EVALUATION OF TORQUE-INDUCED SPATIAL ERROR IN THE STEREOTACTIC DEFINITION OF THE LEKSELL GAMMA KNIFE ICON SYSTEM

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CHAPTER 1. INTRODUCTION AND PURPOSE

Since the 1960s, the Leksell Gamma Knife radiotherapy system has been the pinnacle of neurological tumor treatment using photon beams. This system has been regarded as the most spatially precise method of delivering radiation to a target in the brain among the available methods that include linear accelerator-based Stereotactic Radiosurgery (SRS) and Whole Brain Radiotherapy (WBRT). It is not uncommon for clinical usage of the Gamma Knife system to require and to deliver a radiation dose with a spatial accuracy of less than 1 mm. Over the decades, Gamma Knife has undergone several iterations and improvement cycles, the most recent of which being the Leksell Gamma Knife ICON radiotherapy system. Seven of these systems were installed in 2015-2016 across the United States, and the ICON machine that is the subject of this study was installed at Emory St. Joseph's Hospital in Atlanta, Georgia. The Leksell Gamma Knife ICON system is the first iteration of the Gamma Knife design to include the option of frameless stereotactic radiosurgery with integrated Cone Beam CT (CBCT) imaging while keeping the option of using a traditional skull-mounted frame called the GK frame. Traditionally, the GK frame defines a stereotactic coordinate system via a box containing fiducial markers which mounts to the GK frame during the initial imaging study and uses the known positions of the fiducial markers to make the stereotactic definition. During the 2 years since the ICON was installed at Emory St. Joseph's Hospital, questions have arisen regarding the spatial accuracy of the image registration to CT or MRI coordinate systems using the fiducial box and the GK frame. Specifically, the extent of potential error from warping of the Gamma Knife frame due to torque on the frame posts and warping of the plane containing the fiducial markers in the fiducial box due to the applied torque is unknown. It is the goal of this study to investigate whether or not such a torque-induced error exists, and if it does, to quantify it. If a significant torque-induced error is discovered in the image registration process, it will be important to compare the total spatial precision of the frame and CT-based treatment including this error to the accuracy of the new ICON frameless CBCT option.

CHAPTER 2. BACKGROUND INFORMATION

Dr. Lars Leksell, Professor of Neurosurgery at the Karolinska Institute in Sweden, invented the first instance of stereotactic radiosurgery with an "arc" of Cobalt-60 gamma ray beams in 1967 with first patient treatment in 1968. This was the first instance of the "Gamma Knife" design as it is used today. Since then, the system has chronologically introduced the Gamma Knife models U, B, C, Perfexion, and ICON. The Gamma Knife design is owned by Elekta A.B., a radiation oncology company founded by Dr. Leksell. All of the models are still in use around the world, with Gamma Knife ICON being the most recent. The Gamma Knife is based upon the "center of arc" principle, meaning that there are a number of ^{60}Co sources uniformly arranged around the patient's head. The older models U, B, and C contained 201 sources and used a hemispherical helmet that contained the collimator holes and attached to the GK frame. The newest models, Perfexion and ICON, share an updated physical source arrangement. In this design, the 192 sources are divided into 8 sectors of equal size in a conical geometry. Each of the 8 sectors is capable of independently moving or being blocked with a choice of 4 mm, 8 mm, or 16 mm collimator aperture diameters.

The ^{60}Co sources contained in a Gamma Knife machine emit two gamma photon energies at 1.17 MeV and 1.33 MeV, which may be averaged and treated as a monoenergetic 1.25 MeV photon beam. This is nominally much lower than typical energies of 6 or 18 MV photons that can be produced using a linear accelerator, however, since the average bremsstrahlung photon energy from a linear accelerator is typically (1/3) of the nominal voltage, the difference between Gamma Knife and linear accelerator photon energies is not that great. However, the depth of maximum dose d_{max} to human tissue for a typical 6 MV photon beam is around 1.5 cm, while d_{max} for a Cobalt-60 gamma ray beam is 0.5 cm.

A previous study has evaluated and compared the spatial accuracy of the Gamma Knife stereotactic definition with MRI imaging versus CT imaging methods [1]. This study found that the average difference in stereotactic coordinates defined by MRI vs. CT was on the order of one pixel size (0.9×0.9×1 mm XYZ). The authors of study [1] found that MRI and CT were within clinically acceptable agreement in terms of stereotactic definition, while the MRI images provided better resolution. However, to our knowledge there have not been any published studies specifically addressing the effect of varying levels of torque and/or uneven levels of torque on the stereotactic definition.

2.1 The Gamma Knife (GK) Frame

The Gamma Knife frame consists of four posts of adjustable length and position attached to the corners of a square shaped base frame made of a titanium alloy, and is shown in Figure 1. A previous study of the stability of the Gamma Knife frame found that the frame achieved sub-millimeter accuracy over a set of 40 patients with an uncertainty less than or equal to the uncertainty of the treatment being used [2].

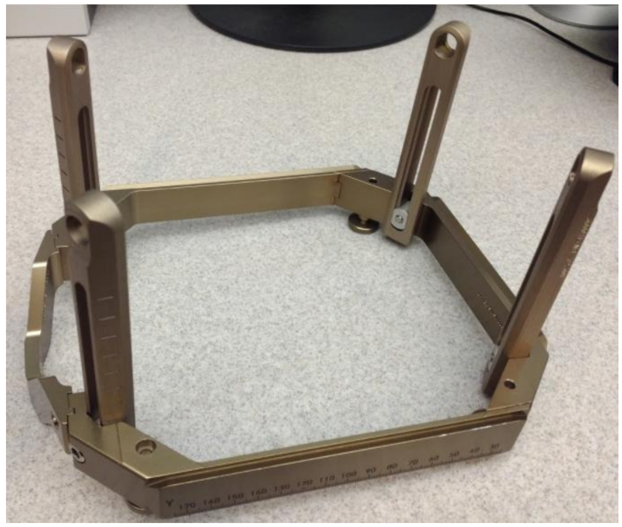

Figure 1: The Gamma Knife (GK) frame.

The posts can be removed and swapped out for alternative posts whose ends are either angled or flat. Each post has a threaded hole that holds a plastic insulator and a titanium pin. The pins come in varying lengths to accommodate different patient head sizes and curvatures. In a typical patient treatment, the anterior posts are angled down and the posterior posts are flat or angled up. The anterior posts will also be raised higher (or have a longer lever arm) than the posterior posts. In this study, all frame posts will be flat like the posts seen in Figure 1.

2.2 Cone Beam Computed Tomography (CBCT)

The Leksell Gamma Knife ICON version is equipped with a Cone Beam CT imaging system, and it is the first iteration of Gamma Knife that has this capability. Cone beam CT is an alternative computed tomography modality from traditional CT. Instead of rotating a fan beam around the axis of the patient, a cone beam CT shoots a cone-shaped beam of x-rays through the patient to a detector on the opposite side, and rotates this beam about the patient. Cone beam CT therefore uses a volumetric or 3D imaging acquisition, whereas a typical CT scanner acquires images using an array of 2D slices from the fan beams. Additionally, the patient is in constant linear motion during a CT acquisition and the patient is not moving during a CBCT acquisition. A previous study [3] found that MRI and cone beam CT are essentially equivalent in terms of the spatial accuracy when defining the stereotactic coordinate system from the GK frame, while MRI still provides better spatial resolution. The integration of cone beam CT to the Gamma Knife system has already allowed for new treatment techniques with Gamma Knife that were impossible before. For example, the first patient to ever be treated using the technique of Adaptive Gamma Knife Fractionated Stereotactic Radiation Therapy (a-gkFSRT) was treated at the University of Heidelberg in Germany in 2016 [4]. This technique involves using ICON's integrated cone beam CT and infrared camera to provide adaptive imaging and motion measurement for in vivo adaptive treatment planning. The development of such new techniques illustrates the continuing relevance and longevity of Gamma Knife in modern radiation oncology departments.

CHAPTER 3. METHODS AND DESIGN

3.1 The Alderson RANDO® Phantom

It was decided at Emory St. Joseph's hospital to begin designing a phantom that could be placed in the GK frame that can replicate the positioning of a human head in the frame. An anthropomorphic head phantom is therefore the obvious choice for this application. One such phantom is the RANDO head phantom sold by Alderson, Inc. The Alderson RANDO phantom may be seen in Figure 1. and Figure 2, and it consists of an imitation of bony anatomy surrounded by a tissue equivalent material which takes the shape of a small human head and neck including small imitations of the nose and ears.

Figure 2: The Alderson RANDO® Phantom.

The Alderson phantom is divided into 10 sections with a typical section width of 2.5cm, however some sections have irregular shapes and deviate from this 2.5cm standard, e.g. the top of the head and the shoulders. The sections may be individually removed, and the phantom is held together by two threaded rods in the coronal plane and two nuts which hold the pieces together tightly.

3.1.1 Alteration of the RANDO Phantom material

As the RANDO phantom was never designed for a GK frame pin to penetrate the outer surface material, it would not be acceptable to place a GK frame on the phantom. This would most likely unacceptably rupture the tissue-equivalent material of the outer surface. Therefore in order to make the RANDO phantom compliant with the project goals, either new identical slices need to be made from an acceptable material to replace the existing slices or the phantom needs to be reconstructed entirely from an acceptable material. There are many materials that could satisfy the goals of the phantom construction including acrylic resin and powder, plaster, 3D-printed ABS plastic, and solid Lucite (another name for acrylic). While 3D printing remains an option even for acrylic material through commercial vendors, the price per cubic centimeter is very high, totaling approximately $13,000 for printing a full-sized head replica. Ultimately, it was decided that replicating two of the phantom slices with solid Lucite is the best option for the current project goals. The replication of the topmost (un-numbered) slice and slice number 1 using the Georgia Tech Machine Shop in the Department of Mechanical Engineering was the most reasonable option. With this option, the price may be kept low while still meeting the requirements of the project.

In addition to the replacement of two tissue-equivalent slices with Lucite, a special cassette was designed and constructed of Lucite as well. This cassette has a 0.3 mm thick and 5 cm × 5 cm square which gives it the ability to hold a 5 cm × 5 cm Gafchromic film with a central pin prick in position for an axial dose delivery. The top piece of the cassette has a 1 mm diameter hole that acts as a fiducial marker made of air in the center of the square. One millimeter of air is a sufficiently visible fiducial marker for target localization in both CBCT and CT. The cassette design may be seen in Figure 3, and the RANDO with the top 3 slices replaced with Lucite including the inserted cassette is seen mounted to the Gamma Knife couch via the GK frame adapter in the cone-beam CT image acquisition position in Figure 4.

Figure 3: The Lucite pieces include an insert wherein a cassette with a Gafchromic film may be placed. Manufactured at the Georgia Tech Dept. of Mechanical Engineering.

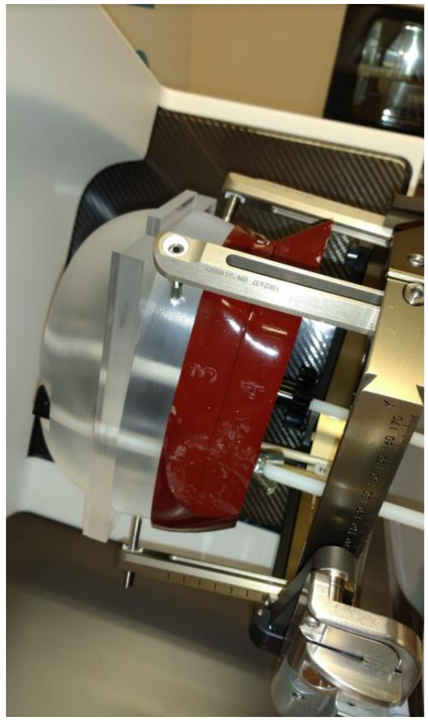

Figure 4: RANDO phantom with Lucite slices and cassette insert in position 1 and 2 and the skull cap. The phantom is mounted to the GK couch via the GK frame adapter and is in the cone beam CT imaging position.

One may insert a Gafchromic film between any two slices in the normal RANDO phantom, however in order to remove the film for analysis it is necessary to unscrew the threaded rods and pull the slices apart to remove the film. This project requires that the phantom and the GK frame must be imaged with both CBCT and CT for every torque level using a single frame application for each torque level. This means that the frame cannot be removed from the phantom when moving from the CBCT to the CT, since that removal of the frame would introduce a non-measurable error when the frame is reassembled. The film must also be removed between CBCT and CT without removing the GK frame from the phantom, and this was the rationale for creating the removable cassette which can be seen in Figure 3 (removed) and Figure 4 (inserted). Using this cassette, the task of removing the Gafchromic film from its position inside the phantom and replacing it with a new film after each dose delivery without introducing new errors is possible. This makes the job of changing Gafchromic films from one analysis to the next faster and more accurate. The cassette itself is subject to only a negligible amount of variation in positioning between each insertion since the cassette dimensions match the hole dimensions to within machine precision, and the insert is held in place in the hole by gravity.

Additionally, four 6 mm diameter by 16 mm depth holes were drilled normal to the surface of the bottom Lucite slice for the purpose of mounting the Gamma Knife frame to the phantom. These holes are slightly wider than the 5 mm pin diameter on the GK frame, and they are discussed more thoroughly in the next section.

3.2 Designing the pin-phantom interface

In order not to crack or otherwise damage the Lucite slice, the GK pins will not come into direct contact with the Lucite itself. Instead, the 6 × 16 mm holes will be filled with an intermediate material that will serve as a "shield" to the Lucite and will bear the majority of the pressure from the Gamma Knife pin tip when it is torqued down with the screwdriver. The idea is that in the case that the intermediate material is ruptured, the crack will not propagate into the Lucite and this material can be easily drilled out and replaced.

Three "shield" materials were tested and evaluated on their ability to withstand the pressure of the Gamma Knife pin tip: Weldwood Contact Cement, J.B. Weld 2-part epoxy mix, and later Castn'Craft "Liquid Plastic" Polyester mix with catalyst. The Weldwood cement and the J.B. Weld epoxy can be seen in their curing stage in Figure 5. The Castn'Craft liquid plastic can be seen in the phantom hole in Figure 6.

Figure 5: The original candidates for intermediate material, Weldwood contact cement and J.B. Weld 2-part epoxy mix. Both were discarded in favor of the "liquid plastic" in Figure 6.

After letting the Weldwood cement and the J.B. epoxy cure in small cups for 24 hours, it was immediately apparent that the Weldwood cement was still soft to the touch and very malleable under pressure, and therefore not a good candidate for placing the Gamma Knife pins into it. The J.B. Epoxy was firm to the touch and did not deform under pressure, and was selected to be poured into the holes and cured. Since the holes are not facing the same directions, the Lucite slice was placed in a vise with one hole upright, and the epoxy was poured into the hole. This was done for each of the four holes, each time allowing ample time for the epoxy to harden before moving to the next.

After letting the J.B. epoxy cure in all four holes, the Lucite RANDO was assembled and the GK frame with pins was mounted onto the phantom. The J.B. epoxy appeared to be holding up, but after several minutes it was apparent that some of the epoxy was bulging out of one of the holes after the GK pin was torqued to 4 inch-lbs. The frame was removed and the epoxy drilled back out and replaced with new epoxy. After curing, a second attempt was made at placing the frame on the epoxy-filled holes. On the second attempt, another hole began bulging epoxy out from under the pin. It was then decided to try the Castn'Craft liquid polyester resin.

The "liquid plastic" resin by Castn'Craft comes with a catalyst to incite the hardening process. The phantom was placed in a vise as previously, and the resin was mixed in a small cup at a ratio of approximately 1 drop of catalyst per ¼ fluid ounce of resin. The mixture is vigorously stirred and then poured into the hole on the phantom slice. The Lucite phantom slice is fixed in a vise with the hole facing upwards and perpendicular to the ground for curing. It was observed that this mixture takes much longer to cure than the J.B. epoxy. It took about 24 hours per hole to cure to a solidified state, but it still retained a "tackiness". The phantom was then placed in a sunlit window for about 2 days to fully cure all the holes, after which the "tackiness" was not observed again.

As in the case of the J.B. epoxy mix, the GK frame and pins were mounted to the phantom with the pins being set as centrally in the holes as possible. All frame posts were flat (no angled posts). The phantom was left to sit in the treatment position with the frame mounted for 24 hours. Unlike the J.B. Epoxy mix, no bulging or movement was detected with the hardened "liquid plastic" after a visual inspection with a magnifying glass. The Castn'Craft Liquid Plastic product was therefore selected to be the material in which to embed the GK pins for this project. The Castn'Craft resin may be seen in one of the holes with a GK pin mounted into it in Figure 6.

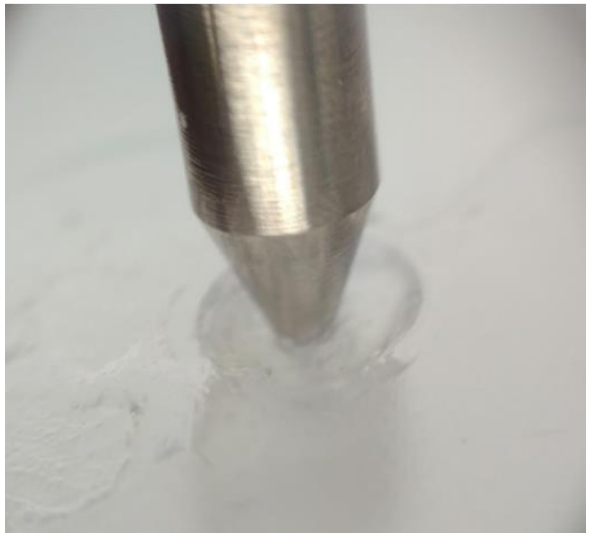

Figure 6: Close-up of the GK pin embedded into the Castn'Craft liquid acrylic surrounded by Lucite.

The physical interaction between the embedment material into which the Gamma Knife pins are forced and the pins themselves affects the amount of torque that is applied about the GK frame base which may cause warping. This interaction is described in the next section.

3.3 Physics of the interaction between the GK pins and the phantom

There are several intricacies about the interface between the plastic resin in the hole and the Gamma Knife frame pin and its effect on the overall torque about the frame post. First, it is important to remember what is the most important factor in determining torque about the frame and subsequent warping of the frame's base plane. In theory, this should be solely determined by the amount of linear normal force exerted by the phantom (or patient head) onto the GK pin and thence onto the GK frame post. This linear force exerted by the phantom material onto the frame post corresponds to a torque about the frame base, and this torque is the suspected culprit of any possible frame warping. See Figure 7 for an illustration of the forces involved.

Figure 7: Illustration of the forces involved.

Now that the linear normal force from the phantom to the pin has been determined to be the most important factor in causing warpage, a detailed analysis of how this normal force is created must be made, including its relationship to the one independent variable in the problem that can be adjusted by the experimenter: the measurable torque applied to the GK pin with a torque wrench. Let us denote $\overrightarrow{T_s}$ to be the torque applied from the torque wrench about the GK screw's longitudinal axis, whose magnitude is the reading on the torque wrench. Also denote $\overrightarrow{T_b}$ to be the torque imparted about the GK frame's base by the GK frame post.

Beginning with the part the gamma knife pin that is attached to the torque wrench and working inward, the first resistive torque that the wrench (i.e. the experimenter's hand) encounters is friction within the head of the GK frame post. The contact between the threaded pin and the threaded hole creates friction between the post and the GK pin. An illustration of this frictional force which exists at all points on the surface of the screw inside the threaded hole and which causes a corresponding resistive torque may be seen in Figure 8. A plastic insulator is also commonly inserted into the post head to prevent burning of the patient's skin while the metal frame is placed in an MRI field. Whether or not the experimenter uses a plastic insulator will change the coefficient of static and kinetic friction inside the post head since the plastic insulator has a different coefficient of kinetic friction than the metal GK pin and since the classical frictional force is $\vec{f} = \mu\overrightarrow{N_t}$, where $\overrightarrow{N_t}$ is the magnitude of the total normal force $\overrightarrow{N_t}$ from the threads to the grooves, and where μ is the coefficient of kinetic friction (or static friction if the screw is stationary). In this experiment, we will be using an insulator to imitate patient setup.

As the GK pin translates linearly inward toward the phantom while being turned, the normal force $\vec{N}$ from phantom to pin increases, and this normal force is equal in magnitude to $\overrightarrow{N_t}$. The thread-groove normal force $\overrightarrow{N_t}$ therefore also increases. The friction $\vec{f}$ inside the threaded post hole increases according to $\vec{f} = \mu\overrightarrow{N_t}$. The resistive torque on a differential area of the contact surface created by this frictional force is $\vec{t} = \vec{r} \times \mu\overrightarrow{N_t}$, where $\vec{r}$ is the radius of the pin and × denotes the cross product. This resistive torque that opposes the turning of the screw by the wrench is then found by integrating the differential torque over the pin's surface area. Finally, the torque about the base of the frame from one post is given by $\overrightarrow{T_b} = \overrightarrow{r_{post}} \times \vec{N}$. It may at first seem superfluous to discuss this internal friction, but in fact it illustrates that the pressure on the patient or phantom surface is not purely a function of the nominal inch-lbs of torque that the physicist or surgeon applies, since much of the applied torque is spent resisting internal friction in the post head. The measured torque reading on the torque wrench is ultimately a function of the normal force from the phantom to the pin and the coefficient of kinetic friction on the contact surface of the metal pin and the interior of the post hole.

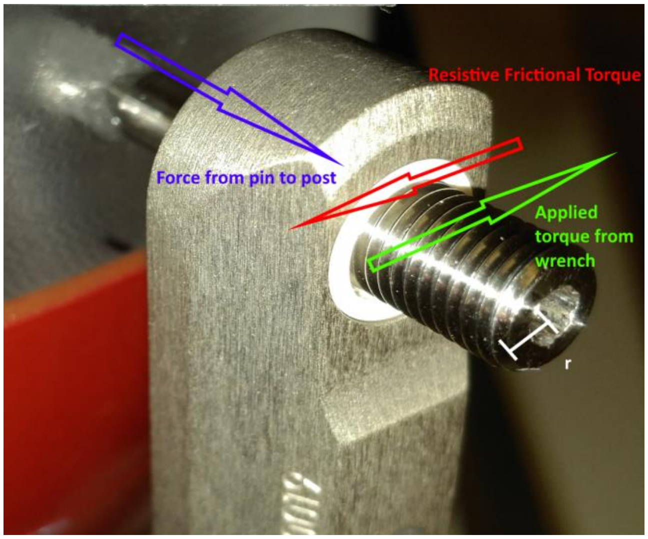

Figure 8: Interior screw friction.

The only other resistive torque that affects the wrench's displayed inch-lbs value is the friction between the GK pin tip and the phantom surface or patient skin. As the pin rotates, there is some rotational friction between the metal pin and the surface material. Based on the experience with this phantom and frame, the author believes that the vast majority of the resistive torque comes from internal friction in the post head, not the pin-surface interface. However, the pin-phantom interface friction still exists.

In addition to the torque applied to the GK pin, linear force from opposing frame posts must necessarily also affect the normal force on a pin. While the pins are not perfectly coplanar and do not exert their force perfectly radially inward, the radial components of their exerted force must cancel out since they are in equilibrium. Therefore, it is quite possible that a given pin with a fixed torque reading from the wrench may still experience a changed linear force if the opposing pin's torque value is changed. Even adjacent pins may contribute somewhat since two adjacent pins with different forces exerted on the phantom will have different horizontal component magnitudes.

The linear force exerted on the frame post creates a torque about the base to which the post is attached, as shown in Figure 7. It is this torque that is the subject of this study. One can easily imagine that if two opposing pins experienced a much larger outward normal force than the other set of opposing pins, the frame base would bend backwards into a "V" shape (in an extreme case). This may be happening on a microscopic level, and should be quantified if the goal of Gamma Knife SRS is to have reliable sub-millimeter accuracy.

A final point about the physics of the pin-phantom interface is the inherent safety built into the four pin holes. Since they are filled with a different material that solidified independently of the Lucite, there is a discontinuity in stress tolerance at the resin-Lucite interface, and any cracks that may form due to excess force from the pin should remain in the resin and not propagate into the Lucite. This allows the Lucite phantom to be reusable if a rupture does occur, since the hole may be drilled out and re-filled.

3.4 Gafchromic Film

Gafchromic film is a simplistic yet effective radiation detection device. It is a flat material that can be easily cut into a desired shape, and darkens when irradiated. The amount of darkening at any point can be used to extract information about the radiation dose that was deposited. Care must be taken to keep the film away from visible light because it may darken over time due to visible light exposure. Usually a reference film is used as a control and kept in the same conditions as the irradiated films, but it is not irradiated. Since the darkening response of Gafchromic film is not linear with dose, film must be calibrated for absolute dosimetry purposes before first use. Even for relative dosimetry, the relationship between two data points is unknown if the film was not calibrated for absolute dosimetry.

The EBT-3 type film that is used in this study is composed of a 28 μm thick active layer, surrounded on both sides by 125 mm thick matte polyester layers. The response of the film is dose-dependent but energy-independent, and the film works optimally in the range of 0.2-10 Gy [5]. The active component inside the active layer forms a blue polymer when it is exposed to radiation, and an increase in dose will cause an increase in the amount of blue polymer that is formed. The change is visible to the naked eye and can be quantified using a flatbed document scanner and a film analysis software such as RIT.

The film can be scanned into a `.tif` image in RIT, and RIT has the ability to extract the Red, Green, and Blue channel values of the film. The Red channel value is used for absolute dosimetry in the optimal dose range. The change in optical density in the red channel values between a reference film and the irradiated film is what can be associated with delivered dose. The change in optical density is defined as

$$\Delta OD = OD_{\text{exposed}} - OD_{\text{unexposed}} \tag{1}$$

where $OD_{exposed}$ refers to the irradiated film's optical density value and $OD_{unexposed}$ refers to the unirradiated film's optical density value [6]. We must also account for the part of the optical density that comes from background radiation. To do this, we keep a film in the same conditions as the irradiated films, but we do not irradiate it. Therefore, it should receive a dose of 0 Gy. However, there will be some slight change in its optical density due to Radon, cosmic rays, and other background dose. So we record the optical density of the 0 Gy film before beginning the irradiations, and we record it again at the same time that we record the other films. Then, the change in optical density of this "control" film is defined as

$$\Delta OD_{\text{control}} = OD_{\text{control,after}} - OD_{\text{control,before}} \tag{2}$$

where “after” refers to after the experiment, and before refers to before the experiment [6]. Finally, we can compute the "net" change in optical density of the films, which corresponds to the actual dose delivered by the Gamma Knife machine [6]. This value is defined as

$$\begin{aligned} \Delta OD_{\text{net}} &= \Delta OD - \Delta OD_{\text{control}} \\ &= OD_{\text{exposed}} - OD_{\text{unexposed}} - \Delta OD_{\text{control}} \end{aligned} \tag{3}$$

While the Gafchromic film in this experiment was calibrated in the manner above, this dose calibration was not technically necessary since the measurements only involved the spatial position of the center of the FWHM of the dose and not the dose values themselves.

3.5 Gafchromic Film Analysis

3.5.1 Film Calibration

Using the spherical film calibration tool for the Leksell Gamma Knife ICON, 5cm x 5cm films were irradiated with doses of 0, 1, 2, 3, 4, 4.5, 5, 5.5, 6, 7, and 8 Gy to their centers. Although the dose information from the film darkening is not very paramount to this project since the project's main purpose is to study the position of the dose and not the magnitude, the EBT-3 film was still calibrated using RIT to produce a dose calibration curve. This curve relates the optical density of the film to the delivered radiation dose to the film at each pixel. The curve is formed by supplying the software with images of the irradiated films that have been irradiated with known doses. It then plots the optical density at the center of the dose distribution versus the delivered dose. To create the dose calibration curve, the RIT software uses a cubic spline interpolation to give the dose at any pixel density. Figure 9 is a plot of the calibration curve for pixel density vs. dose.

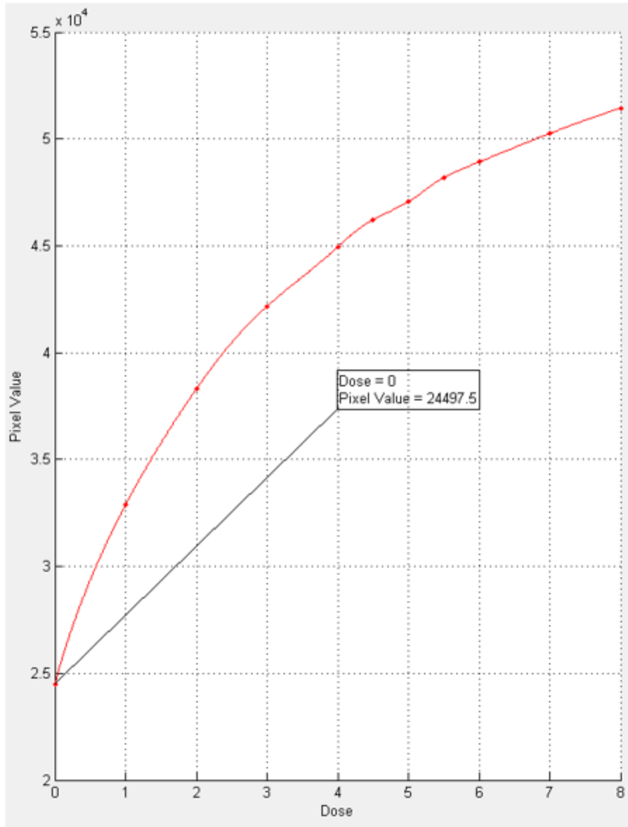

Figure 9: Dose calibration curve for the EBT-3 Gafchromic film used in this experiment, created in RIT.

3.6 Film irradiation for various torque levels

For the torqueing experiments, 5×5 cm films were cut. Each film was labeled with imaging modality (CT or CBCT), the torque value, even (E) or uneven (U) torque, and the torque level on each post if the torque was uneven. Each film was given a small (<1 mm) pin prick in the center with the pin prick tool included with the Gamma Knife QA suite. The imaging workflow for a given level of torque involves image acquisition and subsequent dose delivery. The image acquisition involves taking a CT or CBCT image of the phantom with the cassette inserted, but without film since the X-rays would change the optical density. Next, a treatment plan must be created in Leksell Gamma Plan (LGP), choosing the target to be the point inside the 0.3 mm thick square cavity directly beneath the air fiducial target in the $\hat{z}$ direction (this should be the location of the film's pin prick in the absence of film placement error). The cassette is always mounted in the Lucite phantom such that the air fiducial on the top piece of the inserted cassette is on the superior side of the film with the 1 mm air fiducial abutting the film (i.e. facing inferiorly). The XYZ in stereotactic coordinate space of the chosen target must be recorded for both CT and CBCT images and the Euclidean distance between the two calculated. The mean and max errors for the CT image reported by Gamma Plan are also recorded. These errors are a measure of the slice-by-slice distance from the location of the fiducial box's fiducial markers in the image to where they are supposed to be based upon the stereotactic coordinates defined by the Leksell GK frame that are known by Gamma Plan. Finally, the pin prick on the film must be aligned as perfectly as possible by eye to the air fiducial on the cassette and the film must be fixed in this position to the cassette by tape. This was done by placing the cassette and film over a flat piece of plastic and shining a light underneath in order to finely position the pin prick over the fiducial marker and tape the film. The cassette is then inserted with the film inside, and the film is irradiated with 5 Gy to the 50% isodose line about the target point.

After testing several different workflow processes, the optimal workflow for each torque level was decided to be 1) CBCT the phantom, 2) CT the phantom, 3) plan the CT delivery, 4) irradiate the CT film, 5) plan the CBCT delivery, 6) irradiate the CBCT film. This workflow allows for detection of any potential phantom changes over time and minimizes wasted time between each step. Full details on the workflow can be seen in Appendix A.

3.6.1 Issue: wobbling encountered with the Lucite pieces

It should be noted that after taking the first 4 scans (2 CT and 2 CBCT) and irradiating their corresponding films with torque values of 4 inch-lbs and 5 inch-lbs, it was discovered that the Cassette piece and the Lucite slice adjacent to it were visibly wobbling, or slipping together, while removing one of the films. The cause of this wobbling was discovered to be that the nuts which hold the RANDO phantom together via the threaded rods had wiggled loose in the process of moving back and forth several times from the CT to the Gamma Knife. Their normal force had reduced enough during this process to cause the RANDO phantom slices to become free of friction and to freely move against one another, therefore invalidating the films that were previously taken because it introduced a large spatial inaccuracy that was not accounted for. We had not been checking the nuts at the bottom of the RANDO for stability at each movement from one machine to the other. While there was no immediate modification that could be made to the phantom to solve this problem, it was decided to re-irradiate films at the same torque values and to continue with the experiment. To stop the wobbling from affecting the spatial accuracy at each irradiation, we began to check the tightness and stability of the nuts on the bottom of the RANDO at each film torque level. Ensuring the phantom is stable within one set of scans (CT and CBCT for one torque level) will ensure that the spatial error due to wobbling is eliminated for that specific torque level. If the nuts need to be tightened from one level to the next, it does not guarantee that the cassette's fiducial will be in the same frame of reference from one torque level to the next, however this is thankfully not necessary to conduct the experiment. Any newly designed phantoms should take this wobbling problem into consideration.

3.6.2 Phantom "hanging" within the frame and fiducial box

Originally, the phantom was supported by a pillow when being placed in the CT scanner for imaging. This created a separate problem in that the phantom was being supported with a pillow in the CT scanner but not in the Gamma Knife. The phantom is relatively heavy compared to the frame posts, and there was the possibility that the phantom was inducing some downward force on the frame posts in the unsupported position in the Gamma Knife, but not in the CT. We eliminated this problem by using the CT imaging mount supplied with the GK frame. The imaging mount does not rigidly attach to the Ct couch, but we were able to immobilize it by placing a counterweight on the bottom of the mount opposite to the phantom. The frame mounted into the imaging mount, and the fiducial box then mounted to the frame and the entire structure was held in place by the counterweight.

3.6.3 Setup Error

There are a variety of sources of spatial error in the setup of the phantom within the frame. For example, the selection of a target point in Gamma Plan involves locating the fiducial air marker within the cassette on the imported image. The target location is chosen manually to be the point directly below the air fiducial marker corresponding to the theoretical location of the pin prick on the film. However, it is impossible to perfectly align the pin prick to the air fiducial in practice, so this is one source of setup error. There may be some minute amount of play in the frame adapter mount that mounts the GK frame to the GK couch. Additionally, there is some error in the positioning of the GK and the CT couch. The cumulative sum of the non film-related errors may be estimated using another phantom called the Known Target Phantom. The Known Target Phantom was used to measure this setup error by putting it through the same process of CT and CBCT image acquisition in the GK frame that is used for the RANDO phantom. The distance from the delivered shot's FWHM center location and the pin prick on a film placed in the Known Target phantom at a known location may be regarded as a measure of the "setup error" involved in the Gamma Knife treatment delivery. The distance from dose center to pin-prick location for CT imaging case with the Known Target Phantom was measured in RIT to be 0.18mm, and the distance from dose center to pin-prick for the CBCT imaging case was 0.24 mm. However, this should not be considered to be directly subtractable from the total measured error on the torqued shots, because the Known Target Phantom is not the same phantom as the RANDO phantom. These data do give some idea as to the general order of magnitude of the setup error involved in the process, however.

3.6.4 Even torque measurements

There are several different ways in which the frame posts could be torqued. We began first with the simple case of having an equal torque value on every post, and starting from the recommended value of 4 inch-lbs and increasing the torque and observing the result. Films were irradiated with equal frame post torque levels of 4 inch-lbs, 6 inch-lbs, 8 inch-lbs, 10 inch-lbs, 12 inch-lbs, and 14 inch-lbs. All films were irradiated with 2.5 Gy prescribed to the 50% isodose line. Each torque level received a CT and a CBCT image acquisition, each of which was used to plan a separate film delivery.

After reaching the level of 10 inch-lbs, the GK pins on the anterior side of the phantom had completely extended themselves into the threaded hole, and could not be screwed any further. So, between the 10 and 12 inch-lbs torque levels, the GK pins were rebalanced, screwing the back pins further into the phantom and unscrewing the front pins slightly from the phantom. The final torque wrench value on each post still read 12 inch-lbs after the rebalancing.

One point should be made about the higher torque levels beginning around 10 inch-lbs and higher. It was discovered when adjusting the various frame posts at such high torque levels that the adjustment of any individual post's torque value will always affect the torque value on all other posts. For example, adjusting the Anterior Left post to a torque of 12 inch-lbs will either increase or decrease the torque reading on all of the other posts. The set of GK frame posts and their applied torques therefore form a dynamical system, each post's torque affecting the others. The posts ultimately reach force equilibrium with one another since the phantom is motionless, however the equilibrium is not necessarily uniformly at the torque reading that the torque wrench displays. The reading on the torque wrench is a *minimum* for the actual physical resistive torque that the post will produce on the wrench. It is impossible to make all of the frame posts produce actual torque that matches the exact reading on the torque wrench at high torque levels. However, it is still possible to use these torque readings as data since they represent a minimum on the resistive torque in the post head.

3.6.5 Uneven torque measurements

After irradiating films for torque levels of 4, 6, 8, 10, and 12 inch-lbs equally applied to all four posts, we investigated if uneven levels of torque would cause any other effects on the spatial accuracy. A typical clinical application of a GK frame to a patient head will most likely not result in a perfectly even torque load across each post, and many physicians do not even use a torque wrench to apply the frame, preferring to adjust the tightness according to the feel of the force feedback. This could result in very uneven torque loads. An asymmetrically applied set of forces on the frame posts may cause the frame to warp from its natural square shape into either a parallelogram-shape or possibly to warp in such a way that it is not coplanar with the XY plane.

If the GK frame is warped, the fiducial box in which it is mounted for CT imaging will also be correspondingly warped. This fiducial box has a pair of metal fiducial "Z"'s that are located on the side inside the plastic housing. These metal Z's are detected by Leksell Gamma Plan. Their location is directly related to the location, origin, and orientation of the GK frame's stereotactic coordinate system in an ideal case with zero frame deformation. Therefore, LGP can internally define the location of the GK Frame's stereotactic coordinate system within the CT image coordinates by using the detected location of the metal fiducials and assuming there is no frame deformation. However, if the fiducial box is warped whenever the GK frame is warped, the "true" GK frame coordinates will shape themselves according to the direction of warping, while the LGP internally assumes that there is no warping and the frame's coordinates are orthogonal as they were designed. This discrepancy between the true location of the stereotactic coordinates and the stereotactic definition inside LGP will create a spatial inaccuracy causing the pin prick to deviate from the center of the FWHM.

One common experience in Gamma Knife clinics is that a patient undergoing Gamma Knife treatment has already had a craniotomy from a previous disease or as part of their course of treatment. In these cases, it is common that the neurosurgeon who places the Gamma Knife frame on the patient's head will only torque down 3 of the GK frame posts and leave the other post unattached because it is not possible to mount the fourth post to the craniotomy location. In these cases, it is certain that the GK frame is in an asymmetrical force equilibrium since one frame post must counterbalance the force from both the adjacent frame post and the diagonally opposed frame post with no help from the unattached post. These cases are suspected to be the most prone to errors in the stereotactic definition since this asymmetrically applied torque load could be warping the frame on a sub-millimeter to millimeter scale.

Using the nomenclature AR = Anterior Right, PR = Posterior Right, AL = Anterior Left, PL = Posterior Left followed by the inch-lbs number, we went through the same process of image acquisition and then irradiation beginning with a torque distribution of AL-0 AR-14 PR-14 PL-14. We started with this value since the phantom was already at 14 inch-lbs from the evenly distributed runs. The 14 inch-lbs uneven trial run on 11/2/2017 showed that the distance between the CBCT and the CT coordinate was 1.6mm, so it was decided to take data points on 11/12/2017 with more of these "three-pronged" torque distributions at the same torque levels as the even torque measurements.

An additional important finding was made when testing the first "three pronged" torque level at 14 inch-lbs. While mounting the CT fiducial box to the Gamma Knife frame and preparing the phantom for the CT scan, it was visually observed that the fiducial box could not be made to be flush with the GK frame because the Anterior Right mounting point on the fiducial box would not sit flush in its hole. This phenomenon was not observed at lower torque levels, so we suspect that either the high torque at 14 inch-lbs or the asymmetry of the applied torque caused a warping of the frame base, which led to the inability to make it sit flush with the fiducial box. This is a crucial step in the workflow of both patient and phantom, since the CT of the fiducial box is what will define the stereotactic coordinate system. The fact that the frame is not sitting properly flush with the fiducial box means that the fiducial markers in the box will not accurately describe the location of the true stereotactic coordinate system in physical space, since the frame is offset from the fiducial box.

3.6.6 Removing a frame post after imaging

It became apparent after taking the measurements for the uneven torque distributions that it would be very easy to test the error that could occur when a physician cone beams a patient with four posts and even torque, defines the stereotactic definition from the cone beam, and then removes a post from the GK frame and delivers a "three-pronged" torque distribution without re-imaging. This situation would typically happen in the clinic when after imaging the patient, the planned target would result in a potential collision of one of the frame posts with the internal wall of the machine. In these cases, the physician would remove the post that causes the problem. It is commonly accepted that this is most likely bad practice if the patient is not re-imaged after the post removal, but since we had the opportunity to easily take data on this it will be an additional study of the project. This error caused by stereotactic definition and then post removal followed by dose delivery diverges slightly from the torque-induced error which is the main subject of study of this project, however this error was measured at varying levels of torque distribution to see what effect that has on it.

These data were taken on the same day as the uneven torque measurements. The phantom was given a cone beam CT with four posts at torque levels of 4, 6, 8, 10, 12, and 14 inch-lbs and the stereotactic definition was created from this cone beam in Gamma Plan. Then the Anterior Left frame post was removed after the stereotactic definition and the dose was delivered to the planned target after each consecutive image acquisition.

CHAPTER 4. RESULTS

The original lab data is shown in Table 1. "3 prong" represents the 3-post distribution. "Drop" represents the data on the post removal after imaging. Blacked out cells occur where data was not applicable or not taken. The measured data are then plotted in the following subsections.

Table 1: Original measured laboratory data.

Date	inch lbs	E or U	Mean error (mm)	Max error (mm)	CT X	CT Y	CT Z	CBCT X	CBCT Y	CBCT Z	Displacement in XY plane only
11/2	4	E	0.7	1.5	102.4	104.4	50.2	103.2	104.0	49.7	0.9
11/2	6	E	0.7	1.2	102.1	104.0	48.5	102.9	103.2	49.2	1.1
11/2	8	E	0.7	1.5	102.1	102.8	48.9	102.9	102.3	48.7	0.9
11/2	10	E	0.7	1.6	102.1	101.9	48.3	103.0	101.3	48.7	1.1
11/2	12	E	0.6	1.3	103.2	103.8	48.7	103.8	103.2	48.7	0.8
11/2	14	E	0.6	1.1	103.1	102.9	48.0	103.7	102.7	48.2	0.6
11/12	4 3 prong	U	0.6	1.2	106.1	104.6	44.3	105.5	104.4	44.7	0.6
11/12	6 3 prong	U	0.5	1.1	107.6	106.0	44.6	107.0	105.5	44.2	0.8
11/12	8 3 prong	U	0.4	0.9	108.3	106.5	44.5	107.9	106.2	44.7	0.5
11/12	10 3 prong	U	0.3	0.6	109.0	107.2	44.5	[redacted]			
11/12	12 3 prong	U	[redacted]								
11/2	14 3 prong	U	0.9	2.0	107.7	105.9	48.9	106.1	105.7	49.2	1.6
11/12	4 drop	E then U	[redacted]					105.1	104.9	46.2	[redacted]
11/12	6 drop	E then U	[redacted]					105.6	103.3	45.7	[redacted]
11/12	8 drop	E then U	[redacted]					106.5	104	45.2	[redacted]
11/12	10 drop	E then U	[redacted]					107	103	45.2	[redacted]
11/12	12 drop	E then U	[redacted]					103.2	104.4	43.7	[redacted]

The information in Table 1 was acquired over two measurement days 10 days apart due to availability conflicts with the CT scanner and the Gamma Knife in the clinic at St. Joseph's hospital.

4.1 Pin-prick to Full-Width at Half Maximum center distance

The most important result of this study is the measurement of the difference between the planned target location and the actual delivered location of the radiation dose using Gafchromic film with a pin prick in the planned target location. Figures 10-12 display plots of the measured distances from the pin-prick's center to the center of the Full-Width at Half-Maximum (FWHM) of the optical density distribution on each film respectively for the even and uneven torque distributions and for the cone-beam with post removal. These distances were computed algorithmically using RIT's CyberKnife pin prick analysis tool. This tool automatically outlines the isodose levels on the film and locates the center of the dose distribution. It also automatically finds the pin prick center. It then reports the distance from the two center locations. All pin prick centers were visually inspected before calculating the distances to the FWHM center, but in some cases the automatic pin prick recognition in RIT was not satisfactory, so a manual pin prick location was placed instead with the mouse on the pin prick location.

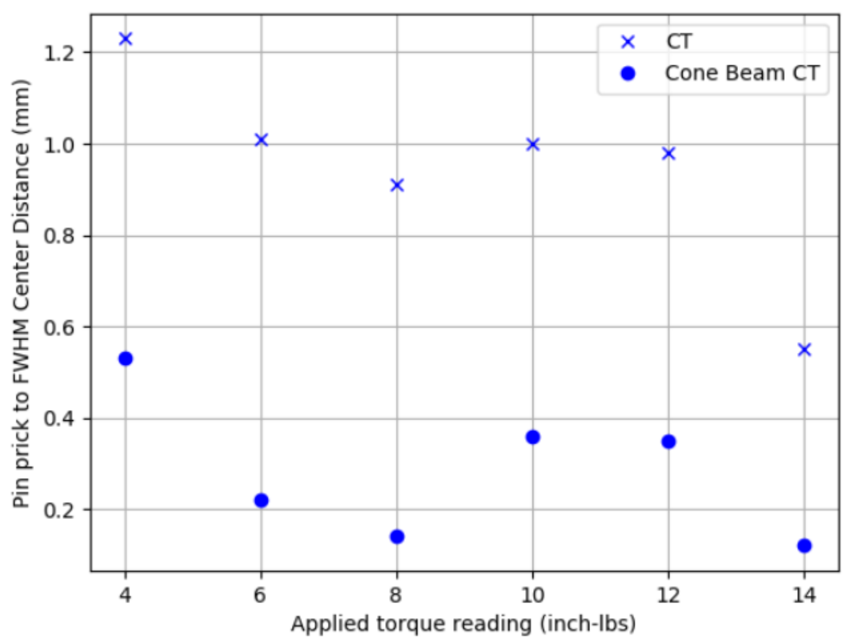

Figure 10: Pin-prick to FWHM center distance vs. torque level for evenly distributed frame torque values.

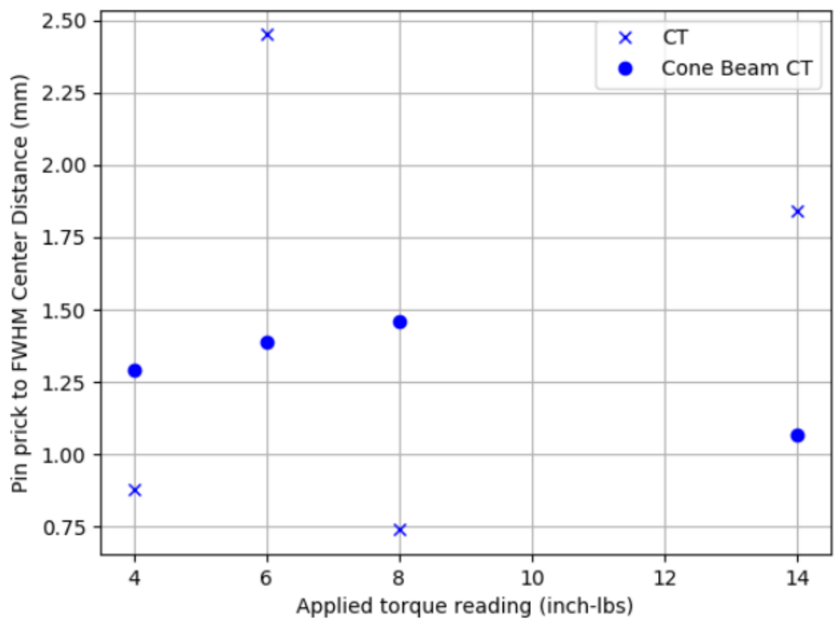

Figure 11: Pin-prick to FWHM center distance vs. torque level for the 3-post torque distribution.

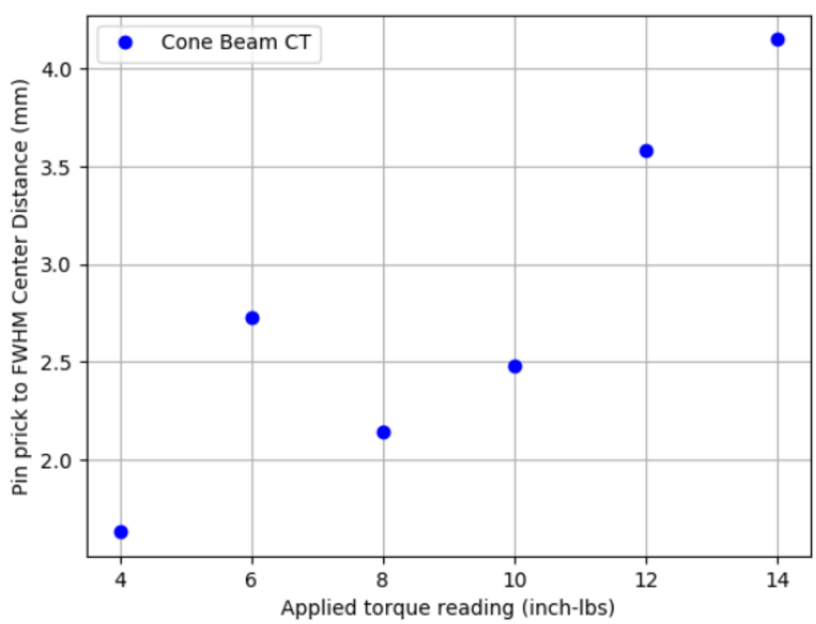

Figure 12: Pin-prick to FWHM center distance vs. torque level for the case of imaging with 4 posts and then removing the AL post before delivery.

4.1.1 Issue: unable to mount 3-post frame at 10 inch-lbs or higher

As shown in Table 1 and Figure 11, the 3-post data for 10 and 12 inch-lbs are absent. On the second day of measurements, after reaching a torque level of 10 inch-lbs on each post it became impossible to mount the GK frame to the frame adapter that mounts the frame to the GK treatment couch. The mounting point on the Posterior Right of the GK frame which attaches to the frame adapter would not slide into the hole even with significant force. It was apparent that at such a high torque level, it is not possible to place the GK frame in the adapter and therefore it was not possible to deliver radiation to the target at 10 inch-lbs or above.

This contrasts with the fact that on the first day of measurements (11/2/2017), the 14 inch-lbs torque distribution for 3 prong was successfully imaged and delivered. The evenly distributed torque measurements had just been completed in that case, and since the phantom was already at 14 inch-lbs from the previous measurements the torque level was not changed. The AL frame post was removed with the other posts remaining at 14 inch-lbs. On the second day of measurements, torqueing of the frame with 3 posts began at 4 inch-lbs and moved upwards. It therefore seems possible to obtain a 3-pronged torque distribution above 10 inch-lbs only if the frame was already torqued above 10 inch-lbs evenly.

4.2 CBCT - CT measured target location offset

During each set of image acquisitions (CBCT first then CT second), the target location was defined to be the point on the film directly abutting the center of the air fiducial in the cassette. The coordinates of this point in Gamma Plan were not the same for CT and CBCT. The distance between the CT and the CBCT target locations in the image is displayed in Figure 13 and Figure 14 for each torque level for the even distribution and for the torque levels of the 3 post distributions where it was possible to take both a CT and CBCT.

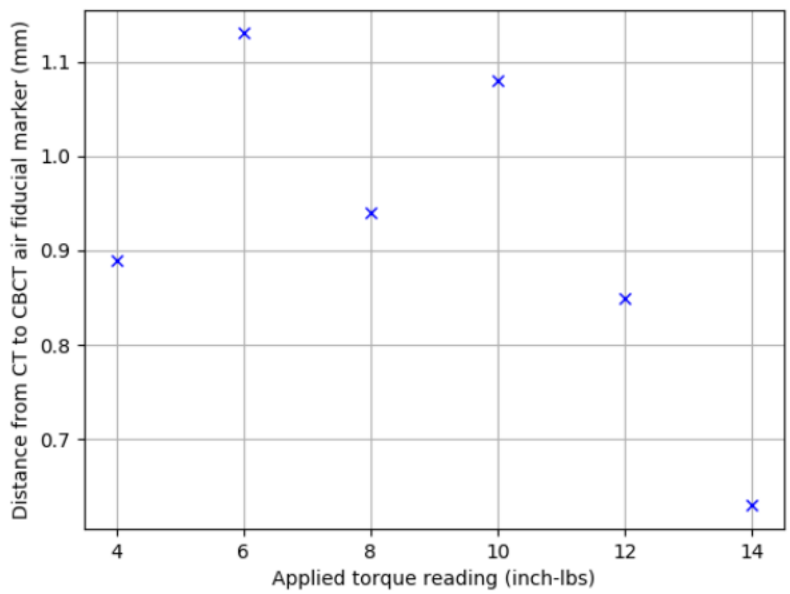

Figure 13: CT to CBCT target location displacement vs. torque level for evenly distributed torque.

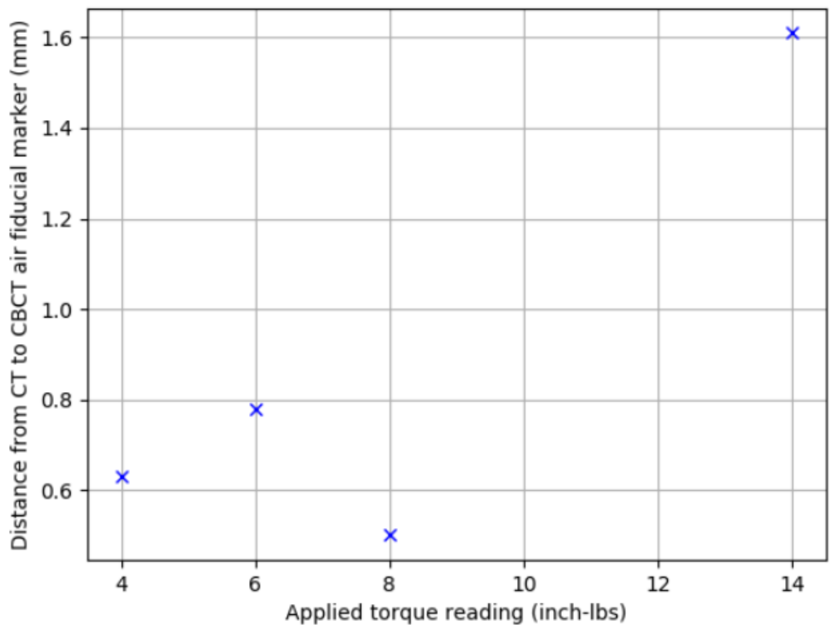

Figure 14: CT to CBCT target location displacement vs. torque level for 3-post torque distribution.

4.3 Mean and max error in Leksell Gamma Plan

Leksell Gamma Plan reports a "mean" and a "max" error whenever a CT image is imported for treatment planning. This is not reported for CBCT images. This error is a measure of the distance between the location of the actual imported image pixels and the location that the Leksell Gamma Plan thinks the pixels should be based on the Leksell Gamma Knife stereotactic coordinates based on the fiducial box. The reported mean and max errors are plotted in Figure 15 and Figure 16 for the even and uneven torque distributions.

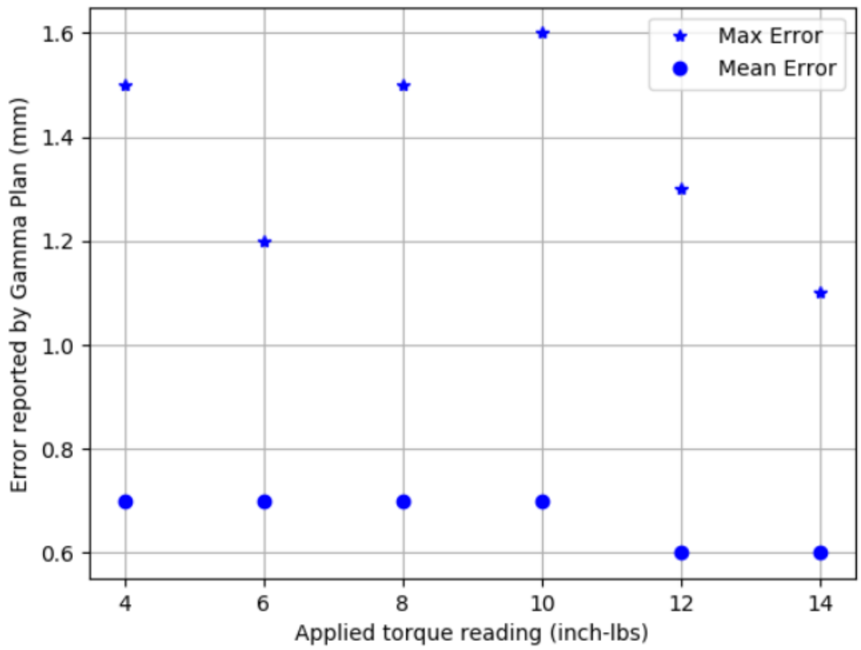

Figure 15: Gamma Plan reported mean and max error for evenly distributed torque.

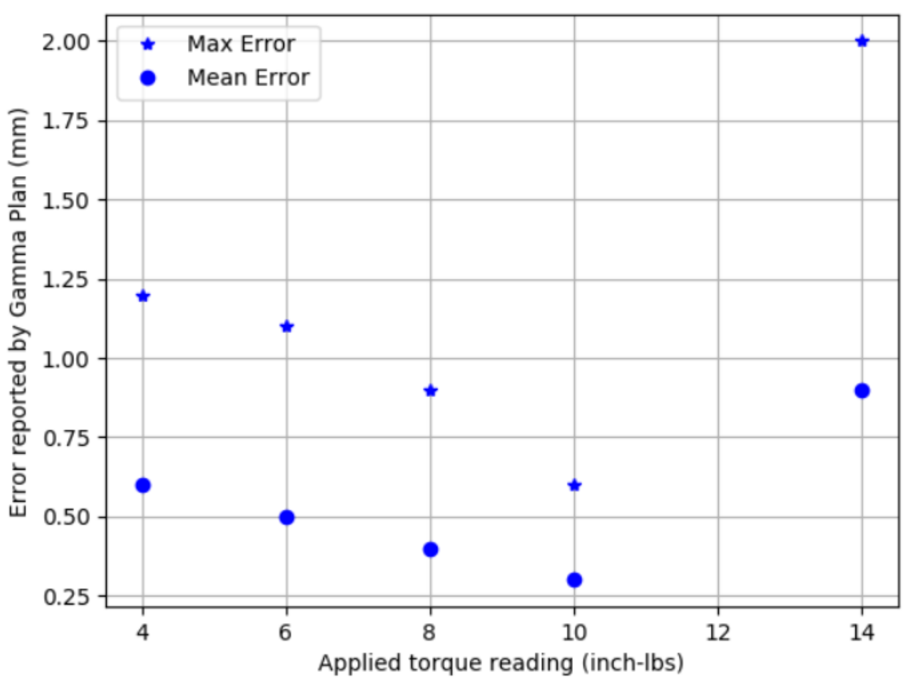

Figure 16: Gamma Plan reported mean and max error for 3-post torque distribution.

CHAPTER 5. DISCUSSION

The pin-prick film measurements provide the bulk of the new information learned about the Leksell Gamma Knife frame's subjectivity to various levels and types of torque on the frame. Contrary to the experimenters' original thoughts that the spatial error would increase with higher torque levels, the evenly distributed torque pin prick measurements appear to indicate a decreasing error in actual dose delivery vs. planned dose delivery as a function of torque. However, there are a very large number of variables that factor into the error between the pin prick location and the FWHM center. There is the setup error that may be caused by microscopic movement within the GK frame adapter. There is the possibility of the GK pins adjusting themselves or "settling in" to either the phantom material or a real patient's tissue and skull between imaging and delivery. The Gafchromic film is also subject to manual placement error on the cassette. This downward trend of spatial error vs evenly applied torque may possibly be explained by the phantom being more "rigidly" held in place at higher torque levels than at lower ones. However, depending upon the direction of the induced error for a given torque distribution, it may be the case that the combination of other factors pushed the error in one direction while the torque-induced error pushed the error back towards 0. Given the amount of variables involved in the creation of the pin-prick error it is difficult to give a single answer.

It is interesting that the CT and Cone Beam pin prick errors in Figure 10 rise and fall together for the even torque distribution, being separated by a nearly constant distance across the torque values (between 0.43mm and 0.79mm, see Appendix B). There are several possible explanations for this relatively constant difference between the two. First, there may be some “settling in” of the GK pins happening in the liquid acrylic bed between imaging and delivery. The “settling in” of the pins into the liquid acrylic may be aggravated by the process of moving the phantom from the GK to the CT and back again, since the 4 pins all must achieve an equilibrium force balance and each pin affects the normal force on all the other pins. If the pin tip moves inward at a constant speed *v* and if the experiment time duration was relatively constant for each torque level, the Cone Beam CT’s spatial error must be affected more by the “settling in” than the CT’s spatial error since the pin tip can only move inward, and the time between CBCT imaging and CBCT dose delivery was always larger than the time between CT imaging and CT delivery. However, the Figure 10 data show that the CT is experiencing a much larger spatial error than the CBCT, which indicates that the effect of settling in is likely small, given that the Cone Beam CT’s error due to settling in must be greater than or equal to the CT error due to settling in. Future studies should torque the posts down and then CBCT the phantom, then wait 1-2 hours and CBCT the phantom again, and check the distance between the coordinates of the GK pin tip in the first image to the coordinates of the tip in the second image. This will tell whether or not “settling in” is occurring, but it will also add a significant amount of time to the workflow.

A second competing explanation is that both the CT and the CBCT are experiencing the same “baseline” error which contributes to the pin-prick-FWHM center distance, but that there is some warping of the fiducial box which gives rise to a further increase in the CT spatial error beyond what the CBCT experiences, since the CBCT does not use a fiducial box for the stereotactic definition. However, one would expect this to cause the difference between the CT and CBCT error to increase with torque, but the opposite is true

(Appendix B). There was indication that the fiducial box was warping at torque values ≥ 10 inch-lbs (see section 3.6.5), but this would not explain the difference between the CT and CBCT at torque values lower than 10 inch-lbs. The data from the Known Target Phantom QA, which used essentially the same process as the torque experiment but did not place any torque on the frame, did not show this large difference between the CT and CBCT pin prick data. This indicates that the applied torque is somehow affecting the CT stereotactic definition process.

The Figure 10 errors appear to follow an almost linear trend downwards with increasing torque, except for the increase at 10 and 12 inch-lbs which might be explained by manual film placement error on the cassette rather than a torque-induced error. The only feasible way to verify this trend would be to perform the experiment over again a statistically significant number of times and create a regression analysis of the data. However, given that each data point takes two people about 20-30 minutes without interruptions to measure and this time competes with clinical patient treatment times, it would be very difficult to pursue such a verification. It would be recommendable to perform a larger averaging study at least on the 4 inch-lbs value alone, since this is the industry standard torque value and it is already experiencing an unacceptable spatial error >1mm with CT definition.

The "3-pronged" pin prick data in Figure 11 do not lend themselves as easily to interpretation. They do not follow the same trend of the CT having a greater error than the CBCT at each torque level and contain unexpected outliers at the 6 and 8 inch-lbs data points for CT. The cone-beam spatial errors are universally higher for the 3-post case versus the 4-post case. This increase in error is likely a combination of the asymmetrical torque distribution causing the frame base to warp, causing a difference between the "ideal" Leksell GK stereotactic coordinate system in Gamma Plan and the actual warped coordinate system of the physical frame. Additionally, the phantom must be moved while mounted in the 3-post frame from cone beam to CT and back again during the workflow, which may have caused “settling in” again.

The CT-CBCT displacement of target coordinates in Figures 13-14 do not appear to follow along exactly with the measured pin prick errors, contrary to our original thoughts and reasoning for measuring this displacement. These displacements do not follow a strictly decreasing trend that the pin-prick errors appear to follow for the even torques. Sometimes the pin-prick error is higher than the image coordinate displacement error, and sometimes the opposite occurs.

The Mean and Max errors reported by Leksell Gamma Plan did appear to roughly approximate the trend of the Figure 10 pin-prick errors for the even torque distribution. For the 3-post distributions, we were able to get the CT for the 10 inch-lbs but could not deliver the dose due to the frame being torqued beyond being able to place it in the frame adapter. The 14 inch-lbs data point was taken on 11/2 and the others were taken on 11/12. The 14 inch-lbs appears not to follow the downward trend that the others follow. Again, the only way to know the trend for sure would be to repeat this experiment a statistically significant number of times and take an average of the data.

Finally, the "bonus" data in Figure 12 that were collected about the removal of the AL post after cone beam imaging and then delivery of the treatment without re-imaging appear to confirm the idea that this is an unacceptable practice. At the recommended torque level of 4 inch-lbs, the error between planned dose center in the cone beam versus the actual delivered dose center was already unacceptably over 1 mm. Further increases in the torque level increased this error to the 2-3 mm range and even over 4 mm at 14 inch-lbs, although 14 inch-lbs is likely higher than any physician has ever or will ever use.

CHAPTER 6. CONCLUSION

This project has addressed a common and unanswered question that many clinical physicists have about the effect on the stereotactic definition of the Leksell Gamma Knife frame that varying levels of applied torque have. It is safe to say that the data in Chapter 4 constitute a demonstration beyond a reasonable doubt that the GK frame is not a rigid body as is commonly assumed, and that the effect of torque on the frame post pins does propagate throughout the GK frame and ultimately affects the accuracy of dose delivery. In other words, the data in Chapter 4 demonstrate the existence of torque-induced error in the Leksell Gamma Knife ICON system, but further studies will need to be made into the magnitude and direction of these errors across a large number of trials. Four conclusions and recommendations may be made from the data collected in this experiment.

First, while there is a general downward trend of spatial error in the stereotactic definition with evenly applied torque, this trend would have to be verified by conducting a statistically significant number of repeat experiments in the same conditions. Additionally, the benefit of higher accuracy with higher torque may come at the expense of tissue and bone integrity at those higher applied torques.

Second, the practice of applying only three GK frame posts instead of all four posts to the patient should be avoided if at all possible, as it is associated with dose delivery inaccuracies ranging anywhere from ~0.7 mm to ~2.2 mm depending on the torque level. In cases such as previous craniotomy patients where this practice is unavoidable, the physician has the ultimate responsibility for deciding whether this error is acceptable in the interest of patient welfare.

Third, the commonly held belief that it is an unacceptable practice to remove a frame post after taking a cone beam CT and then to deliver the planned treatment without re-imaging the patient is confirmed.

Finally, we recommend that all Gamma Knife ICON treatments use the integrated Cone-beam CT as the imaging modality for the definition of the stereotactic coordinate system in Leksell Gamma Plan. The data in Figure 10 demonstrate that CBCT imaging reliably experiences less spatial error in dose delivery across varying torque levels than CT imaging, and in fact the CBCT with evenly distributed torque across the frame posts is the only treatment workflow which reliably gave sub-millimeter accuracy in this experiment.

6.1 Future Work

In future studies of torque-induced error on the GK frame's stereotactic definition, it may be interesting to attempt to develop a "correction factor" to cancel out the effect of torque on the error in planned dose center and delivered dose center. This factor would have to take into account both the magnitude and direction of the displacement from the pin prick to the FWHM center. It could be applied in the treatment planning system to the planned dose delivery after all treatment planning has finished based upon the CT or CBCT image, and it would effectively "shift" the delivered dose with a displacement canceling out the displacement caused by torque-induced error. Such a correction factor would require further verification of the relationship between applied torque and spatial error, and it would also require studies into which direction is the error moving depending on the level of applied torque and the symmetry or asymmetry of the applied torque. “Settling in” of the pins should also be measured via time-spaced imaging described in Chapter 5.

APPENDIX A. QA PROCEDURE FOR EVALUATION OF TORQUE-INDUCED ERROR USING THE CARTER-GILES PHANTOM.

A. 1: Naming Conventions

Naming Convention for frame posts

PL = posterior left post

PR = posterior right post

AL = anterior left post

AR = anterior right post

Anterior and posterior refer to standard anatomical directions.

Naming Convention for Gafchromic Film

C = CT

CB = cone beam CT

E = even torque

U = uneven torque

Example:

CBE4 = cone beam even torque at 4 inch-lbs

CU AL3AR4PL3PR4 = CT uneven torque at

PL = 3 in.lb. PR = 4in.lb. AL = 3in.lb. AR = 4in.lb.

A. 2: Procedure

RANDO Phantom preparation

This procedure requires the head section of the Alderson RANDO Phantom and the Lucite alterations to the RANDO described in the thesis.

1. Replace the top (un-numbered) RANDO slice and Slices 1 and 2 with the provided corresponding Lucite slices, placing the cassette holder between the two Lucite slices with the square hole facing anterior and the thicker cassette holder slice inferior to the thinner slice. Ensure that the threaded rods on the RANDO are tightly clamped with the included nuts and that the RANDO slices do not move under considerable force.
2. Place the top cassette piece (the piece with the air fiducial holes) superior to the bottom piece, with the fiducial holes facing inferior.
3. Insert the completed cassette into the square hole with the air fiducials on the superior side.

Frame placement on the RANDO

From this point onward, you will need to do all listed steps for each of the following torque values (X): 4 inch-lbs, 6 inch-lbs, 8 inch-lbs, 10 inch-lbs, 12 inch-lbs, 14 inch-lbs.

Even Torque Measurements

1. Adjust the GK frame to match the hole height, and insert the frame pins into the Lucite holes as if it were a patient.

2. Check tightness / bulging (REMEMBER to TIGHTEN if the phantom slices are loose.)
3. Torque to X inch-lbs.
4. CBCT the phantom with the cassette inserted but without film.
5. CT the phantom with the cassette inserted but without film. Use the CT GK frame mount with a counterweight on the CT couch to prevent its movement.
6. Plan the CT dose delivery with 2.5 Gy to the 50% isodose line. Choose the target to be the point in the square 0.3 mm thick cavity of the cassette that directly abuts the center air fiducial. This is the location of the film's pin prick in the absence of film placement errors. Record the target location XYZ and the Mean and Max reported error.
7. Deliver CT with Film labeled CE[X inch-lbs]
8. Plan the CBCT dose delivery with 2.5 Gy to the 50% isodose line in the same manner as the CT above. Record the target location XYZ, there is no Mean/Max error for CBCT.
9. Deliver CBCT with Film labeled CBE[X inch-lbs]

Uneven (3-pronged) Torque Measurements

1. Adjust the GK frame to match the hole height, and insert the frame pins into the Lucite holes as if it were a patient. Choose one of AR, AL, PR, PL and refrain from inserting this pin and post.
2. Check tightness / bulging (REMEMBER to TIGHTEN if the phantom slices are loose.)
3. Torque the 3 used posts to X inch-lbs.

4. CBCT the phantom with the cassette inserted but without film.
5. CT the phantom with the cassette inserted but without film. Use the CT GK frame mount with a counterweight on the CT couch to prevent its movement.
6. Plan the CT dose delivery with 2.5 Gy to the 50% isodose line. Choose the target to be the point in the square 0.3 mm thick cavity of the cassette that directly abuts the center air fiducial. This is the location of the film's pin prick in the absence of film placement errors. Record the target location XYZ and the Mean and Max reported error.
7. Deliver CT with Film labeled CU AL[X inch-lbs]AR[X inch-lbs]PL[X inch-lbs]PL[X inch-lbs]. The AL/AR/PR/PL that you chose should be 0 inch-lbs.
8. Plan the CBCT dose delivery with 2.5 Gy to the 50% isodose line in the same manner as the CT above. Record the target location XYZ, there is no Mean/Max error for CBCT.
9. Deliver CBCT with Film labeled CBU AL[X inch-lbs]AR[X inch-lbs]PL[X inch-lbs]PL[X inch-lbs]

Analysis of Gafchromic Film Results

1. Use your preferred Gafchromic film analysis software to compute the dose profile of the film. Record the Center and the Full-Width at Half Maximum (FWHM) of the dose.
2. Measure the distance from this recorded FWHM center location to the location of the pin-prick. This is the spatial error. It is recommended to use RIT's Cyberknife Pin Prick analysis tool as it can automatically outline the dose distribution, locate the pin prick and center locations, and compute their distance.

APPENDIX B. PIN PRICK DATA

Table B.1: Pin Prick to Dose FWHM Center data measured in RIT

Evenly Distributed Torque			
Inch-lbs of Torque	CT (mm)	CBCT (mm)	Difference (absolute value)
4	1.23	0.53	0.7
6	1.01	0.22	0.79
8	0.91	0.14	0.77
10	1	0.36	0.64
12	0.98	0.35	0.63
14	0.55	0.12	0.43
3 - post distribution			
Inch-lbs of Torque	CT (mm)	CBCT (mm)	Difference (absolute value)
4	0.88	1.29	0.41
6	2.45	1.39	1.06
8	0.74	1.46	0.72
14	1.84	1.07	0.77
Image with 4 then remove AL			
Inch-lbs of Torque	CT (mm)	CBCT (mm)	
4	[redacted]	1.63	
6	[redacted]	2.73	
8	[redacted]	2.14	
10	[redacted]	2.48	
12	[redacted]	3.58	
14	[redacted]	4.15	

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