBCT, it does not require or give recommendations on the frequency of performing the dose measurement as part of a quality assurance program. At Roswell Park, we have established the tolerance criteria for this test to be ± 5% of our $CTDI_w$ baselines, and will continue to perform this test on an annual basis as recommended by AAPM Task Groups 142[37] and 179.[38]
### 2.4. CONCLUSION

<table>
<thead>
<tr>
<th>CBCT Preset</th>
<th>Measured Average ± SD (mGy)</th>
<th>Nominal Value (mGy)</th>
<th>Ratio (Measured/Nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTDI 2.5</td>
<td>2.3 ± 0.0</td>
<td>2.5</td>
<td>0.92</td>
</tr>
<tr>
<td>CTDI 6.3</td>
<td>5.7 ± 0.1</td>
<td>6.3</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Table 2.3.2:** Results of CTDI measurements (during the commissioning and two annual) with the manufacturer specification of each preset.

In this study, we evaluated the current routine quality assurance checks required by the manufacturer for the Gamma Knife Icon's CBCT as part of the image-guidance system. We found our system performance to meet the manufacturer specifications and our set limits, and to be comparable to other reported values in the literature. These tests, however, are limited to the CBCT part of the image-guidance system and they only check few aspects of the CBCT system.
CBCT-based Stereotactic Space Stability and Agreement with Frame-based Stereotactic Space

This chapter describes a test we developed to investigate the CBCT-based stereotactic space stability and its agreement with the gold-standard Frame-based stereotactic space over a period of 6-weeks. The test was also repeated four months later, and when the department acquired a new CT-simulator device. The work described in this chapter has been published as part of a manuscript in the Journal of Applied Clinical Medical Physics.[39]

3.1 INTRODUCTION

Traditionally, Gamma Knife stereotactic radiosurgery treats intracranial lesions and involves localizing the target coordinates based on an invasive frame fixed to the patient skull.[2] With the advances in image-guided radiotherapy, the possibility of localizing targets using images allows for non-invasive frameless stereotactic radiosurgery, as well as for fractionated stereotactic radiotherapy. The newest Gamma Knife model, Leksell Gamma Knife® Icon™, includes a cone-beam CT (CBCT) which can be used to define the 3D stereotactic coordinate space without the need for an invasive frame system. The CBCT can be used to define the stereotactic space coordinates for either G-frame treatments or the new frameless thermoplastic mask.
3.2. MATERIAL AND METHODS

system. This study evaluates the stability of the CBCT-based stereotactic space definition and confirms it is in agreement with the standard Frame-based stereotactic coordinate system throughout a large volume of the defined stereotactic space, as one element in the overall delivery accuracy chain of the Gamma Knife Icon. Other studies have looked at the accuracy of Gamma Knife delivery when using a thermoplastic mask system for skull immobilization with an IR camera and CBCT [28], and at quantifying translational and rotational shifts when using the invasive frame on a prototype CBCT image-guided Gamma Knife Perfexion unit.[40]

3.2 MATERIAL AND METHODS

3.2.1 CBCT STEREOTACTIC SPACE DEFINITION AND QA TEST

A special calibration tool is used by the manufacturer’s service engineer to find the CBCT to Leksell coordinate transform between the uncalibrated CBCT image and the radiation delivery unit (FIG. 3.2.1a). The tool consists of six steel ball-bearings with known Leksell coordinates. An algorithm running in service mode uses the projection images of a CBCT scan of this special tool to calculate the transformation matrix between CBCT image and the Leksell coordinates systems.[14] This calibration procedure was performed once by the manufacturer’s service engineer at the time of LGK Icon unit commissioning. The manufacturer also provides a user QA tool (QA tool Plus) to enable each user to test the CBCT precision (FIG. 3.2.1b). This CBCT precision check test is performed daily as part of a comprehensive Gamma Knife QA program, and was described earlier in Chapter 2. The pre-programmed CBCT precision test algorithm finds the location of the four ball-bearings from a CBCT scan of this tool and compares them with their baseline coordinates given during the calibration of the tool by the service engineer.[15, 16] The algorithm calculates each fiducial deviation as well as the maximum deviation of tests points in the reconstructed CBCT image volume, and the test is considered “passed” if the maximum deviation in image volume is within the acceptable limit (<

---

1The transformation matrix parameters can be viewed in the CBCT calibration settings file, which can be exported from the LGK treatment console with administration rights.
3.2. MATERIAL AND METHODS

Figure 3.2.1: (a) The manufacturer’s CBCT tool used for calibrating the CBCT position; and (b) The QA tool Plus used in daily CBCT precision tests.

The CBCT Precision test was carried out daily during the six weeks period of our study. A limitation of the QA tool Plus is that it cannot be attached to the standard CT fiducial indicator box to be CT-scanned and determine the traditional Frame-based Leksell coordinates, making it problematic for the user to independently verify the validity of Leksell stereotactic coordinates based on CBCT.

3.2.2 IN-HOUSE MARKER TOOL

A simple tool with fixed fiducial markers that can be easily localized in both CT and CBCT scans was designed and implemented, similar to the tool used in a previous work by the Roswell Park medical physics group[41], to independently test the stability and accuracy of the CBCT-based stereotactic space coordinates. The tool consists of a taut string that is attached to an assembled stereotactic frame (Leksell model G, Elekta Instruments A.B., Stockholm, Sweden), drawn from the left anterior post to the right posterior post. Five ball-bearing fiducial markers (0.5 mm diameter) were rigidly attached to the string, spanning a broad portion of the stereotactic space (70 mm × 120 mm × 55 mm) and distributed such that each of the five markers gives a unique lateral (X), vertical (Y), and longitudinal (Z) coordinates (FIG.3.2.2). For the reference
3.2. MATERIAL AND METHODS

Frame-based stereotactic coordinate definition, CT scans of this tool attached with the standard CT fiducial indicator box (FIG. 3.2.3a) were acquired using a CT simulator (LightSpeed RT16, GE, San Diego, CA) in an axial mode with a 0.625 mm slice thickness at 120 kV and 350 mA. The CT fiducial box was aligned with a set of CT-simulation lasers that are well-maintained in a strict quality assurance program. The CT images were imported to the Leksell GammaPlan (LGP) software V 11.0.2, where the Frame-based Leksell coordinates were determined for each marker. The CT scans were acquired at the beginning, midway, and at end of this study period (six weeks) to confirm the stability of our tool. For the CBCT-based stereotactic coordinate definition, CBCT images of the tool (FIG. 3.2.3b) were taken every working day for six weeks using the two pre-defined scanning settings: CTDI 6.3 mGy (high-quality) preset at 90 kV and 25 mA; and CTDI 2.5 mGy (low-dose) preset at 90 kV and 10 mA. The CBCT images were automatically imported to the LGP software upon scanning. The pixel sizes for both the CT and CBCT images were 0.5 mm (X) by 0.5 mm (Y). However, when projecting these images in the LGP software, the pixel sizes are interpolated and became 0.1 mm (X) by 0.1 mm (Y). The LGP software was used to determine the \((X_{frame}, Y_{frame}, Z_{frame})\) and \((X_{CBCT}, Y_{CBCT}, Z_{CBCT})\) coordinates of each marker for each image set of the CT and CBCT scans, respectively. The geometric center of each marker was determined by a single observer looking for the center of each “fuzzy” enhancement in maximum zoomed-in and maximum contrasted images, as shown in FIG. 3.2.4.

To examine the reproducibility of determining the marker center, the coordinates of each marker were read three times in separate instances by the observer, and the average of the three readings was reported. The magnitude of vector difference \((r)\) between the mean coordinates of Frame-based and CBCT-based was calculated as:

\[
r = \sqrt{(X_{frame} - X_{CBCT})^2 + (Y_{frame} - Y_{CBCT})^2 + (Z_{frame} - Z_{CBCT})^2}.
\]

Furthermore, an additional CBCT of the markers frame tool was scanned four months later to determine the long-term stability of the CBCT-based stereotactic coordinate system. About a year later from conducting the first 6-weeks study, the department acquired a new CT-simulator device (Discovery RT, GE, San Diego, CA), so we reassembled the marker tool and repeated and the stereotactic
3.3 RESULTS AND DISCUSSION

The daily CBCT precision QA test using the manufacturer's QA tool Plus for the six weeks period resulted in a mean of 0.13 mm maximum deviation in image volume between the daily tests and the calibration, with a standard deviation of 0.05 mm and a maximum of 0.22 mm. These daily tests met the manufacturer's limit of 0.4 mm in maximum deviation in image volume, indicating a good reproducibility in CBCT coordinate positions, as shown in FIG. 3.3.1. The reproducibility in determining the markers centers can be quantified as the mean of the standard deviations of three readings of markers coordinates in each CT/CBCT scan set. This was found to be approximately 0.05 mm, with a maximum of 0.13 mm. There was no statistical significant difference (P-value > 0.05 using t-test) in determining the marker positions in CBCT images taken using the two different scanning preset settings (CTDI 6.3 mGy vs. CTDI 2.5 mGy). This is expected in our case as the ball-bearings are easily identified in either scanning preset because
Figure 3.2.3: Flowchart showing the CBCT-based stereotactic space definition vs reference Frame-based dentition experiment method using our in-house marker tool: (a) CT scanning of the in-house marker tool with the CT indicator box attached to for Frame-based stereotactic space definition; and (b) the same tool mounted on the Gamma Knife Icon couch adapter in preparation for CBCT-based stereotactic space definition.
3.3. RESULTS AND DISCUSSION

Figure 3.2.4: A snapshot of the Leksell GammaPlan treatment planning software showing a zoomed-in and maximally contrasted CBCT image of one of the markers (marker (a) is shown here). The coordinates reported for each marker were the average of three readings of the geometrical center of markers as determined visually by a single observer.

of their high contrast with the surrounding air, and as the CBCT to Leksell coordinates calibration is independent of scanning preset used. The daily variations in the difference between mean Frame-based and CBCT-based of each of the five markers positions in the lateral, vertical, and longitudinal directions and the $r$ vector difference magnitudes are shown in FIG. 3.3.2. The graphs indicate good stability of the CBCT-based coordinates over the six weeks period, with standard deviations being less than 0.1 mm for markers positions. The maximum deviation in the magnitude of vector difference ($r$) of the CBCT-based from the Frame-based stereotactic definition during this period was noted to be 0.4 mm, at the end edges of the stereotactic frame (i.e., marker (a) & (e)). The magnitude of vector difference ($r$) between mean coordinates of the Frame-based and the CBCT-based for the five markers ranged from 0.2 to 0.3 mm (Table 3.3.1). Small shift trends in the magnitude and direction of the Frame- and CBCT-based coordinate mean differences were noted as we go from one edge of the stereotactic space to another; i.e., from marker (a) at the most left-anterior-superior point to marker (e) at the most right-posterior-inferior point. In the lateral direction, the mean difference between Frame- and CBCT-based coordinates (i.e., $(X_{frame} - X_{CBCT})$) ranged from 0.2 mm for marker (a) to -0.2 mm.
for marker (e), with the positive sign indicating the Frame-based coordinate being larger than CBCT-based coordinate value. In the vertical direction, the mean difference \((Y_{frame} - Y_{CBCT})\) ranged from 0.1 mm for marker (a) to -0.2 mm for marker (e). In the longitudinal direction, the mean difference \((Z_{frame} - Z_{CBCT})\) ranged from -0.3 mm for marker (a) to 0.1 mm for marker (e).

The data suggests there is a small systematic difference between the Frame-based and CBCT-based stereotactic spaces in our particular unit. The data also suggests that the Leksell space as determined by the CBCT in our unit is "compressed" compared to the frame-based space, i.e. by about 0.5% in the X-direction (69.2 mm in the CBCT case vs. 69.6 mm in the frame case), 0.3% in the Y-direction (120.6 vs. 120.9 mm), and by 0.7% in the Z-direction (53.9 vs. 54.3 mm). Though the differences are small in our explored stereotactic volume (limited to 70 mm x 120 mm x 55 mm), the trend might indicate a larger discrepancy in the whole stereotactic space.

Unit-specific assessments, using an independent tool similar to what we described in this study, can be used in assisting decision-making of selecting which stereotactic reference (i.e. CBCT-based vs. frame-based) to be used for determining the Leksell coordinates depending on the accuracy required for each clinical case. Johansson et. al. evaluated the geometric accuracy of the Gamma Knife Icon with an end-to-end phantom test case and measured the error to be < 0.2 mm, and concluded that the CBCT system of the Icon can accurately be used for patient positioning.\[42\] The markers tool was also scanned four months later to determine the prolonged stability of CBCT-based stereotactic definition. The coordinates of the five markers were within the range of measurements performed in the initial six-week study period, indicating good CBCT-based coordinate definition prolonged stability. The test was also repeated a year later for the new GE CT-simulation installed at Roswell Park, and the mean deviation vector \((r)\) was 0.5 ± 0.1 mm with a maximum of 0.7 mm. The full data are shown in Table 3.3.2. Chung et al. used a CIRS 605 head phantom to assess 15 landmarks and reported a similar mean 3D deviation of 0.5 ± 0.2 mm between Frame-based and CBCT-based coordinates — with a maximum up to 0.8 mm.\[43\] Sarfshnia et. al used a tool similar to ours with BBs embedded in plastic rods spanning the whole imaging volume, and reported the largest discrepancy in the Z-axis with an average of 0.48 mm and a maximum of 0.6 mm. Their overall average was 0.15 ±
Figure 3.3.1: Results of daily CBCT precision QA test over the 6-week study period. The graph shows the variation of maximum deviation in image volume between the daily QA tool Plus and the expected baseline obtained during calibration of the tool.

0.14 mm, however.[32] The agreement of the CBCT-based and Frame-based coordinate system can be easily tested using our tool. Taking into consideration the limitations of our testing tool and methodology, we suggest setting a 1 mm tolerance criteria for this test, and performing the test on a bi-annual schedule and after major changes in the Icon’s CBCT (such as re-calibrating the CBCT coordinate system by the manufacturer) or in CT-simulator equipment.

3.4 CONCLUSION

A simple in-house tool was used to test the stability of the CBCT defined stereotactic space in Gamma Knife Icon and its agreement with the standard Frame defined stereotactic space, independently from the manufacturer provided tool and methodology. CBCT-based stereotactic space definition in Gamma Knife Icon was found to be stable over a period of four months, and in good agreement with the standard Frame-based stereotactic space definition.
Figure 3.3.2: Daily variations of CBCT-based stereotactic coordinates from the mean Frame-based in the lateral, vertical, and longitudinal directions and the magnitude of vector difference $(r)$ of each marker over a period of six weeks.
### Table 3.3.1: Mean ± standard deviation and range of coordinates of each marker in Frame-based stereotactic space \((X_{\text{frame}}, Y_{\text{frame}}, Z_{\text{frame}})\) and CBCT-based stereotactic space \((X_{\text{CBCT}}, Y_{\text{CBCT}}, Z_{\text{CBCT}})\). The standard deviation is calculated over all daily readings taken. The magnitude of vector difference \(r\) is calculated as: 
\[
r = \sqrt{(X_{\text{frame}} - X_{\text{CBCT}})^2 + (Y_{\text{frame}} - Y_{\text{CBCT}})^2 + (Z_{\text{frame}} - Z_{\text{CBCT}})^2}.
\]

<table>
<thead>
<tr>
<th>Marker ID</th>
<th>Frame-Based Coordinates</th>
<th>CBCT-Based Coordinates</th>
<th>(r) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(X_{\text{frame}})</td>
<td>(Y_{\text{frame}})</td>
<td>(Z_{\text{frame}})</td>
</tr>
<tr>
<td>a</td>
<td>136.3 ± 0.2</td>
<td>157.7 ± 0.2</td>
<td>61.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>(136.0-136.4)</td>
<td>(157.4-158.0)</td>
<td>(60.9-61.4)</td>
</tr>
<tr>
<td>b</td>
<td>121.2 ± 0.3</td>
<td>128.4 ± 0.1</td>
<td>75.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>(120.9-121.6)</td>
<td>(128.3-128.6)</td>
<td>(75.3-75.9)</td>
</tr>
<tr>
<td>c</td>
<td>105.9 ± 0.2</td>
<td>101.4 ± 0.1</td>
<td>85.4 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>(105.8-106.3)</td>
<td>(101.3-101.5)</td>
<td>(85.3-85.6)</td>
</tr>
<tr>
<td>d</td>
<td>86.0 ± 0.2</td>
<td>71.9 ± 0.1</td>
<td>97.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>(85.7-86.4)</td>
<td>(71.7-71.9)</td>
<td>(97.2-97.5)</td>
</tr>
<tr>
<td>e</td>
<td>66.7 ± 0.3</td>
<td>36.8 ± 0.1</td>
<td>115.3 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>(66.4-67.0)</td>
<td>(36.6-36.8)</td>
<td>(115.1-115.6)</td>
</tr>
</tbody>
</table>

### Table 3.3.2: Data and results of the stereotactic agreement test for using new GE CT-simulator. The values reported are an average of three readings by a single observer. The magnitude of vector difference \(r\) is calculated as: 
\[
r = \sqrt{(X_{\text{frame}} - X_{\text{CBCT}})^2 + (Y_{\text{frame}} - Y_{\text{CBCT}})^2 + (Z_{\text{frame}} - Z_{\text{CBCT}})^2}.
\]

<table>
<thead>
<tr>
<th>Marker ID</th>
<th>Frame-Based Coordinates</th>
<th>CBCT-Based Coordinates</th>
<th>Displacement in (mm)</th>
<th>(r) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(X_{\text{frame}})</td>
<td>(Y_{\text{frame}})</td>
<td>(Z_{\text{frame}})</td>
<td>(X_{\text{CBCT}})</td>
</tr>
<tr>
<td>a</td>
<td>78.2</td>
<td>141.4</td>
<td>68.2</td>
<td>77.8</td>
</tr>
<tr>
<td>b</td>
<td>101.0</td>
<td>107.1</td>
<td>83.2</td>
<td>100.7</td>
</tr>
<tr>
<td>c</td>
<td>120.0</td>
<td>78.0</td>
<td>97.4</td>
<td>119.7</td>
</tr>
<tr>
<td>d</td>
<td>136.8</td>
<td>53.1</td>
<td>109.6</td>
<td>136.5</td>
</tr>
<tr>
<td>e</td>
<td>154.1</td>
<td>24.5</td>
<td>122.8</td>
<td>153.8</td>
</tr>
</tbody>
</table>
Investigation of the Accuracy of Intra-Fraction Motion Management (IFMM) system, Co-registration Algorithm, and Delivery-after-shifts

In this chapter, we describe a methodology developed for testing the accuracy of some of the novel features introduced in LGK Icon using a translational/rotational stage tool. Our stage tool can be used to test the Intra-Fraction Motion Management (IFMM) system, the co-registration Algorithm, and the unit deliverability after introducing intra-fraction shifts. The work described in this chapter has been published as part of a manuscript in the Journal of Applied Clinical Medical Physics.[33]

4.1 INTRODUCTION

Leksell Gamma Knife Icon comes with a motion management system for tracking patient motion and correcting for inter- and intra-fraction shifts. The application of motion management system is particularly important when using a non-rigid thermoplastic immobilization system as
it is more prone to motion compared to the invasive stereotactic frame immobilization technique. We developed an in-house tool that can be used in the assessment of motion management systems accuracy of the Icon system, namely the Intra-Fraction Motion Management (IFMM) system, the co-registration algorithm, and also to test the accuracy of delivering shots after translational and rotational shifts are introduced. A typical frameless patient treatment workflow starts with planning on a non-stereotactic CT or MRI images of the patient skull that provides the needed anatomical information for treatment planning. A reference CBCT on the Icon system is taken with the patient head laying on a custom pillow and immobilized with the frameless thermoplastic mask system. This reference CBCT image is used to define the Leksell stereotactic coordinates and is co-registered with the planning CT/MRI image in Leksell GammaPlan (LGP) software (V11.0.2, Elekta Instruments, A.B., Stockholm, Sweden). Prior to treatment delivery, the patient is immobilized again with the custom thermoplastic mask, and a setup CBCT is taken in the treatment position. This setup CBCT is co-registered with the reference CBCT to determine the inter-fractional shifts. Any translation or rotation differences between the setup CBCT and reference CBCT are calculated by the LGP software and an optimum translational couch shift is proposed. A new dose distribution plan is shown for physician approval taking into account the changes in the plan due to rotational/translational shifts. During the treatment delivery, the intra-fractional motion is determined by tracking a reflector marker placed on the tip of patient nose detected by the couch mounted IR camera. A displacement of this reflector above a threshold, that can be set between 0.5 to 3 mm, triggers an automatic delivery stop when using the "active" monitoring mode. Intra-fractional setup CBCTs can be acquired and co-registered with the reference CBCT if the marker displacement did not return back below the threshold, and the process of co-registration with the reference CBCT and plan adaptive is repeated.[21]
4.2 MATERIAL AND METHODS

We used a manual linear translation stage (Velmex Inc., Bloomfield, NY) with a submillimeter shift accuracy in the three perpendicular planes: X (lateral), Y (vertical), and Z (longitudinal). A rotary component added to this stage allowed for sub-degree rotation around the vertical Y-axis (yaw). A Lucite platform is attached to the translation stage such that it falls in the CBCT field of view when scanning the tool. A post is attached to the platform with an infrared reflector marker for testing the IFMM system movement accuracy. The platform also hosts two mini-phantoms as film holders that can be embedded with Gafchromic EBT2 films (International Specialty Products, NJ) in two different locations and positions; one being parallel to the couch motion plane (XZ plane), while the other is perpendicular to the couch motion plane (YZ plane), as shown in (Fig.4.2.1). The holder phantoms have holes for punching the embedded films that are visible in CBCT images and are used for radiation shots placements when planning.

For performing the accuracy tests, a treatment plan was created based on CT simulator images (LightSpeed RT 16, GE, San Diego, CA) with two shots placed on the film planes just under the visible holes using the smallest collimator available (4 mm). A reference CBCT was then taken.
4.2. MATERIAL AND METHODS

**Tx Planning:**

- Reference CBCT
- Plan shots at mini-phantom hole centers

**Tx Delivery:**

- Introduce a shift
- Setup CBCT after the shift
- Co-registering Setup CBCT with Reference CBCT
- Accept adapted plan to apply translational corrections
- Punch Film
- Deliver shots

**Figure 4.2.2:** A flowchart showing steps for the end-to-end accuracy test using the translational tool

with the Icon system and co-registered with the planning CT. A shift was introduced with the stage prior to the setup CBCT to mimic an inter-fraction motion, and the IFMM system was checked for reading accuracy against this shift. A setup CBCT was taken next and was co-registered with reference CBCT to calculate the shifts with the LGP co-registration algorithm which was checked against the actual introduced shifts. Two shift scenarios were tested in our work: 1) A simple shift test (2 mm in X, 2 mm in Y, and 2 mm in Z directions); and 2) A complex shift test (20 mm in Z, 5 mm in X, and 5 mm in Y followed by a clockwise rotation of 1 degree).

The shifts delivery was carried out for the same scenarios described above. The films were scanned with an Epson Perfection V700 flatbed color scanner (Epson America, Long Beach, CA) and processed in MATLAB® release 2015b (The MathWorks, Inc., Natick, MA) to determine the deviation of radiation shot center from the punch point. The matlab code developed to analyze these films can be found in Appendix A.1. Fig.4.2.2 shows a flowchart of the steps for this end-to-end test. These accuracy tests were repeated six times each for establishing baselines.

A second method to check the co-registration and IFMM accuracy was to apply the rotational and translational shift parameters indicated by the LGP co-registration algorithm in a rigid transformation matrix formula to calculate the new coordinates of a selected reference point after
the shifts. As described by Wright et al., the predicted coordinates \((x_b, y_b, z_b)\) can be calculated from the reference coordinates \((x_a, y_a, z_a)\) after translational shifts \((\Delta x, \Delta y, \Delta z)\) and rotational shifts around the Leksell Coordinate Space (LCS) center \((100, 100, 100)\) as: [21]

\[
\begin{bmatrix}
  x_b \\
  y_b \\
  z_b
\end{bmatrix} = \begin{bmatrix}
  x_a - 100 \\
  y_a - 100 \\
  z_a - 100
\end{bmatrix} + T
\]

where \(T\) is the translation matrix

\[
T = \begin{bmatrix}
  x + 100 \\
  y + 100 \\
  z + 100
\end{bmatrix}
\]

and \(R\) is the rotation matrix

\[
R = R_z(\theta_z).R_y(\theta_y).R_x(\theta_x)
\]

with

\[
R_z(\theta_z) = \begin{bmatrix}
  \cos(\theta_z) & -\sin(\theta_z) & 0 \\
  \sin(\theta_z) & \cos(\theta_z) & 0 \\
  0 & 0 & 1
\end{bmatrix}
\]

\(\theta_z\) being the angle of rotation about the Z-axis (roll);

\[
R_y(\theta_y) = \begin{bmatrix}
  \cos(\theta_y) & 0 & \sin(\theta_y) \\
  0 & 1 & 0 \\
  -\sin(\theta_y) & 0 & \cos(\theta_y)
\end{bmatrix}
\]
4.3 RESULTS AND DISCUSSION

\( \theta_y \) being the angle of rotation about the Y-axis (yaw); and

\[
R_x(\theta_x) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\theta_x) & -\sin(\theta_x) \\
0 & \sin(\theta_x) & \cos(\theta_x)
\end{bmatrix};
\tag{4.6}
\]

\( \theta_z \) being the angle of rotation about the X-axis (pitch).

The calculated coordinates were compared with the actual coordinates of the same point as identified in the treatment console of post-shift CBCT images. We tracked two points in our stage tool while applying the complex shift test: point (A) being close to the reflective marker, and point (B) being at the punch hole of the vertical film holder. The three-dimensional vector displacement magnitude of point (A), between a reference and calculated coordinates, was used to compare and check the IFMM reading accuracy.

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4.3 RESULTS AND DISCUSSION

The discrepancy between IFMM reading and the actual movements in each of the X, Y, and Z direction is shown in Fig.4.3.1 for both simple and complex shift tests scenarios. The average difference is -0.01 ± 0.08 mm with a maximum of 0.16 mm for the simple shift test, and 0.03 ± 0.17 mm with a maximum of 0.29 mm for the complex shift test. In the complex test, the larger discrepancy could be attributed to the large travel in the Z direction (20 mm) that caused it to sag and move out of plane.

Fig.4.3.2 shows the results for the co-registration accuracy test in both simple and complex shift test scenarios. The average difference for the simple shift test was 0.01 ± 0.04 mm with a maximum difference of 0.09 mm. For the complex shift test, the average was 0.05 ± 0.09 mm with a maximum difference of 0.23 mm. We found the co-registration rotation shift values dependant on the initial position of the phantom when performing the complex shift test, and thus it is important to keep consistent positioning of the tool. The co-registration algorithm determines the rotation around the center of the unit (i.e. point 100, 100, 100), while our tool
Figure 4.3.1: IFMM accuracy test results using the translation stage tool for the (a) Simple shift test; and (b) Complex shift test.
axis of rotation is located outside of the Leksell coordinates system and the exact location is needed to determine the expected shift. In our calculation we used a transformation matrix to determine the expected shift values in each axis, however since the location of the rotational point could not be determined exactly this lead to uncertainty in our comparison when performing the complex shift test that included a rotational shift.

The results for the delivery-after-shift test (films shots) are shown in Fig. 4.3.3 for both simple and complex shift test scenarios. For the simple shift test, the average difference between the center of the shot and film punch point was $0.26 \pm 0.09$ mm with a maximum of 0.40 mm. Similarly for the complex shift test, the average difference was $0.22 \pm 0.08$ mm with a maximum of 0.38 mm.

The histogram in Fig. 4.3.4 shows the distribution of differences in coordinates between those predicted by the transformation matrix and those observed from the images for two Points (Point A at the post top, and Point B at the XY holder central hole). The coordinates calculations using the transformation matrix agrees within 0.2 mm of the observed ones in about 86% of the coordinates tested (i.e. in 31 coordinates out 36). The maximum discrepancy was 0.5 mm. Also, the three-dimensional vector displacement of Point A (close to the IR reflective marker) was compared to the IFMM reading, and the average discrepancy was less than 0.1 mm with a maximum of 0.15 mm in the six trails. We found the transformation matrix method to be a reliable alternative method for checking the co-registration algorithm accuracy, and for checking the IFMM accuracy using a point close to the reflective marker.

Table 4.3.1 summarizes our results for the accuracy tests of IFMM system, co-registration algorithm, and delivery-after-shift. For the IFMM system, the instantaneous reading value can fluctuate by up to $\pm 0.1$ mm while tracking a stationary object, and we found the accuracy of the system to be within that range. The maximum differences we found were 0.23 mm when assessing only the translational IFMM accuracy (for a 5 mm shift in X direction), and -0.27 mm when adding the 1 degree rotation to the combination of translational large shift. Dorenlot and
4.3. RESULTS AND DISCUSSION

Co-registration Accuracy Check
(Simple Shift)

Co-registration Accuracy Check
(Complex Shift)

Figure 4.3.2: Co-registration algorithm accuracy test results using the translation stage tool for the (a) Simple shift test; and (b) Complex shift test.
**Figure 4.3.3:** Delivery-after-shift accuracy test results using film shots in the 3D stage tool for the (a) Simple shift test; and (b) Complex shift test.
4.3. RESULTS AND DISCUSSION

Figure 4.3.4: A distribution of the deviation of predicted coordinates (using the transformation matrix method) from the observed coordinates (in mm).

Champudry reported IFMM accuracy of 0.01 mm with a maximum error of 0.05 mm when assessing the translation accuracy with a micrometer screw. Blake et al. reported IFMM readout agreement of 0.04 mm with their independent system. Sarfheinia et al. reported an average IFMM agreement of 0.05 with a maximum of 0.23 mm. The co-registration algorithm test also showed accuracy in the order of 0.1 mm, with a maximum of 0.23 mm difference in the Z direction. The agreement in the rotational shift averaged 0.01 ± 0.01 degrees with a maximum of 0.03 degree. Sarfheinia et al. reported an average co-registration agreement of 0.1 mm with a maximum of 0.23 mm (translational), and average of ±0.2° (rotational).

We found the transformation matrix method we used to test the accuracy of the co-registration algorithm and the IFMM system to be a useful test with sub-millimeter accuracy. This method can easily be applied in clinical settings to check the co-registration algorithm, provided that coordinates of a landmark are identified in both the reference CBCT and setup CBCT in the treatment console. As described by Wright et al., the IFMM system can be checked in a clinical setting by utilizing a second setup CBCT to calculate the three-dimensional vector of a point.
4.3. RESULTS AND DISCUSSION

close to the IR reflector on patient's nose. This calculated vector would correspond to the IFMM displacement magnitude.\[21\] One limitation of the transformation matrix method is that it is based on an accurate reading of coordinates in Icon's CBCT images, which has a voxel size of 0.5 mm. Our accuracy test results for the film test were close to the values reported by the manufacturer\[14\], indicating a sub-millimeter accuracy of the Icon to deliver accurate radiation shots based on its image-guidance system. Zeverino et. al. carried out an experiment by delivering a 16-mm shot sets at the center of a Ball Cube phantom placed in CBCT LSC center, with embedded orthogonal films, after shifting (15 mm lateral, 10 mm vertical, and 20 mm longitudinal) and reported a maximum CBCT correction (i.e. co-registration error) of 0.4 mm. Their experiment also indicated CBCT isocenter to be within 0.2 mm of the radiological focus.\[30\] Two of accuracy tests (co-registration and delivery-after-shift) could potentially be affected by CBCT artifacts. We have kept the metallic base of our tool out of CBCT field to avoid any metal artifact streaks that would affect the image co-registration quality. Another source that could affect the accuracy would be the inaccuracy with using FDK algorithm in CBCT reconstruction for planes with non-orthogonal beam, as structures would appear elongated or smeared out in the longitudinal direction as you move away from the frame fixation (beam is orthogonal close to frame fixation, and the FDK reconstructing is exact in that plane).\[19\] This might affect the co-registration accuracy which in turn could affect delivery-after-shift accuracy in these extreme locations corresponding to the top of the skull areas. However, we don't anticipate that our tool (with small rectangular holders and tiny holes) will be able to detect the small additional error due to such artifact. In clinical practice, one ambiguity the user faces is that the system proposed translational corrections are not visible to the user in terms of updated couch position coordinates after the co-registration of the setup CBCT with the reference CBCT to account for patient inter-fractional shifts. Therefore, the user is left to trust the system's automatic application of these shifts without any verification. We feel that testing the unit's determination of shift and applying it correctly is an important routine QA test to ensure the safe use of the system. We suggest performing these accuracy tests of IFMM, co-registration algorithm, and deliver-after-shift on annual bases. Taking into consideration the limitations of
4.4 CONCLUSION

<table>
<thead>
<tr>
<th>Test</th>
<th>Average difference ± SD (mm)</th>
<th>Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFMM Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3D Stage Method)</td>
<td>0.00 ± 0.12</td>
<td>[-0.27, 0.23]</td>
</tr>
<tr>
<td>(Transformation Matrix Method)</td>
<td>0.08 ± 0.08</td>
<td>[-0.07, 0.15]</td>
</tr>
<tr>
<td>Co-registration Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3D Stage Method)</td>
<td>0.03 ± 0.06</td>
<td>[-0.06, 0.23]</td>
</tr>
<tr>
<td>(Transformation Matrix Method)</td>
<td>-0.01 ± 0.13</td>
<td>[-0.48, 0.21]</td>
</tr>
<tr>
<td>Delivery-After-shift Accuracy</td>
<td>0.24 ± 0.09</td>
<td>[0.08, 0.42]</td>
</tr>
</tbody>
</table>

Table 4.3.1: Summary results of accuracy tests of the Intra-fraction Motion Management system (IFMM), co-registration algorithm, and delivery-after-shift to a film. The results for IFMM and co-registration (3D stage method) and the shot measurements are averaged over a simple shift (2 mm in each of X, Y, and Z direction) and a complex shift (5 mm in X and Y directions, 20 mm in Z direction, and 1 degree rotation along Y) test scenarios. The difference is calculated as measured value minus expected value.

our testing tool and methodology, we suggest setting a 0.5 mm tolerance criteria for each test, and a 0.5 degree for the co-registration algorithm test. Furthermore, the U.S. Nuclear Regulatory Commission (NRC) requires a monthly check of the IFMM system functionality by performing a test, without a patient present aiming to check its quantitative output.[18]

4.4 CONCLUSION

Our tool and methodology were successfully implemented for verifying the accuracy of the Leksell Gamma Knife Icon’s motion management system to be within 0.5 mm. Our experience with testing the system accuracy is being implemented in a comprehensive quality assurance program for LGK Icon’s image-guidance system. This tool is portable and can be used in quality assurance tests of other radiosurgery devices as well.
This final chapter outlines our proposal for a comprehensive quality assurance program of the image-guidance system used in Leksell Gamma Knife Icon; an attempt to cover the gap in this important area.

5.1 INTRODUCTION

The WHO (World Health Organization) defines quality assurance (QA) in radiotherapy as "all procedures that ensure consistency of the medical prescription, and safe fulfillment of that prescription, as regards to the dose to the target volume, together with minimal dose to normal tissue, minimal exposure of personnel and adequate patient monitoring aimed at determining the end result of the treatment".[44] The term "Quality Control" is often used interchangeably with "Quality Assurance" but it typically refer to the itemized tests within a QA program. In order to fulfill the QA requirements, participation from the entire radiation oncology team (i.e. radiation oncologists, medical physicists, therapists, and nurses) is a must. Quality assurance is one of the primary tasks of medical physicists that fall under their scope of practice, as they are active in the acceptance, commissioning, and periodic quality control of radiation treatment
equipment\cite{45} including the image guidance systems/techniques used in radiation therapy.\cite{25} The image-guidance in stereotactic radiosurgery QA program should be established by a qualified medical physicist (QMP)\footnote{The American Association of Physicists in Medicine (AAPM) defines the Qualified Medical Physicist (QMP) as “an individual who is competent to independently provide clinical professional services in one or more of the subfields of medical physics.” The specific medical physics subfield in our context is Therapeutic Medical Physics. A qualified medical physicists credentials include master’s or doctoral degree in medical physics or related fields from an accredited university; and certification in the specific subfield by an appropriate national certifying body and meeting its requirements for continuing education. In North America, the subfield of Therapeutic Medical Physics certification is granted by The American Board of Radiology; The American Board of Medical Physics; and The Canadian College of Physicians in Medicine.\cite{46}} who is trained in SRS to ensure the safety, reliability, consistency in operation of an image-guidance technology accounting for the goals, such as geometric correction and adaptive radiotherapy, to be achieved with such a system.\cite{38} This includes establishing and monitoring a program of daily, monthly, and annual quality control (QC) tests for IGRT sub-systems.\cite{25} A comprehensive QA program is particularly important in stereotactic radiosurgery (SRS) to ensure the prescribed dose delivery to the target, given the small volume and rapid dose fall-off needed to save the nearby healthy brain structures in cranial radiosurgery. The QA program should be reviewed by a second qualified medical physicist trained in SRS. The routine quality control tests may be performed by an appropriately trained medical physicist, such as Medical Physicist Assistant (MPA)\cite{47}, but must be reviewed and co-signed by the QMP in charge. If a system is found out of tolerance, the affected modules should be promptly adjusted, and the QMP should verify its performance before resuming the clinical service. The design for such a QA program should include the policy and procedure of QC tests, frequencies, tolerance levels, non-compliance actions, education and training of personnel performing the tests, record keeping and review of results and adherence to the QA program by the QMP. There are several publications that describe safety and QA recommendation for SRS delivery in general\cite{37,48,49}, image-guidance systems\cite{25,38,50,51}, and some focuses on tests applicable in particular to the Gamma Knife.\cite{8,10,30-32} As of the writing of this dissertation, the American Association of Physicists in Medicine (AAPM) released a draft of a new report (AAPM TG-178) that outlines QA specifically for Gamma Knife for AAPM members feedback. However, even this new report does
not specifically address QA protocols for add-on devices in Gamma Knife (i.e. CBCT and IFMM used for image-guidance).[52] As the image-guidance application is still relatively new to Gamma Knife, there is no comprehensive QA program guidelines for this system. In this chapter we describe our proposed QA program that can be implemented to ensure the safe use of the image-guidance system in Gamma Knife Icon delivery.

5.2 QUALITY CONTROL TESTS, FREQUENCIES, AND TOLERANCES

Based on the experience we obtained throughout this work with the current QC tests required and recommended by the manufacturer[16]; our user-defined tests[33, 39]; the limited published work by others[30, 32]; and regulatory requirements[18], we came up with a comprehensive list of QC tests with their frequencies and tolerances. Table 5.2.1 summaries our comprehensive image-guidance quality assurance program for Gamma Knife Icon.

Commissioning tests are also listed in this proposed QA program as they are important in obtaining performance baselines and ensuring the safe use of introduced technology. The followings are brief descriptions and notes of each quality control test:

**Commissioning Tests:**

C1. The CBCT functionality and connection tests the functionality of the CBCT scanning and its ability to communicate and transfer reconstructed and calibrated CBCT images from the unit to the console and to Leksell GammaPlan.

C2. The IFMM system functionality and connection tests the functionality of the Intra-fraction Motion Management system and its ability to communicate with the treatment console and to pause treatment if marker shift exceeded the set threshold in active mode.

C3. The CBCT radiation field boundaries test checks the boundary of the imaging radiation field with respect to boarder landmarks on the head support and IFMM reference reflective markers posts to ensure there is no unnecessary exposure to patient organs (e.g. thyroid). This test is performed with Gafchromic CT Multi-rule films that can be marked
and easily checked for radiation exposure. See Fig. 5.2.1.

C4. Calibration of CBCT coordinates is performed by the manufacturer service engineer using their Service Calibration tool and a special algorithm in service mode to detect the imaged fiducial markers which have known Leksell stereotactic coordinates. The transformation matrix is calculated and stored to be used for converting CBCT images into the Leksell coordinate space.

C5. The shot delivery accuracy post shifting test is performed by the manufacturer service engineer using their head phantom that can be embedded with a film piece. The film is punctured with a pin and a shot is planned to target the punctured center. The process of frameless treatment is carried out by introducing a displacement to the head phantom and the shot is delivered after the unit corrects for the displacement. See Fig. 5.2.2.

**Daily Tests**

D1. CBCT Precision tests the constancy of CBCT coordinate calibration using the pre-programmed CBCT precision test algorithm, which finds the location of the four ball-bearings from a CBCT scan of QA Plus Tool and compares them with their baseline coordinates obtained during the calibration of the tool by the service engineer.[15, 16]. The algorithm calculates each fiducial deviation as well as the maximum deviation of tests points in the reconstructed CBCT image volume, and the test is considered “passed” if the maximum deviation in image volume is less than 0.4 mm.[16]

**Monthly Tests:**

M1. The image spatial resolution is determined by an observer finding the highest numbered line pair that can be seen in a CBCT image of the Catphan 503 phantom. Minimum of 6 lp/cm is required for both low-dose (CTDI 2.5) and high-quality CBCT (CTDI 6.3) scanning presets.[16]

M2. The image contrast to noise ratio (CNR) is calculated from an image of a polystyrene and LDPE inserts in the Catphan 503 phantom using the equation:

\[
CNR = \frac{I_{PS} - I_{LDPE}}{\sqrt{\sigma_{PS}^2 + \sigma_{LDPE}^2}}
\]  

(5.1)
where $\bar{I}_{PS}$ and $\bar{I}_{LDPE}$ indicate the mean pixel values using a 5-mm square image probe for the polystyrene and LDPE, respectively; and $\sigma_{PS}$ and $\sigma_{LDPE}$ indicate the standard deviation values for the same inserts. A CNR larger than 0.5 is required for low-dose CBCT scanning preset ($CTDI_{2.5}$), and larger than 0.8 for the high-quality preset ($CTDI_{6.3}$).

M3. The image uniformity is determined by taking five readings at the center, 12, 3, 6, and 9 o'clock positions of an image of a homogenous section of the Catphan 503 phantom using a 10-mm square image probe. The uniformity can be then calculated using the formula:

$$Uniformity = 100 \% \times \frac{\bar{I}_{max} - \bar{I}_{min}}{\bar{I}_{max} + 1000}$$

where $\bar{I}_{max}$ is the maximum mean pixel value, and $\bar{I}_{min}$ is the minimum mean pixel value of the five readings. A uniformity value smaller than 14% is required for both low-dose ($CTDI_{2.5}$) and high-quality CBCT ($CTDI_{6.3}$) scanning presets.

M4. The IFMM system simple-shift accuracy is tested by shifting a reflected marker posted on the translation stage 2 mm in each of $X$, $Y$, and $Z$ directions and comparing the IFMM reading against the actual shift. Maximum of 0.3 mm deviation between actual shift and reported IFMM reading is required.

Bi-annual Tests:

BiA1. The CBCT- vs. Frame-based Leksell Coordinate Space test checks the agreement of the CBCT-based coordinates with the golden-standard Frame-based coordinates. The test is performed by comparing the coordinates of ball-bearing markers hanged on our in-house frame tool in Icon CBCT defined space with the Frame defined space of a CT image of the tool. Three-dimensional vector deviation that is less than 1 mm is required.

Annual Tests:

A1. The IFMM system complex-shift accuracy is tested by shifting a reflected marker posted on the translational stage 5 mm in each of $X$, $Y$, and $Z$ directions and 1 degree along $Y$-axis ($yaw$), and comparing the IFMM reading against the actual shift. Maximum of 0.3
5.2. QUALITY CONTROL TESTS, FREQUENCIES, AND TOLERANCES

mm deviation between actual shift and reported IFMM reading is required.

A2. The co-registration algorithm accuracy is tested by CBCT the platform attached to the
translation stage in a reference position, then shifting the platform and taking a setup
CBCT for the LGP co-registration algorithm to calculate the shift. Maximum of 0.5 mm
(translational) and 0.5° (rotational) deviation between actual and reported shift is
required.

A3. The delivery-after-shift accuracy is tested by delivering a radiation shot to films hosted in
the translation stage after the Icon system has implemented the needed corrections based
on co-registration of setup CBCT with reference CBCT on which the original radiation
plan applies. Maximum of 0.5 mm deviation is required between radiation shot center
visible on the film and planned shot center as indicated by a punch hole.

A4. The CTDI dose is measured in a Lucite head phantom using with a calibrated 10-cm
pencil ionization chamber/electrometer combination. The head phantom is placed on a
Styrofoam spacer on the Icon’s patient head support to bring the phantom central in the
CBCT field of view. The weighted CTDI ($CTDI_w$) is derived from the weighted average
of central and peripheral dose measurements values using the formula:[34]

$$CTDI_w = \frac{1}{3} CTDI_{center} + \frac{2}{3} CTDI_{periphery}$$

Note: At Roswell Park, this test is typically performed by a provided by a third-party
physics consulting service (Advanced Medical Physics, Inc.). However, a
cross-calibration of our pencil chamber (Victoreen 500-100/SN 207) and electrometer
(Keithly 35040/SN 59171 / -300 V bias) with a calibrated system (Radcal Mod 10xs-3ct
/SN 9123) was carried out under Icon’s CBCT beam and resulted in a calibration
coefficient of 9.24 mGy/nC (or 1.062 R/nC) for our chamber/electrometer system
combination.

A4. Image-guidance QA program review is performed by a qualified medical physicist in
<table>
<thead>
<tr>
<th>Designator</th>
<th>Quality Test</th>
<th>Tolerance</th>
<th>QA Tools/Equipment/Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commissioning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>CBCT Operation &amp; Connectivity</td>
<td>Functional</td>
<td>NA</td>
</tr>
<tr>
<td>C2</td>
<td>IFMM Operation &amp; Connectivity</td>
<td>Functional</td>
<td>NA</td>
</tr>
<tr>
<td>C3</td>
<td>CBCT Radiation Field Boundaries</td>
<td>&lt; 0.5 cm</td>
<td>Gafchromic CT Multi-rule films (Fig.5.2.1)</td>
</tr>
<tr>
<td>C4</td>
<td>Calibration of CBCT Coordinates</td>
<td>Complete</td>
<td>Service Calibration Tool (Fig.3.2.1.a)</td>
</tr>
<tr>
<td>C5</td>
<td>Shot Delivery Accuracy after a Shift</td>
<td>≤ 0.5 mm</td>
<td>Manufacturer phantom, Gafchromic films (Fig.5.2.2)</td>
</tr>
<tr>
<td><strong>Daily</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>CBCT Precision Test</td>
<td>≤ 0.4 mm</td>
<td>QA Tool Plus (Fig. 2.2.1) / Daily Form (Fig.5.3.1)</td>
</tr>
<tr>
<td><strong>Monthly</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>Image Spatial Resolution</td>
<td>minimum 6 lp/cm</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Image Contrast to Noise Ratio</td>
<td>&gt; 0.5 (CTDI 2.5); &gt;0.8 (CTDI 6.3)</td>
<td>Catphan® 503 Phantom (Fig.2.2.2) / Monthly Form (Fig.5.3.2)</td>
</tr>
<tr>
<td>M3</td>
<td>Image Uniformity</td>
<td>&lt; 14%</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>IFMM System Accuracy (simple shift)</td>
<td>≤ 0.3 mm</td>
<td>In-house 3D stage; Reflective marker (Fig.4.2.1) / Monthly Form (Fig.5.3.2)</td>
</tr>
<tr>
<td><strong>Bi-annually</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA1</td>
<td>CBCT-based vs. Frame-based Stereotactic</td>
<td>≤ 1 mm</td>
<td>In-house Marker Tool (Fig. 3.2.1) / Bi-annual &amp; Annual Form (Fig.5.3.3)</td>
</tr>
<tr>
<td><strong>Annually</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>IFMM System Accuracy (complex shift)</td>
<td>≤ 0.3 mm</td>
<td>In-house 3D stage; Reflective marker (Fig. 4.2.1) / Bi-annual &amp; Annual Form (Fig.5.3.3)</td>
</tr>
<tr>
<td>A2</td>
<td>Co-registration Algorithm Accuracy</td>
<td>≤ 0.5 mm &amp; &lt; 0.5°</td>
<td>In-house 3D stage (Fig. 4.2.1) / Bi-annual &amp; Annual Form (Fig.5.3.3)</td>
</tr>
<tr>
<td>A3</td>
<td>Delivery-after-shift Accuracy</td>
<td>≤ 0.5 mm</td>
<td>In-house 3D stage, Gafchromic Films (Fig. 4.2.1) / Bi-annual &amp; Annual Form (Fig.5.3.3)</td>
</tr>
<tr>
<td>A4</td>
<td>CTDI Dose Measurement &amp; compliance</td>
<td>± 5% of baseline</td>
<td>CTDI head phantom, Calibrated pencil ion chamber (Fig.2.3.3/Bi-annual &amp; Annual Form (Fig.5.3.3))</td>
</tr>
<tr>
<td>A5</td>
<td>Review of test results &amp; compliance</td>
<td>Complete</td>
<td>Annual Review Form (Fig.5.3.4)</td>
</tr>
</tbody>
</table>

Table 5.2.1: Quality Assurance Program for Icon's Image Guidance System.
* or upon CBCT service calibration
Figure 5.2.1: Setup for the CBCT radiation boundaries test using Gafchromic CT Multi-rule films.

charge of Gamma Knife operation to ensure compliance of tests performing and results.
5.2. QUALITY CONTROL TESTS, FREQUENCIES, AND TOLERANCES

(a) Head Phantom with film insert
(b) Punching center of planned radiation shot
(c) Re-inserting film holder into position
(d) Setup of head phantom prior to delivery
(e) Delivered film shot with a centered punch

Figure 5.2.2: Shot delivery accuracy test after introducing a random shift performed during Icon’s commissioning by Elekta service engineers.
5.3 RECORDING AND DOCUMENTATION

An important part of any quality assurance program is the recording and documentation of tests performed. Checklists have been used in medical[53, 54] and non-medical fields[55, 56] and proven to reduce the risk of error caused by lapses of concentration, distractions, exhaustion or burnout.[57] In order to keep track of the different image-guidance system QC tests results performed and their adherence to frequencies and tolerance levels, the daily and monthly QA checklist forms used currently at Roswell Park by the medical physics team have been updated to include the CBCT Precision Test results (daily) and the image quality tests and IFMM simple shift results (monthly). These checklist forms are shown in Fig.5.3.1 and Fig.5.3.2, respectively. A new checklist form is introduced to document the bi-annual CBCT vs. Frame-based stereotactic coordinate agreement test, and the annual IFMM accuracy; co-registration accuracy; delivery-after-shift accuracy; and CTDI measurement tests, as shown in Fig.5.3.3. For the annual QA review, a new form is introduced to keep track of reviewing and compliance of this QA program, as shown in Fig. 5.3.4.
# 5.3. RECORDING AND DOCUMENTATION

**Roswell Park Cancer Institute**  
**Gamma Knife – Daily Quality Assurance**  
**ICON Serial Number 6047**

<table>
<thead>
<tr>
<th>Date:</th>
<th>Signature:</th>
</tr>
</thead>
</table>

**Note:** All questions below should be answered “Yes”. If not, contact physics before treating patients.

## 1. Visual and aural checks

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Are both patient viewing monitors and cameras on and functioning?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>Are the patient audio communications functioning?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c)</td>
<td>Does the emergency light flash and the alarm sound when the emergency test is performed?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d)</td>
<td>Are the emergency procedures posted?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e)</td>
<td>Is the door lock intact and functioning?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f)</td>
<td>Interlock check:</td>
<td>Docking</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Treatment room door</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Siderrail (right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Siderrail (left)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## 2. Treatment QA

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Run 'Sector Activation' in 'Test' Mode</td>
<td>Pause (blue)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Door Interlock</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emergency Off</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Positions OK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tx completion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>Focus Precision Test (passed within last month)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c)</td>
<td>CBCT Precision Test (passed within last month)</td>
<td></td>
<td>&lt; 0.4 mm</td>
</tr>
<tr>
<td>d)</td>
<td>Does the timer countdown properly?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e)</td>
<td>While the beam is running:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Is the red light above the room door lit?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Is the in-room radiation monitor functioning?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Does the machine status indicator function (green = beam off, red = beam on)?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## 3. Gamma Plan QA

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Is the Gamma Plan computer functioning?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>Is the dose rate correct for today?</td>
<td>Gymin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure 5.3.1:** Modified daily QA form with the CBCT precision test added section.
### 3.181 Roswell Park Comprehensive Cancer Center

**Gamma Knife – Monthly Quality Assurance**

**ICON Serial Number 6047**

<table>
<thead>
<tr>
<th>Date:</th>
<th>Signature:</th>
</tr>
</thead>
</table>

#### 1. Daily Checks
- Are the daily quality assurance checks complete and satisfactory?

#### 2. Couch Movement Time
- Perform a 1.0 minute timer run. Record the time, with a stopwatch, required for the couch to move in and out.

<table>
<thead>
<tr>
<th>Time in:</th>
<th>Time out:</th>
</tr>
</thead>
</table>

#### 3. Radiation Output and timer linearity
- Measure output with the 16 mm helmet, an ionization chamber and the 16 cm diameter qa sphere. Record results. Output (Gy/min) difference (%)

<table>
<thead>
<tr>
<th>Calculated (July 3, 2014: 3.325 Gy/min)</th>
<th>Gamma Plan Output</th>
<th>Measured Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

- Does the measured dose rate agree with both the calculated and gamma plan dose rates?

- Is the radiation output linear with planned time?

- Is the lag time calculated to be within 0.0 minutes (+ 0.05 minutes)?

- Is the measured output consistent with the calculated output?

#### 4. QA Clearance Tool Test
- Are the observed clearances consistent with the test?

#### 5. Gamma Plan Software
- Using the calculated output, determine the time required to deliver 100 Gy to the center of a 16 cm diameter sphere.
- Are all the calculated and software times within 0.1 minutes?

<table>
<thead>
<tr>
<th>Helmet</th>
<th>Calculated time (min)</th>
<th>LGP time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm helmet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 mm helmet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 mm helmet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 6. CBCT Image Quality Tests
- Are the spatial resolution values for both CTDI setting > 6 lp/cm?

- Is the CNR value: > 0.5 (for CTDI 2.5) & > 0.8 (for CTDI 6.3)?

- Is the uniformity (% difference values) < 14% for both CTDI setting?

#### 6. IFFM Accuracy (simple shift test)
- For a simple shift test of 2 mm (in X), 2 mm (in Y), and 2 mm (in Z), is the IFFMM reading ≤ 0.3 mm of the expected compound displacement?

#### 7. Collision Test: Does Alarm sound and Sources Retract when there is a collision with the helmet cap?

**Figure 5.3.2:** Modified monthly QA form with the CBCT Image Quality and IFFMM accuracy (simple shift) tests added section.
## 1. CBCT vs. Frame-based Stereotactic Coordinates Agreement (Bi-annual)

<table>
<thead>
<tr>
<th>Marker</th>
<th>$X_{Frame}$</th>
<th>$Y_{Frame}$</th>
<th>$Z_{Frame}$</th>
<th>$X_{CBCT}$</th>
<th>$Y_{CBCT}$</th>
<th>$Z_{CBCT}$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Do the $x,y,z$ coordinates of all BBs in CBCT reference images agree with the corresponding ones in the frame-based CT image within ±1 mm?

b) Is the vector $r = (X_{Frame} - X_{CBCT})^2 + (Y_{Frame} - Y_{CBCT})^2 + (Z_{Frame} - Z_{CBCT})^2$ ≤ 1 mm for all markers?

### 2. Image-Guidance Accuracy Tests (Annual)

a) Is the IFMM Accuracy Test ≤ 0.5 mm?

<table>
<thead>
<tr>
<th>Translation (mm)</th>
<th>(vs 9.0)</th>
<th>(vs 5.0)</th>
<th>(vs 5.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation (°)</td>
<td>(vs 0°)</td>
<td>(vs 0°)</td>
<td>(vs 0°)</td>
</tr>
</tbody>
</table>

b) Is the Co-registration Accuracy Test ≤ 0.5 mm (translation) and ≤ 0.5° (rotation)?

<table>
<thead>
<tr>
<th>$X$</th>
<th>$Y$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3. CTDI Dose Measurements (Annual)

a) Is the measured CTDI dose for CTDI 2.5 CBCT preset within ±5% of baseline? (Baseline = 2.3 mGy) Measured CTDI$_{2.5}$ = mGy

b) Is the measured CTDI dose for CTDI 5.3 CBCT preset within ±5% of baseline? (Baseline = 5.7 mGy) Measured CTDI$_{5.3}$ = mGy

---

*Figure 5.3.3:* Bi-annual and annual quality assurance tests form for Icon's image-guidance system.
5.3. RECORDING AND DOCUMENTATION

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**Roswell Park Comprehensive Cancer Center**  
**Gamma Knife – Annual Review for Image-Guidance Physics QA**  
**ICON Serial Number 6047**

**Review Year: 20__**

| Note: All questions below should be answered "Yes" if they meet their corresponding frequencies and tolerances. If not, a Medical Physicist will review compliance. |  
|---|---|
| **D. Commissioning (Pre-formed and/or baseline updated)** |  
| C1. CBCT Operation & Connectivity |  
| C2. IFMM Operation & Connectivity |  
| C3. CBCT Radiation Field Boundaries |  
| C4. Calibration of CBCT Coordinates by Elekta |  
| C5. Shot Delivery Accuracy after a Shift (by Elekta) |  
| **D. Daily Test** |  
| D1. CBCT Precision |  
| **E. Monthly Tests** |  
| M1. Image Spatial Resolution |  
| M2. Image CNR |  
| M3. Image Uniformity |  
| M4. Tridac System Accuracy (simple shift) |  
| **E. Bi-annual Test** |  
| B1. CBCT-based vs. Frame-based stereotactic space coordinate agreement |  
| **F. Annual Tests** |  
| A1. IFMM System Accuracy (complex shift) |  
| A2. Co-Registration Algorithm Accuracy |  
| A3. Delivery-alike-shift Accuracy |  
| A4. CTDI Dose Measurement |  

---

**Figure 5.3.4:** Annual quality assurance review checklist form for Icon's image-guidance system.
5.4 EDUCATION AND TRAINING

Prior to the Icon's clinical use, a manufacturer's training program on the use of the new Icon's capabilities included all involved personnel. Additional training was provided to the physics team for the QC tests required by the manufacturer (i.e. daily CBCT precision test and monthly CBCT image quality tests). Fig. 5.4.1 shows an example of the checklist documenting manufacturer training. At Roswell Park, the routine Gamma Knife QC tests are performed by the medical physicist assistants (MPA) supervised by a qualified medical physicist. Training of new MPAs to work in Gamma Knife is carried out internally by shadowing a senior MPA who has been credentialed to work with Gamma Knife and has experience in carrying out the tests independently. The new MPA is then tested and vetted by a qualified medical physicist before he or she can independently perform such tasks. To facilitate the training of performing these QC tests and to maintain a standardized protocol, step-by-step instructions have been developed for each test. These instructions are shown in Fig. 5.4.2 for the daily CBCT precision test; Fig. 5.4.3 for the monthly image quality tests; Fig. 5.4.4 for the monthly IFMM simple shift test; Fig. 5.4.5 for the bi-annual the CBCT-based vs. Frame-based stereotactic coordinates agreement test; Fig. 5.4.6 for the annual IFMM, co-registration, and delivery-after-shift accuracy tests; and Fig. 5.4.7 for the annual CTDI measurement. Hands-on sessions were held for each test and the procedures explained to personnel involved in Gamma Knife QA.
Figure 5.4.1: An example of the checklist used for manufacturer training of personnel involved with Icon’s operation. (Page 1/2)
Figure 5.4.1: (Cont.) An example of the checklist used for manufacturer training of personnel involved with Icon’s operation. (Page 2/2)
Leksell Gamma Knife® Icon™

CBCT Precision Check

**Frequency:** Daily (when there is a mask frameless treatment); required Monthly by Elekta

**Tools:** QA Check Tool and Frame Adapter (A) (both are located on the cart inside the gamma knife room)

**QA Check Tool Setup:**

1. Release the securing screw and the 3 levers on the frame adapter
2. Insert the pins on the frame adapter into the corresponding holes at the base plate of the QA tool
3. Lock the 3 levers and tighten the securing screw

4. With the QA tool pointing toward the Gamma Knife unit, place the frame adapter on the docking device such that the attachment pins align
5. Ensure the correct gamma angle (90 degree)
6. Lock the docking device.

**CBCT Scan Procedure:**

1. On the operator console’s Main tab, click the QA button
2. Select the CBCT precision check
3. Go into the treatment room, and follow the instruction on the treatment room monitor to:
   a. Accept that Setup is complete (Press & hold Continue on the couch’s manual control)
   b. Move the couch into scanning position (Press & hold Continue)
   c. Move the tilt gantry into the horizontal position (Press & hold Continue)
   d. Move the C-arm into scanning position (Press & hold Continue); ensure NO collision between C-arm and QA tool
4. The system is ready for scanning now; exit the treatment room and close the bunker door
5. On the operator console, Press and hold the START and ENABLE buttons to perform the scan.
   • Note, releasing the START or ENABLE buttons will stop the scan, and you will have to manually park the CBCT arm and restart from beginning.
6. After the QA tool is scanned, the system calculates the coordinates of the steel balls and compares them to the ones obtained during the calibration of the QA tool by Elekta’s engineer. The results are displayed for the Maximum deviation in image volume, Calculated fiducial deviation, and Result (passed or fail)
7. If the result is PASSED:
   a. write down the Maximum deviation in image volume (mm) value in the Daily QA Form
   b. Click Save to store the date and result of this QA CBCT precision check,
      NOTE: If the result is FAILED, inform the Gamma Knife physicist before proceeding to save or discard.
8. To park the CBCT, click on Automatic to automatically park the CBCT (if no collision with phantom is anticipated, otherwise use Manual parking if in doubt)

Ref: Leksell Gamma Knife® Icon™ Instructions for Use – by Elekta. Document ID: 1505134 Rev. 01 Published 2015-05 – Pages 157 & 161-163

Figure 5.4.2: Step-by-step procedure for the daily CBCT precision check test.
Figure 5.4.3: Step-by-step procedure for the monthly CBCT image quality tests. (Page 1/3)
7. Once the scan is completed, you can park the CBCT by clicking on Automatic to automatically park the CBCT (if no collision with phantom is anticipated, otherwise use Manual parking if in doubt).

8. The phantom CBCT image will be displayed on the image viewer window at the operator console for image quality tests to be performed.

   - Note: Do NOT click “Accept” or “Reject” CBCT images yet, otherwise the images will be sent over to the LGP system and you will not be able to analyze them on the operator console.

**Image Quality Tests:**

The following tests are to be performed for each CBCT setting (High Quality CTDI 6.3 and Low Dose CTDI 2.5)

<table>
<thead>
<tr>
<th>Test</th>
<th>Module Figures</th>
<th>Tolerance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Spatial Resolution</td>
<td><img src="image" alt="Spatial Resolution Module Figure" /></td>
<td></td>
</tr>
<tr>
<td>a. Scroll the view to the line pairs image (approx. slice z=59)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Adjust the window/level from top of the window for best contrast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Zoom-in (by right-clicking and dragging) to see full view of line pairs module</td>
<td></td>
<td>Spatial</td>
</tr>
<tr>
<td>d. Find the highest numbered line pair that can be seen clearly</td>
<td><img src="image" alt="Spatial Resolution Module Figure" /></td>
<td>Resolution &gt; 6 lp/cm (for both CTDI settings)</td>
</tr>
<tr>
<td>2. Contrast to Noise Ratio (CNR)</td>
<td><img src="image" alt="Contrast to Noise Ratio Module Figure" /></td>
<td></td>
</tr>
<tr>
<td>a. Scroll the view superiorly to the material inserts image (approx. slice z=29). Its center image can be identified by the marker (#4 in the Figure on the right)</td>
<td></td>
<td>CTDI 2.5: CNR &gt; 0.5</td>
</tr>
<tr>
<td>b. Adjust the window/level from top of the window for best contrast</td>
<td></td>
<td>CTDI 6.3: CNR &gt; 0.8</td>
</tr>
<tr>
<td>c. Zoom-in (by right-clicking and dragging) to see full view of inserts module</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Click on “Show” Image Probe to set its Box Size to 5.0 mm</td>
<td><img src="image" alt="Contrast to Noise Ratio Module Figure" /></td>
<td></td>
</tr>
<tr>
<td>e. Use the image probe to measure the mean pixel value (( \bar{T} )) and its standard deviation (( \sigma )) for both the polystyrene and LDPE inserts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f. Calculate: [ (CNR) = \frac{\bar{T}<em>{PS} - \bar{T}</em>{LDPE}}{\sqrt{\sigma_{PS}^2 + \sigma_{LDPE}^2}} ]</td>
<td><img src="image" alt="Contrast to Noise Ratio Module Figure" /></td>
<td></td>
</tr>
</tbody>
</table>

**Leksell Gamma Knife® Icon™ CBCT Image Quality Tests**

Figure 5.4.3: (Cont.) Step-by-step procedure for the monthly CBCT image quality tests. (Page 2/3)
3. Uniformity

a. Scroll the view inferiorly to the homogenous section (approx. slice z = 99). Its center image can be identified by an anterior marker (#2 in the Figure).
b. Adjust the window/level from top of the window for best contrast.
c. Zoom-in (by right-clicking and dragging) to see full view of uniformity module.
d. Set the Box Size for the image probe to 10.0 mm.
e. Use the image probe to measure the mean pixel value (f) and find the maximum and minimum pixel values at these five positions:
   (1) Phantom Center: X = Y = 100 (± 3 mm)
   (2) RT: X = 55, Y = 100 (± 1 mm)
   (3) POS T: X = 100, Y = 55 (± 1 mm)
   (4) LT: X = 145, Y = 100 (± 1 mm)
   (5) ANT: X = 100, Y = 145 (± 1 mm)
f. Calculate:
   \[ \% \text{diff.} = \left( \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}} + 1000} \right) \times 100\% \]
Leksell Gamma Knife® Icon™

IFMM (Simple Shift) Test

**Frequency:** Monthly

**Tool:** Velmex translation stage tool

**Description:** This is a test designed to check the intra-fractional Motion Management (IFMM) system on Leksell Gamma Knife (LGK) icon. The test is to be performed monthly as per NRC Licensing Guidance (see https://www.nrc.gov/docs/ML1610/ML16109A208.pdf). A post on the translation stage has a reflective marker to test the accuracy of the IFMM system when performing a simple compound shift of 2 mm x 2 mm x 2 mm in the X, Y, Z directions.

**Translation Stage Setup:**

**In LGK treatment room:**
1. Remove the mattress off the unit couch
2. Dock the patient mask adapter to the couch
3. Place solid water slabs so that you have a flat surface on the couch (I use 1 mm + 0.5 cm + 1 cm solid water topped by 20x20x0.5 cm Lucite sheet)
4. Place the translation stage on top of the Lucite sheet, bringing it to the edge of the couch and centered in the head opening
5. Reset the stage positions to: center in Lateral (X), low post in Vertical (Y), far sup in Longitudal (Z)
6. Reset all knobs readings to Zeros, including the rotational knob
7. Ensure a reflective marker is stuck to the stage’s post

**Test Delivery:**

**In Treatment Console:**
8. Load the Test called “Mask, treatment”
9. Enter today’s date and proceed
10. Click on “CBCT”

**In LGK treatment room:**
11. Test the patient alarm button and accept patient ID verification and setup in treatment room
12. Move IFMM camera arm up into the tracking-ready position
13. Move the translation stage by 2 mm LEFT, 2 mm ANT, 2 mm INF (i.e. two full knob rotations). Note down the IFMM readings for each shift in the “Monthly QA” form
   - Note: The IFMM<sub>expected</sub>= 2 mm after X shift; 2.83 mm after Y shift; and 3.46 mm after Z shift
14. Once done with measurements, press on “X” at the couch side panel for 3 seconds to abort CBCT, then “V” to confirm abortion

**In Treatment Console:**
15. Cancel the CBCT and discard the treatment

---

**Figure 5.4.4:** Step-by-step procedure for the monthly IFMM simple shift test.
CBCT-based and Frame-based Leksell Stereotactic Space Agreement

Frequency: Semi-annually

Tools: Stereotactic Frame, Five 0.5 mm Ball-bearings on a string; Frame Holder, CT Fiducial Box; Clamps;

Description: This is a test designed to check the agreement of the Leksell stereotactic coordinates space (LCS) defined using the CBCT vs. the gold-standard Frame-based definition. A simple tool with fixed fiducial markers that can easily be localized in both CT and CBCT. The testing tool consists of a taut string that is attached to an assembled stereotactic frame drawn from the left anterior post to the right posterior post, with five ball-bearing fiducial markers (0.5 mm diameter) rigidly attached to the string. The tool is scanned with a CT-sim for Frame-based LCS definition and with Icon’s CBCT for CBCT-based LCS definition.

Tool Preparation: (in case the tool is not already assembled as shown in the right figure)
1. Assemble the "Physics Test" stereotactic frame (located in Dr. Podgorsak Office)
2. Run a string from left anterior post to the right posterior post, and ensure it is tightly strung
3. Attach five 0.5 mm diameter ball-bearings (BB) along the string, avoiding being too close to either post (i.e. area of metal artifacts in images)

CBCT-based coordinated determination:

In LGP planning software:
4. Load the patient named “PHYS_SemiAnnual_QA”
5. Request Stand alone CBCT (Patient > Request CBCT > Stand Alone) & Proceed with acquiring the reference CBCT

In Treatment Console
6. Load patient “PHYS_SemiAnnual_QA” CBCT request
7. Click on “CBCT”

In LGK treatment room:
8. Accept patient ID verification and setup in treatment room
9. Move CBCT arm into scanning position

In Treatment Console
10. Perform the CBCT scanning with either CBCT preset
11. Accept images to be transferred to LGP

In LGP planning software:
12. Define the CBCT images as a reference image (Click on CBCT image label tab->Define Stereotactic Reference
13. Locate the first BB (most superior with smallest Z coordinate) and determine its center.
14. Note down the X, Y and Z coordinates in the “Semiannual & Annual QA” form
15. Repeat for the rest of BBs

Figure 5.4.5: Step-by-step procedure for the bi-annually CBCT-based and Frame-based stereotactic space agreement. (Page 1/2)
5.4. EDUCATION AND TRAINING

Frame-based coordinated determination: (performed with our CT-Simulator; ask the CT-tech for assistance)

In CT-Simulator room:
1. Align the physics frame holder near the end of the CT couch
2. Insert the SRS frame into the frame holder
3. Clamp the holder to the CT couch, ensuring the clamps won’t hit the CT core when you move the couch in. (Alternatively, you could use cushions or towels to keep the tool from flipping when attaching the CT fiducial box in the next step)
4. Attach the CT fiducial box and align it using the CT lasers
5. With the help of the CT-tech, bring the couch into scanning position and zero its position.

In CT-Simulator Console:
6. The CT-tech will create a new patient for your test, use the Gamma Knife/brain scanning protocol
7. Set slice thickness to 0.652 cm
8. Ensure the scanning volume is covering the BBs with 1-2 cm margin
9. Perform the scanning, and review the images before removing the tools from CT
10. Transfer the CT images to Gamma Knife DICOM folder

In LPS planning software:
11. Load the patient named "PHYS_SemiAnnual_QA"
12. Import CT images (Patient—> Import DICOM—> Select the CT images
13. Once imported, the system will take you to the LCS “Define Study” module
14. Go to the most inferior image that shows the fiducial on the CT indicator box
15. Define the 3 fiducials on each side, then Click on “Define”
16. The system should go through all slices and find box fiducials on each one automatically
17. Review the box fiducial definition and accept it. The CT images coordinates are now defined in LPS
18. Locate the first BB (most superior with smallest Z coordinate) and determine its center.
19. Note down the X, Y and Z coordinates in the "Semiannual & Annual QA" form
20. Repeat for the rest of BB.
21. Calculate the vector \[ r = \sqrt{(x_{Frame} - x_{CBCT})^2 + (y_{Frame} - y_{CBCT})^2 + (z_{Frame} - z_{CBCT})^2} \] for each BB, and note it down in the "Semiannual & Annual QA" form

*If the module failed to define LCS automatically, try manual definition: starting with the superior slice, define 3 fiducials on each side, check the “Define Manually” box, then Click “Define” and go through each slice definition manually adjusting as needed.

See Also:

Figure 5.4.5: (Cont.) Step-by-step procedure for the bi-annually CBCT-based and Frame-based stereotactic space agreement. (Page 2/2)
5.4. EDUCATION AND TRAINING

Leksell Gamma Knife® Icon™

IFMM, Co-registration and Delivery-after-shift Accuracy Tests

Frequency: Annually

Tools: Velmex translation stage tool; 2x Gafchromic film cuts (about 1.5 x 1.5 cm²)

Description: This is essentially an end-to-end test designed to check several accuracy aspects of LGK Icon. A post on the translation stage has a reflective marker to test the accuracy of the Intra-fractional Motion Management (IFMM) system. A radiation treatment plan is to deliver 5 Gy to centers of two films placed on horizontal and vertical planes with a 4 mm shots using Leksell GammaPlan (LGP) software. The centers of the radiation shots are on the holders’ central hole at film planes, and are to be marked on the films with a pushpin before treatment delivery. The accuracy of the co-registration algorithm is also tested with this tool.

Translational Stage Setup:

1. Cut an EBT films into 1.5 x 1.5 cm² pieces, label the first as “Horizontal” and the X & Z sides; and second as “Vertical” and the X & Y sides. Label each films with the date of experiment
2. Load the two film holders with cut EBT films such that the films land under the central hole plus about a 1 cm of film material margin
3. Screw tight to hold films in place
4. Punch the centers of films with a pushpin

In LGK treatment room:

5. Remove the mattress off the unit couch
6. Bring couch level to Zero, using the side panel ▲▼ buttons
7. Dock the patient mask adapter to the couch
8. Place solid water so that you have a flat surface on the couch (I use 2 mm + 0.5 cm + 1 cm solid water topped by 20x20x0.5 cm Lucite sheet)
9. Place the translation stage on top of the Lucite sheet, bringing it to the edge of the couch and centered in the head opening
10. Reset the stage positions to: ±1.5 cm in Lateral (X); ± 3.3 cm in Vertical (Y), ±2.5 cm in Longitudal (Z)
11. Reset all knobs readings to Zeros, including the rotational knob
12. Ensure a reflective marker is placed on the stage’s post

Figure 5.4.6: Step-by-step procedure for the annually accuracy tests of Icon’s image-guidance using the translation stage tool. (Page 1/3)
Planning:

In LGP planning software:
13. Load the latest treated plan of the patient named PHYS_Shift_QA
14. Click Plan ➔ Re-plan; fill up operator information
15. Delete old CBCTs in the new plan
16. Request Stand alone CBCT (Patient ➔ Request CBCT ➔ Stand Alone) to acquire a reference CBCT

In Treatment Console
17. Load patient “PHYS_Shift_QA” CBCT request

In LGK treatment room:
18. Accept patient ID verification and setup in treatment room
19. Move CBCT arm into scanning position

In Treatment Console
20. Perform the CBCT scanning with either CBCT preset
21. Accept images to be transferred to LGP
22. Park the CBCT arm

In LGP planning software:
23. Perform the co-registration with the planning CT, ensuring films holders holes are matching
24. Assign fixation configuration to mask (Plan ➔ Fixation Configuration ➔ Mask; Check Reviewed for plan approval)
25. Click on Sum plan (Σ) on top right corner, then proceed to approving (Plan ➔ Approve) and printing plan documents (Patient ➔ Print)
26. Transfer protocol to treatment console (Patient ➔ Export Protocol)
27. Enable Treatment mode (Tools ➔ Treatment mode)

Test Delivery:

In Treatment Console
28. Load patient “PHYS_Shift_QA” in treatment console
29. Click on “CBCT”

In LGK treatment room:
30. Move IFMM camera arm into the tracking position
31. Test patient alarm button, and accept patient ID and Setup,
32. Move the translation stage by 5 mm LEFT, 5 mm ANT, 5 mm INF, (i.e. five full knob rotations each), and 1 degree clock-wise. Note down the IFMM reading for each shift in the “Bi-annual & Annual QA” form
   Note: The IFMM_Expected = 5 mm after X shift; 7.07 mm after Y shift; 8.66 mm after Z shift; and 11.4 mm after 1 degree.
33. Move CBCT arm into scanning position and proceed with acquiring the setup CBCT

In Treatment Console
34. Perform CBCT scanning in Console with either CBCT preset
35. Accept images to be transferred to LGP

Figure 5.4.6: (Cont.) Step-by-step procedure for the annual accuracy tests of Icon’s image-guidance using the translation stage tool. (Page 2/3)
5.4. EDUCATION AND TRAINING

In LGP planning software:
36. Perform the co-registration with reference CBCT. Note down the co-registration parameters (translation & rotation XYZ shifts) in the “Bi-annual & Annual QA” form
   Note: Expected values: Rotation around Y = -1.0 degree; Translational X = 9 mm; Y = 5 mm; Z = 5.1 mm
37. Approve the co-registration and plan distribution DVH to proceed with treatment

In Treatment Console
38. Accept the transfer of shifts
39. Proceed with treatment delivery until completed

In LGK treatment room:
40. After treatment delivery, remove films from the stage and store for 12-24 hrs before processing

Films Scanning and Processing:
41. Turn ON the Epson Perfection V700 flatbed color scanner (located in Physics Staff area), and place both films on the scanner glass faced-down
42. Open the Epson Scan software – shortcut icon should be on the Desktop of scanner’s PC
43. Select Professional Mode
44. Settings: Film Type: Positive Film; Image Type: 24-bit color; Resolution: 600 dpi; NO filters checked
45. Click on Preview and select an area containing both films. Scan and Save the file
46. Use the Matlab Code “radshot.m” to calculate the deviation between the centers of radiation shots and punched holes in both films
   a. Change the “fileName” in the code to your scanned film file name.
   b. Your scanned film will be shown when the code is executed. Select an area around one of the radiation shots then right click ➔ Crop Image
   c. Zoom in (if needed) and Place the mouse cursor on the center of the punched hole; click then hit Enter key
   d. The code will show the fitted radiation shot with its center and center of punched hole. As well as the difference in r between the two centers. Note down the value of r in the “Bi-annual & Annual QA” form

Note: if the matlab code failed to fit an ellipse to the radiation shot, try changing the threshold level “t” used in the code for binarizing the image into black & white before fitting.

See Also:

Figure 5.4.6: (Cont.) Step-by-step procedure for the annual accuracy tests of Icon’s image-guidance using the translation stage tool. (Page 3/3)
Leksell Gamma Knife® Icon™

CBCT CTDI Measurement

**Frequency:** Annual; CTDI measurement is typically performed by a third-party consulting service. Described here is an alternative method using a cross-calibrated chamber.

**Tools:** 1) CTDI head phantom; 2) Pencil Ionization Chamber (Victoreen 500-100/SN 207); 3) Electrometer (Keithly 35040/SN 59171); 4) Thermometer & barometer; and 5) A 3 cm-thick Styrofoam piece.

Note: A cross-calibration of our pencil chamber (Victoreen 500-100/SN 207) and electrometer (Keithly 35040/SN 59171 / -300 V bias) with a calibrated system (Radcal Mod 10xs-3ct / SN 9123) provided by a third-party physics consulting service (Advanced Medical Physics, Inc.) was carried out (April 2016) under Icon’s CBCT beam and resulted in a calibration coefficient of 1.062 R/nC, or 9.24 mGy/nC, for our chamber/electrometer system combination.

**CTDI Head Phantom Setup:**

1. Dock the **patient mask adapter** to the couch
2. Place the **CTDI head phantom** on the mask adapter on a Styrofoam piece bringing it central to the imaging plane
3. Connect the **pencil chamber** to the **electrometer** (bias = -300 V)
4. Place the **pencil chamber** in the central axis hole of the phantom
5. Ensure all **other holes** are filled with plugs
6. Place the **thermometer/barometer** on the couch and take a reading mid way through the experiment – to be used for charge reading T&P correction.

**CBCT CTDI Measurement Procedure:**

**Hint:** Requesting a stand alone CBCT from any QA patient will do; alternatively you could load the Test "Mask, CBCTscan" in the operator console directly without the need of using LGP

1. Request a **Stand Alone CBCT** from the Leksell GammaPlan (LGP) station:
   a. **Login** to the LGP station
   b. **Load** the patient named (Physics, Monthly QA)
   c. From the **Patient** menu, select **Request CBCT→ Stand Alone**

**Figure 5.4.7:** Step-by-step procedure for the weighted CT dose index measurement using a cross-calibrated pencil ionization chamber. (Page 1/2)
2. On the **operator console**, open the CBCT request made in LGP:
   a. In the Main tab, click on the **Treatment** button
   b. Double click to select the **Monthly QA Physics** patient
   c. Verify and **Accept** patient data

3. Go into the **treatment room**, and **follow the instruction on the treatment room monitor** to:
   a. Accept that Setup is complete (Press \( \text{v}\) **Accept** on the couch’s sidepanel)
   b. Move the couch into scanning position (Press & hold \( \text{►} \) **Continue**)
   c. Move the tilt gantry into the horizontal position (Press & hold \( \text{►} \) **Continue**)
   d. Move the C-arm into scanning position (Press & hold \( \text{►} \) **Continue**)

4. Exit the treatment room and **close the bunker door**

5. On the operator console, Click the **CBCT** button and select **CBCT preset**

   **Hint:** start first with the Low Dose CTDI 2.5 preset as you will be able to do 5-6 CBCT runs before the tube overheats

6. **Press and hold the START and ENABLE** buttons to perform the scanning.

7. Once the scan is completed, **REJECT** the CBCT image so the system prompts you to repeat the scan

8. Enter the **treatment room**, and **Record** the charge reading

9. **Exchange** the pencil chamber with the next periphery plug (12, 3, 6, or 9 o’clock)

10. **Repeat the CBCT scan** and charge measurements for **all other positions** (Steps 3 to 9)

11. **Repeat the CTDI measurement for the other preset.** You will probably have to take breaks as the tube will overheat and you will have to wait for cool down (can be up to 20 mins)

---

**Weighted CTDI Calculations:**

- Convert the charge reading to dose by multiplying the temperature-pressure corrected charge reading with the dose calibration coefficient (9.24 mGy/nC)
- \[ \text{CTDI}_{w} = \frac{1}{3} \text{CTDI}_{\text{center}} + \frac{2}{3} \text{CTDI}_{\text{periphery}} \]\n
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Ref.: Leksell Gamma Knife® Icon™ Instructions for Use – by Elekta. Document ID: 1505194 Rev. 01 Published 2015-05 – Pages 196-198

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**Figure 5.4.7:** (Cont.) Step-by-step procedure for the weighted CT dose index measurement using a cross-calibrated pencil ionization chamber. (Page 2/2)
Summary and Future Work

6.1 SUMMARY

Leksell Gamma Knife (LGK) Radiosurgery System has been playing a major role in delivering stereotactic radiosurgery treatments from the establishing of this mode of therapy by Dr. Lars Leksell in the 1950s. The latest model of LGK systems, the Icon, is well-equipped for image-guidance radiation therapy. The Icon is integrated with a cone-beam CT unit and an infrared tracking system with software capabilities of co-registration image modalities and online plan adaptive that makes it convenient to deliver hypofractionated frameless stereotactic radiosurgery treatments. These novel features require tight quality assurance (QA) program that implements tests and checks to ensure the safe and accurate delivery to the patient. As the Icon is relatively new in the market, there are no published guidelines on a comprehensive QA program for the novel add-ons to be performed. The manufacturer does provide limited test guidelines, and there are limited literature published on the commissioning and performance assessments results. Nevertheless, there is still a gap in this area to be filled. The purpose of this dissertation was fill this gap and develop a comprehensive QA program for Icon's image-guidance system. We started by building up the experience on the current test required by the manufacturer (i.e. CBCT precision and image qualities), together with a CT dose index measurement following the manufacturer methodology. Our results are consistent with the manufacturer specification[16] and with the few published results.[30, 32, 35, 36] We have also investigated other tests with our
independent tools to check the CBCT-based vs. Frame-based stereotactic coordinates; Intra-fraction motion management system accuracy; co-registration algorithm accuracy; and the delivery-after-shift accuracy, and have established baselines for these tests. Based on this experience, we have successfully developed a QA program for Icon’s image-guidance that is summarized in Table 5.2.1, accompanied with checklist forms for documentations and step-by-step instructions for training and standardization, as presented in Chapter 5.

This dissertation focused on quality assurance of the image-guidance component elements pertaining to the Gamma Knife Icon unit itself. We did not extend here to cover the QA of imaging devices used for planning (such as CT, MRI, and angiography), or QA of the process and workflow of frameless delivery. Both of these aspects are also important components to ensure the overall accuracy and safety of frameless and image-guided stereotactic radiosurgery treatments.

6.2 FUTURE WORK

Throughout the work of this dissertation, we have encountered several challenges and questions with the use of Icon’s image-guidance for frameless radiosurgery that needed further research. These are listed here with the preliminary work we have done and our suggestions for proceeding with further investigations.

6.2.1 A GEOMETRICAL DISTORTION CHECK TOOL FOR FRAMELESS PATIENT MRIS

In the traditional skull immobilization of Gamma Knife using the invasive frame, the attachment of an MR fiducial box used for stereotactic coordinates definition during planning MRI has an underlying advantage of checking the MRI images for geometrical distortion. A large deviation in the rigid MR fiducial box separation in MRI images would trigger a warning message the LGP software which could be a result of by large geometrical distortion in the images. With frameless treatments, however, the MR fiducial box is not used since the stereotactic space is defined with CBCT, and this makes it possible to miss geometrical distortions in the planning MRI images
leading to a compromised positional accuracy in target delineation and radiation shot placement. Sources of distortion in MR images include differences in pulse sequences, differences in magnetic susceptibilities of individual patients, the presence of magnetic objects such as surgical clips. Investigators have shown that distortions in MRI images used for Gamma Knife treatments can be up to 1 mm.[58] A possible solution to check for MRI distortion is to have a simple tool or a light frame with MRI fiducial markers placed at known distances to be scanned with the patient during planning MRI. A commercially-available MRI markers samples (LiquiMark MRI Markers, The Suremark Company, Simi Valley, CA) of different shapes and sizes were acquired for possible use with such a QA tool. An investigation of the LiquiMark visibility in MRI was performed with a General Electric (GE) CSI 4.7T MR scanner (GE NMR Instruments, Fremont, CA) incorporating AVANCE electronics console (Bruker Medical, Billerica, MA), available for small animal studies through the Roswell Park’s Translational Imaging Shared Resource (TISR). Four LiquiMark of different shapes were imaged with multiple commonly used clinical scan protocols, and these images are shown in Fig. 6.2.2. The investigations under 4.7T MRI revealed strong signal for the LiquiMark in both T1 and T2-weighted images. Multiple chemical species within the LiquiMark can lead to chemical shift artifact (“blurring”) on low bandwidth scans. The measured T1 times were 500 ms at 4.7T (estimated data, likely to be shorter at 1.5T). This can be compared to normal brain tissue that has T1 times of 650/1200 ms at 1.5T, and 840/1600 ms at 3T for white/grey matter, respectively.[59] A prototype of the suggested geometrical distortion check tool was constructed and tested with a water-filled glass head phantom in clinical 1.5 T and a 3.0 T MRI. The LiquiMark MRI Markers of different shapes and sizes were placed on a plastic frame fitted in an MRI-compatible mask adapter (Elekta Instruments, A.B., Stockholm, Sweden) as shown in Fig. 6.2.1. The smallest LiquiMark is 8 mm round and can be easily identified in the MRI images. The reference distances between markers center were determined in a CT scan of this tool and confirmed with a caliber. Table 6.2.1 shows the distances between the markers in MRI images and compare them with the reference distances as determined with CT. Large differences would indicate geometrical distortion in MRI images. Further development of this tool could possibly turn it into a valuable clinical
6.2. FUTURE WORK

Note: 1% Agarose with 1mM CuSO4 included for comparison

T1w Spin Echo  T2w Fast Spin Echo  T2w Fast Spin Echo  3D SPGR

TE/TR = 6/512ms, BW=90kHz TE/TR = 10/2500ms, BW=50kHz TE/TR = 60/3000ms, BW=12.5kHz TE/TR/FA = 3/15/25° BW=71kHz

Visible Chemical Shift Artifact at low Bandwidth

Figure 6.2.1: 4.7T MRI images of LiquiMark MRI Markers using multiple commonly used clinical scan protocols, shown next to a rodent and an Agarose with 1mm CuSO4 for comparison.

A product that confirms the geometrical quality of MRIs used for frameless treatments. One possible improvement is to construct or 3D-print a wearable frame, as shown in Fig.6.2.3, with fiducial markers or filled with CuSO4 at known distances such that it can fit easily into the MRI coil but also covers the whole imaging field. A software code could also be developed to automatically extract the image of the QA tool from MRI and compare it with a reference image and calculate any patient-specific image distortion prior to the use of the MRI images in frameless stereotactic treatment planning.

6.2.2 IMPLEMENTATION OF TG-100 AND FMEA ANALYSIS

Errors in radiation therapy are not entirely caused by device or software failures, but can also be due to failures in workflows and processes. In recent years, there has been an increased interest in
**Figure 6.2.2:** Picture of the MRI geometrical distortion check tool prototype with a water-filled glass head phantom.

**Figure 6.2.3:** A design for a 3D-printed prototype of an eyeglasses frame with MRI markers (red dots) positions as a wearable MRI geometric distortion check tool.
6.2. FUTURE WORK

<table>
<thead>
<tr>
<th>Panel</th>
<th>Vector</th>
<th>Difference (mm)</th>
<th>(CT-1.5T MRI)</th>
<th>(CT-3T MRI)</th>
<th>(1.5T-3T MRI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r(C-Ant)</td>
<td>-0.7</td>
<td>0.0</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>r(C-Post)</td>
<td>0.6</td>
<td>-0.2</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(Ant-Post)</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Sup)</td>
<td>1.23</td>
<td>-0.2</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Inf)</td>
<td>0.1</td>
<td>-0.6</td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(Sup-Inf)</td>
<td>1.3</td>
<td>-0.7</td>
<td>-2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Ant)</td>
<td>-0.2</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>r(C-Post)</td>
<td>0.5</td>
<td>-0.6</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(Ant-Post)</td>
<td>0.2</td>
<td>-0.3</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Sup)</td>
<td>0.7</td>
<td>-1.6</td>
<td>-2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Inf)</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(Sup-Inf)</td>
<td>0.7</td>
<td>-1.3</td>
<td>-2.1</td>
<td></td>
</tr>
<tr>
<td>Sup</td>
<td>r(C-Ant)</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(Left-Right)</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Left)</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r(C-Right)</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.2.1:** Differences in distances between markers in 1.5 T, 3.0 T, and the reference CT of the MRI geometrical distortion check tool prototype. Note: The 1.5 T MRI images had a wrap-around artifact, hence the markers placed on Sup panel had incorrect coordinates and analysis could not be performed for these markers.
the radiation oncology community in developing quality management programs that focuses on the design and execution of various radiotherapy processes and workflows to prevent such failures, rather than just the traditional focus on monitoring all aspects of the technical performance of radiotherapy equipment by comparing parameters against strict tolerances levels. Implementing such a quality management program would lead to improved cost-effectiveness as it will help direct the limited resources efficiently to areas that produce the optimum patient care without compromising safety. The recently published AAPM Task Group 100 Report (TG-100) introduced guidelines to such new approach to quality management in radiation therapy. A team-based approach with active participation of representatives from all treatment team member categories (physicians, physicists, dosimetrist, therapists, nurses, IT supports, machine maintenance, radiation safety officers, schedulers and administration, etc.) are recommended to work together and use risk assessment and industrial quality management tools, such as process mapping, failure modes and effects analysis, and fault tree analysis in order to develop clinic- and site- specific quality management programs addressing work practices in individual clinics. The tools suggested in TG-100 includes a process tree, which works as a visual illustration of the physical and temporal relationships between the different steps of a process that demonstrates the flow and inter-relationship of these steps from process start to end. Another tool is a Failure modes and effects analysis (FMEA) that assesses the likelihood of failures in each step of a process and considers their impact on the final process outcome. The team works on identifying the ways in which a process could fail (i.e. failure modes) for each process step, the potential causes for each failure mode, and the impact of each failure mode on the process outcome. Also, for each failure mode, the team assigns numerical values to three parameters: Occurrence (O): the likelihood for a cause to happen; Severity (S): the severity of impact on process outcome; and Detectability (D): the likelihood the failure will not be detected in time to prevent the failure. The multiplication of these parameter gives a risk priority number, or 
\[ RPN = O \times S \times D, \] 
that helps in ranking the importance of failure modes and direct the efforts to prevent them. A third tool described in TG-100 is a fault tree, which provides a visual overview to identify the steps in practice not covered in a quality management program of a
particular process. The Gamma Knife team at the University of Pittsburgh Cancer Institute has recently published their process for developing such a quality management program for Frame-based Gamma Knife Radiosurgery based on TG-100.\[60\] There is a potential opportunity to implement the TG-100 methodology for developing a quality management program for the Icon’s frameless radiosurgery specific to our practice at Roswell Park Comprehensive Cancer Center. Fig.6.2.4 shows a process tree for the Gamma Knife frameless treatment at our institute that could be used as a start point in developing such a program.

6.2.3 INVESTIGATION OF TARGET DISPLACEMENT IN RELATION TO THE NOSE MARKER DISPLACEMENT

To allow for dose fractionation, Elekta has introduced a frameless thermoplastic patient immobilization system used with Icon’s CBCT. However, the non-rigid thermoplastic mask has limited capability when it comes immobilization patient skull movement compared to the tradition rigid and invasive frame system. Addressing this issue, the provided stereoscopic infrared camera is used during treatment delivery to monitor skull movement by tracking an infrared marker placed on the tip of patient nose relative to four reflectors fixed into the patient head support. This works under the assumption that the nose movement is an appropriate surrogate for intracranial targets movements. It is assumed that the intracranial target moves with equal or less amount to the tip of nose movement. This would be true for purely translational skull shifts in the X, Y, and/or Z planes. However, when rotational skull shifts occur, as typically in clinical cases, there will be some situations when the intracranial target movement is larger than the tip of the nose movement. A hypothetical example for such scenario is when the point of skull rotation is centered on the patient nose, i.e. the nose is fixed and does not move while the head rotates resulting in target movement being larger than that of nose tip. A possible clinical example is when the center of rotation is in the neck region.\[29\] An attempt was carried out to simulate patient movement with a head phantom by introducing rotation using the translation stage tool we have. However, we were able to rotate the phantom only around a point that
6.2. FUTURE WORK

Figure 6.2.5: Experimental setup for simulating skull rotation with our translation stage tool. The tool’s center of rotation is at the edge of the couch just inferior to the patient head support, mimicking a rotation centered on a point at the patient neck region.

corresponds to the neck region as the stage tool center of rotation lies on the couch edge outside of the head support, as shown in Fig.6.2.5. It was difficult to rotate the phantom around a center of rotation similar to what happens in real patients with our tool, which is probably is at the back of the rested head. Nevertheless, this simple experiment revealed that there are some situations where the target can potentially move in a larger amount than nose tip movement. A suggested mathematical retrospective study is to use transformation matrix of real patient co-registration data between two setup CBCTs in the same treatment session and find out what cases would potentially have targets movements larger than the nose tip, and also study the dosimetric and clinical impacts for such cases. A Matlab code we developed, shown in Appendix A.3, could be used for batch transformation of target/marker points based on co-registration parameters using Wright et. al. methodology. [21]
References


REFERENCES


REFERENCES


A.1 ANALYZING DELIVERY-AFTER-SHIFT TEST FILMS

% This code is used for calculating the deviation between the center of
% punched hole and center of radiation shot on a film irradiated as
% described in the delivery—after—shift test for Leksell Gamma Knife
% Icon using the 3D translational stage.
% The code asks the user to first crop the film to zoom in area of the
% radiation shot on film, and to identify the center of punched holes.
% The code will then binarize the film into a B/W image and fit an
% ellipse to the edge of radiation shot then calculate its center, as
% well as the difference between center of punched hole and fitted
% radiation shot.

% @2018-07-23
% Ismail AlDahlawi, Ph.D student
% Roswell Park Comprehensive Cancer Center

%%% Beginning of Code
clear all
dpi = 600; % setting the pixel per inch of scanned film
fileName = 'posto36.tif'; % change to scanned film file name
Araw = imread(fileName);
Acrop = imcrop(Araw);

%%% Manually select the center of punch
figure
imshow(Acrop,'InitialMagnification',300);
[Xp,Yp] = getpts;
close All;

%%% Converting image to BW for circle fitting
t = 119; % change 110–140 to detect circle (try 107–118 for H to get
% area=90mm2; +10 for V to get area=116mm2; using 5 Gy)
Igray = rgb2gray(Acrop);
IT = im2bw(Igray, t/255); % apply the threshold
A.1. ANALYZING DELIVERY-AFTER-SHIFT TEST FILMS

```matlab
12 \text{I}_2 = -IT; \quad \% \text{get a negative image}
13 \text{I}_3 = \text{bwareaopen}(\text{I}_2, 90, 8); \quad \% \text{get rid of small unwanted pixels}
14 \text{I}_{\text{circ}} = \text{imclearborder}(\text{I}_3, 8); \quad \% \text{clear pixels of the borders}

%%%%%% Fitting circle to radiation shot
17 \text{s} = \text{regionprops} (\text{I}_{\text{circ}}, \{'\text{Centroid}', '\text{MajorAxisLength}', '\text{MinorAxisLength}', '\text{Orientation}'\});
18 \text{t} = \text{linspace} (0, 2*\pi, 50);
19 \text{for} \ k = 1: \text{length} (\text{s})
20 \quad \text{a} = \text{s}(k).\text{MajorAxisLength} / 2;
21 \quad \text{b} = \text{s}(k).\text{MinorAxisLength} / 2;
22 \quad \text{Xc} = \text{s}(k).\text{Centroid}(1);
23 \quad \text{Yc} = \text{s}(k).\text{Centroid}(2);
24 \quad \text{phi} = \text{deg2rad} (\text{--s}(k).\text{Orientation});
25 \quad \text{x} = \text{Xc} + a*\cos (\text{t})*\cos (\text{phi}) - b*\sin (\text{t})*\sin (\text{phi}) ;
26 \quad \text{y} = \text{Yc} + a*\cos (\text{t})*\sin (\text{phi}) + b*\sin (\text{t})*\cos (\text{phi}) ;
27 \text{end}

%%%%%% Calculating difference between the two centers, and area of circle
28 \text{calib} = 1/(\text{dpi}/25.4);
29 \text{XPixDiff} = \text{Xc} - \text{Xp};
30 \text{YPixDiff} = \text{Yc} - \text{Yp};
31 \text{XmmDiff} = \text{XPixDiff} * \text{calib} ;
32 \text{YmmDiff} = \text{YPixDiff} * \text{calib} ;
33 \text{r} = \text{sqrt} (\text{XmmDiff}^2 + \text{YmmDiff}^2);
34 \text{area} = \pi * (\text{s}(k).\text{MajorAxisLength} * \text{calib}) * (\text{s}(k).\text{MinorAxisLength} * \text{calib});

%%%%%% Outputing results
37 \text{fprintf} (\text{\'Xdiff. = %.3f mm;\n\text{(or Z) diff. = %.3f mm;\nRdiff. = %.3f mm\narea of Rad. shot= %.1f mm2\n'}, \text{XmmDiff}, \text{YmmDiff}, \text{r}, \text{area})

%%%%%% Showing images
40 \text{subplot} (2, 2, 1) ; \text{imshow}(\text{Acrop}); \text{title} ('\text{Cropped Image with selected punch point}') ;
41 \text{hold on}
42 \text{plot} (\text{Xp}, \text{Yp}, '{\text{'bX'}}');
43 \text{hold off}
44 \text{subplot} (2, 2, 2) ; \text{imshow}(\text{I}_{\text{circ}}); \text{title} ('\text{Cropped in B&W and Fitted}')
45 \text{hold on}
46 \text{plot} (\text{x}, \text{y}, '{\text{'r'}}', '{\text{'Linewidth'}}', 2)
47 \text{plot} (\text{Xc}, \text{Yc}, '{\text{'bo'}}');
48 \text{plot} (\text{Xp}, \text{Yp}, '{\text{'bX'}}');
49 \text{hold off}
50 \text{subplot} (2, 2, 3) ; \text{imshow}(\text{I}_{\text{gray}}, '{\text{'InitialMagnification'}}', '{\text{'fit'}}')
51 ; \text{title} ('In Gray') ;
52 \text{hold on}
53 \text{plot} (\text{x}, \text{y}, '{\text{'r'}}', '{\text{'Linewidth'}}', 2)
```

99
A.1. ANALYZING DELIVERY-AFTER-SHIFT TEST FILMS

```matlab
plot(Xc,Yc,'bo');
plot(Xp,Yp,'bX');
zoom on
hold off

zerosImg = ones(128,128,3);
subplot(2,2,4);imshow(zerosImg);

XmmDiff = %.0f Xdiff. = %.3f mm; Y(or Z)diff. = %.0f Ydiff. = %.3f mm;
area = %.1f area of Rad. shot = %.1f mm^2

%% END of Code
```
A.2 Transformation Matrix for Icon’s co-registration Algorithm

clear all

% optional: Enter observed IFMM reading (mm) for comparison with a nose point (reference point)
IFMM_Observed=20.51;

% Enter [X;Y;Z] coordinates of a reference point in the reference CBCT
XYZ_Ref=[98.97;191.27;92.22];

% Enter rotational shift parameters [thetaX;thetaY;thetaZ] as indicated by LGP co-registration
Thetasref = [-0.01; -1.01; 0.02];

% Enter translational shift parameters [deltaX;deltaY;deltaZ] as indicated by LGP co-registration
Deltasref = [-0.93; -5.4; -19.82];

% Starting transformation for reference point

% Inputting original coordinates of a point So (ex. nose marker in ref CBCT) & calculating its new coordinates after shifting using co-registration parameters from LGP w/ setup CBCT
So=XYZ_Ref;

% Input Co-registration Translation parameters from LGP
deltaX=Deltasref(1,1);
deltaY=Deltasref(2,1);
deltaZ=Deltasref(3,1);

% Input Co-registration Rotation parameters from LGP
thetaX=Thetasref(1,1);
thetaY=Thetasref(2,1);
thetaZ=Thetasref(3,1);

% Calculating Translation Matrix (around 100,100,100)
T=[deltaX+100; deltaY+100; deltaZ+100];
% Calculating Rotation Matrix (around 100, 100, 100)
Rx = [1 0 0; 0 cos(deg2rad(thetaX)) -sin(deg2rad(thetaX)); 0 sin(deg2rad(thetaX)) cos(deg2rad(thetaX))];
Ry = [cos(deg2rad(thetaY)) 0 sin(deg2rad(thetaY)); 0 1 0; -sin(deg2rad(thetaY)) cos(deg2rad(thetaY))];
Rz = [cos(deg2rad(thetaZ)) -sin(deg2rad(thetaZ)) 0; sin(deg2rad(thetaZ)) cos(deg2rad(thetaZ)) 0; 0 0 1];
R = Rz * Ry * Rx;

% Calculating coordinates of the point after shift (S1)
S1 = R * (So - [100]) + T;

%%%%%%
%% End of transformation for reference point
%%%%%%

% To show results in Command Window, uncomment the following:
printf('S1 =
X1 = %.2f
Y1 = %.2f
Z1 = %.2f', S1(1,1), S1(2,1), S1(3,1))

% Calculating vector magnitude
A_temp = (S1 - So);
Vector_Calc = sqrt(sum(A_temp .^ 2));

% Calculating ratio of point displacement to IFMM nose displacement % (optional)
PointIFMM_ratio = Vector_Calc / IFMM_Observed

%%%%%% END
A.3. NOSE MARKER VS. TARGET DISPLACEMENT USING ICON'S
CO-REGISTRATION ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

A.3 NOSE MARKER vs. TARGET DISPLACEMENT USING ICON'S CO-REGISTRATION
ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

Ismail AlDahlawi, MSc, MCCPM June 2018

Data from Steve deBoer, MSc, DABR // Roswell Park, Buffalo

Following Wright G, "Validity of the use of nose tip motion as a
surrogate for intracranial motion in mask-fixated frameless Gamma

Beginning of Code

clear All

Reading input data file IFMMCBCTData.csv & assigning values to variables

filename = 'IFMMCBCTData.csv';
M = csvread(filename, 3, 0); % ignoring headers and Pt ID column (i.e. row 0-2 and column 1)
H = size(M, 1) ; % determine # of rows

% reading XYZ coordinates of nose marker in the reference CBCT
XYZ_NoseRef = M(:, 2:4);

% reading XYZ coordinates of isocenter in the reference CBCT
XYZ_IsoRef = M(:, 5:7);

% reading observed IFMM
IFMM_Observed = M(:, 8);

% reading observed rotation thetas from CBCT1 setup/CBCT Ref co-registration
ThetasRef = M(:, 9:11);

% reading observed translation deltas from from CBCT1 setup/CBCT Ref co-registration
DeltasRef = M(:, 12:14);

% reading observed rotation thetas from CBCT2 setup/CBCT1 setup co-registration
ThetasSetup = M(:, 15:17);

% reading observed translation deltas from from CBCT2 setup/CBCT1 setup co-registration
DeltasSetup = M(:, 18:20);

Starting transformation for Nose marker points

Input original coordinates of a point So (nose marker in ref CBCT) & calculating its new coordinates after shifting using co-registration
A.3. NOSE MARKER VS. TARGET DISPLACEMENT USING ICON’S CO-REGISTRATION ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

%parameters from LGP w/ CBCT1 setup

for i=1:H
    So_temp=XYZ_NoseRef(i,:);
    So_temp=So_temp';
end

%Input Co-registration Translation parameters from LGP
deltaX_temp=Deltasref(i,1);
deltaY_temp=Deltasref(i,2);
deltaZ_temp=Deltasref(i,3);

%Input Co-registration Rotation parameters from LGP
thetaX_temp=Thetasref(i,1);
thetaY_temp=Thetasref(i,2);
thetaZ_temp=Thetasref(i,3);

%Calculating Translation Matrix (around 100,100,100)
T=[deltaX_temp+100; deltaY_temp+100; deltaZ_temp+100];

%Calculating Rotation Matrix (around 100,100,100)
Rx = [1 0 0; o cosd(thetaX_temp) -sind(thetaX_temp));
     o sind(thetaX_temp) cosd(thetaX_temp)];
Ry = [ cosd(thetaY_temp) o sind(thetaY_temp); o 1 o;
     -sind(thetaY_temp) cosd(thetaY_temp)];
Rz = [ cosd(thetaZ_temp) -sind(thetaZ_temp); o sind(thetaZ_temp);
     o o 1];
R=Rz*Ry*Rx;

%Calculating coordinates of the point after shift (S1)
S1_temp=R*(So_temp-100)+T;

%Storing results of new Nose coordinates after shift in a matrix
XYZ_NoseCBCT1(i,:)=S1_temp';

%To show results in Command Window, uncomment the following:
%sprintf('S1=[%0.1f %0.1f %0.1f; %0.1f %0.1f %0.1f; %0.1f %0.1f %0.1f]', S1(1,1), S1(2,1), S1(3,1))

end

%I believe co-reg parameters of CBCT2 Setup is for co-registration
%between CBCT2 setup and Ref CBCT (NOT CBCT2 with CBCT1); so I am
%calculating new Nose coordinates after setup 2 using the original ref
%nose coordinates
for i=1:H
    So_temp=XYZ_NoseRef(i,:);
    So_temp=So_temp';
end

%Input Co-registration Translation parameters from LGP
deltaX_temp=Deltasetup(i,1);
deltaY_temp=Deltasetup(i,2);
deltaZ_temp=Deltasetup(i,3);

%Input Co-registration Rotation parameters from LGP
thetaX_temp=Thetasetup(i,1);
A.3. NOSE MARKER VS. TARGET DISPLACEMENT USING ICON’S CO-REGISTRATION ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

% Calculating Translation Matrix (around 100, 100, 100)
T = [deltaX_temp + 100; deltaY_temp + 100; deltaZ_temp + 100];

% Calculating Rotation Matrix (around 100, 100, 100)
Rx = [1 0 0; 0 cos(degtorad(thetaX_temp)) -sin(degtorad(thetaX_temp));
     0 sin(degtorad(thetaX_temp)) cos(degtorad(thetaX_temp))];
Ry = [cos(degtorad(thetaY_temp)) 0 sin(degtorad(thetaY_temp)); 0 1 0;
     sin(degtorad(thetaY_temp)) cos(degtorad(thetaY_temp))];
Rz = [cos(degtorad(thetaZ_temp)) -sin(degtorad(thetaZ_temp));
     sin(degtorad(thetaZ_temp)) cos(degtorad(thetaZ_temp)) 0; 0 0 1];
R = Rz * Ry * Rx;

% Calculating and showing coordinates of the point after shift (S1)
S1_temp = R * (So_temp - [-100; -100; -100]) + T;

% Storing results of new Nose coordinates after shift in a matrix
XYZ_NoseCBCT2 (i, :) = S1_temp;
A.3. NOSE MARKER VS. TARGET DISPLACEMENT USING ICON’S CO-REGISTRATION ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

%Calculating Translation Matrix (around 100,100,100)
T=[deltaX_temp +100; deltaY_temp +100; deltaZ_temp +100];

%Calculating Rotation Matrix (around 100,100,100)
Rx = [1 0 0; 0 cos (degtorad(thetaX_temp)) -sin (degtorad(thetaX_temp));
      0 sin (degtorad(thetaX_temp)) cos (degtorad(thetaX_temp))];
Ry = [cos (degtorad(thetaY_temp)) 0 sin (degtorad(thetaY_temp)); 0 1 0;
      -sin (degtorad(thetaY_temp)) cos (degtorad(thetaY_temp))];
Rz = [cos (degtorad(thetaZ_temp)) -sin (degtorad(thetaZ_temp)) 0;
      sin (degtorad(thetaZ_temp)) cos (degtorad(thetaZ_temp)) 0; 0 0 1];
R=Rz*Ry*Rx;

%Calculating coordinates of the point after shift (S1)
S1_temp=R*(So_temp -100)+T;

%Storing results of new Nose coordinates after shift in a matrix
XYZ_IsoCBCT1(i,:)=S1_temp';

%To show results in Command Window, uncomment the following:
%sprintf('S1=
 X1 = %0.1f 
 Y1 = %0.1f
 Z1 = %0.1f', S1(1,1), S1(2,1), S1(3,1))
end

%I believe co-reg parameters of CBCT2 Setup is for co-registration
%between CBCT2 setup and Ref CBCT (NOT CBCT2 with CBCT1); so I am
%calculating new iso coordinates after setup 2 using the original ref
%iso coordinates
for i=1:H
So_temp=XYZ_IsoRef(i,:);
So_temp=So_temp';

%Input Co-registration Translation parameters from LGP
deltaX_temp=Deltasetup(i,1);
deltaY_temp=Deltasetup(i,2);
deltaZ_temp=Deltasetup(i,3);

%Input Co-registration Rotation parameters from LGP
thetaX_temp=Thetasetup(i,1);
thetaY_temp=Thetasetup(i,2);
thetaZ_temp=Thetasetup(i,3);

%Calculating Translation Matrix (around 100,100,100)
T=[deltaX_temp +100; deltaY_temp +100; deltaZ_temp +100];

%Calculating Rotation Matrix (around 100,100,100)
Rx = [1 0 0; 0 cos (degtorad(thetaX_temp)) -sin (degtorad(thetaX_temp));
      0 sin (degtorad(thetaX_temp)) cos (degtorad(thetaX_temp))];
Ry = [cos (degtorad(thetaY_temp)) 0 sin (degtorad(thetaY_temp)); 0 1 0;
      -sin (degtorad(thetaY_temp)) cos (degtorad(thetaY_temp))];
Rz = [cos (degtorad(thetaZ_temp)) -sin (degtorad(thetaZ_temp)) 0;
      sin (degtorad(thetaZ_temp)) cos (degtorad(thetaZ_temp)) 0; 0 0 1];
R=Rz*Ry*Rx;

%Calculating and showing coordinates of the point after shift (S1)
S1_temp=R*(So_temp -100)+T;
A.3. NOSE MARKER VS. TARGET DISPLACEMENT USING ICON’s CO-REGISTRATION ALGORITHM PARAMETERS IN TRANSFORMATION MATRIX

%Storing results of new Nose coordinates after shift in a matrix
XYZ_IsoCBCT2(i,:) = S1_temp ;
end

%Calculating vector magnitude
A_temp = (XYZ_IsoCBCT2 - XYZ_IsoCBCT1);
IsoVector_Calc = sqrt(sum(A_temp.^2, 2));

%%% End Iso points transformation & analysis

%%% Calculating ratio of iso displacement to nose displacement
IsoNose_ratio = IsoVector_Calc / IFMM_Calc

%%% END of Code