Evaluation of torque-induced spatial error in the stereotactic definition of the Leksell Gamma Knife ICON System

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History of imaging for Gamma Knife

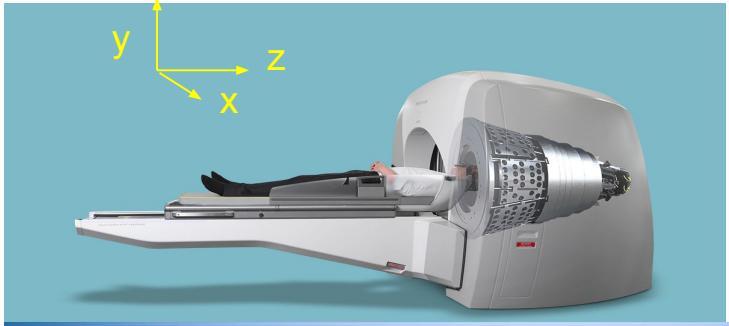
GK first treatment - 1968. Since then, has undergone 5-6 iterations (currently used are U, B, and C models, Perfexion, and ICON)

Until 2015, all Gamma Knife treatments used a frame with its own coordinate system.

Fiducial localizer box is mounted to frame during CT/MRI for image registration with frame coords.

Leksell Gamma Knife ICON - Emory St. Joseph's Hospital 2015, one of the first seven.

First model to include integrated CBCT imaging and stereotactic definition based off the CBCT. Still has option to use frame.

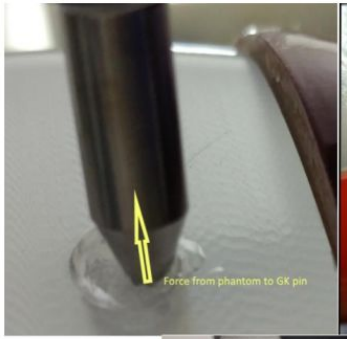


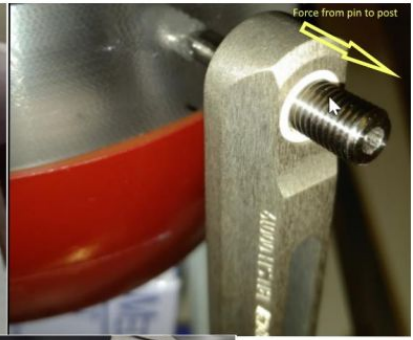
Goals of the project

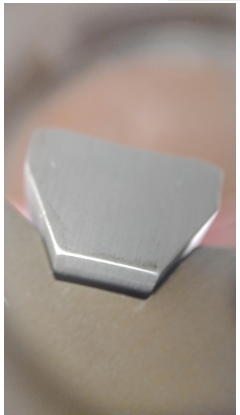
- Questions have arisen regarding the spatial accuracy of the image registration to CT/MRI coordinate systems using the fiducial box and the GK frame.

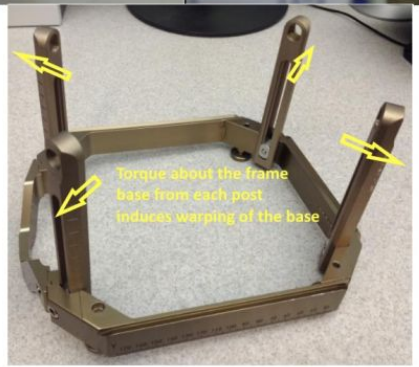
- Extent of potential error from warping of the Gamma Knife frame due to torque on the frame posts and warping of the plane containing the fiducial markers in the fiducial box due to the applied torque is unknown.

- Goal: find out whether this torque-induced error exists and what its magnitude is.







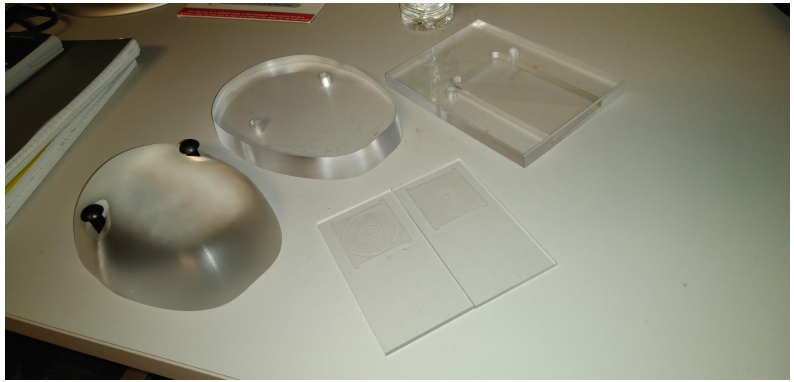


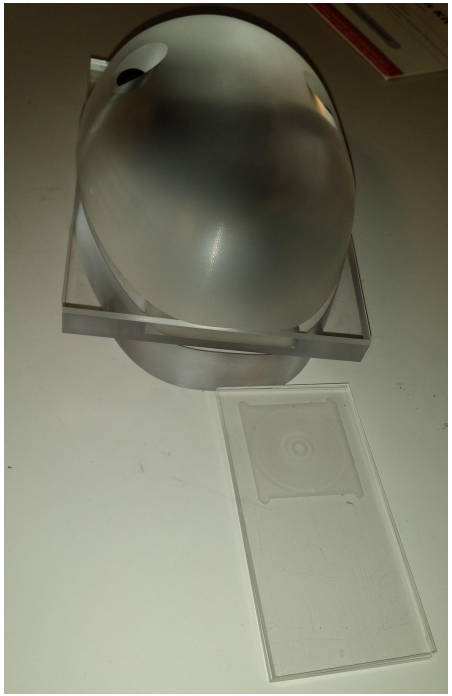
Production of a new phantom

Based on the Alderson RANDO Phantom.

- Many materials to choose from.
- Originally wanted to 3D - print full replica of RANDO. Cost ~ $13,000 from Shapeways.com
- Decided upon using the GT Mech. Eng. lab to reproduce 3 of the RANDO slices out of Lucite (acrylic).
- These slices replace the normal RANDO slices and contain a removable cassette which holds gafchromic film.

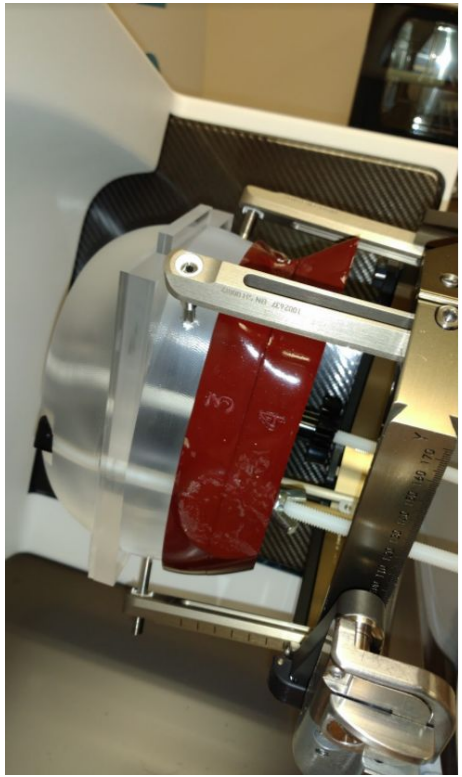
Production of a new phantom

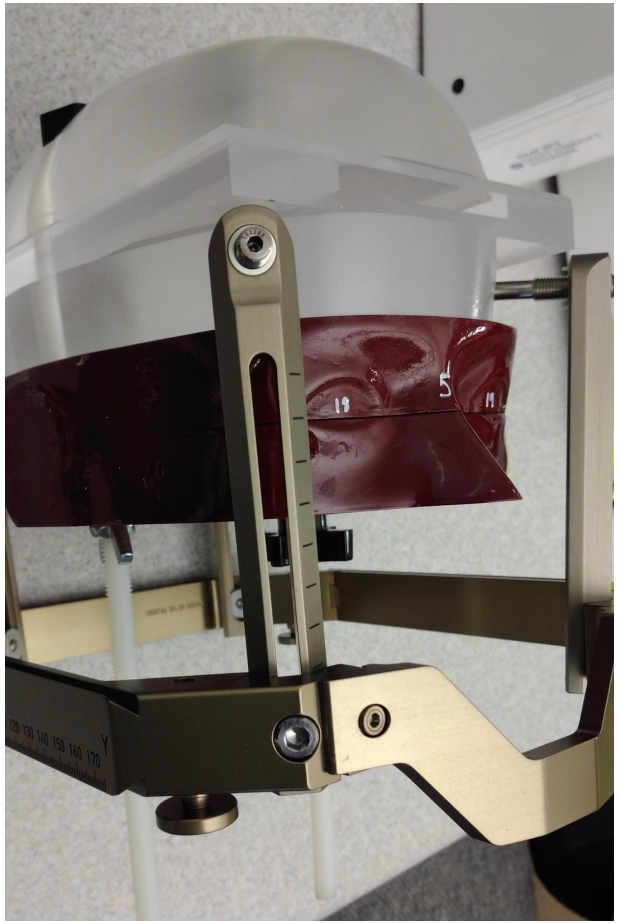


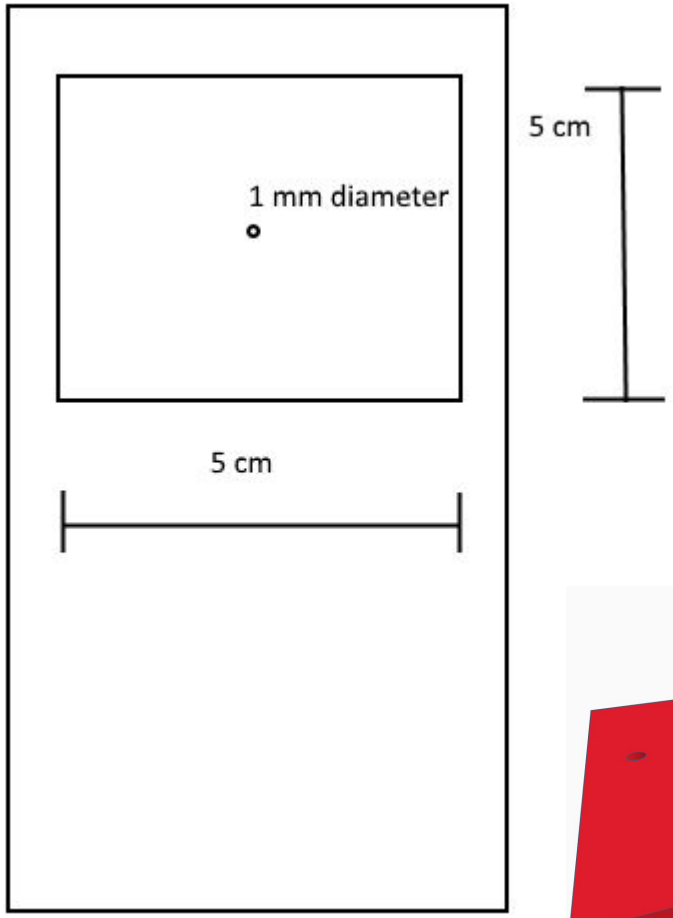


Production of a new phantom

- The removability of the film without removing the frame from the phantom is key. Disassembly and reassembly of the frame would cause uncertainty in measurements.
- Frame must be moved from CBCT to CT and back to the GK using different films (or no film) each time without altering the frame torque/position.

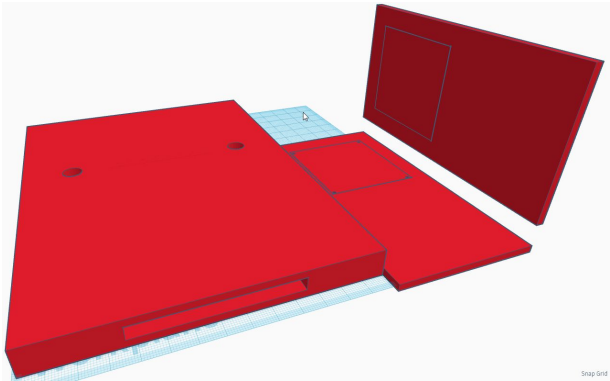






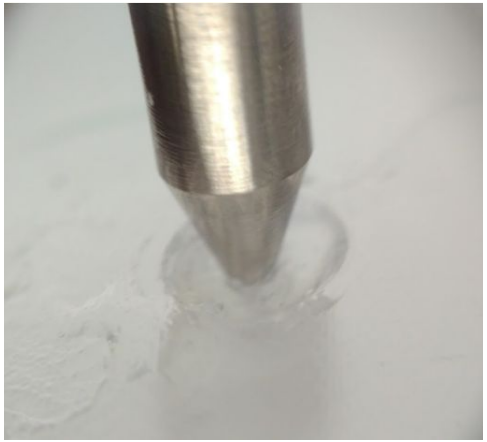
Err slightly less than 5x5cm for film.

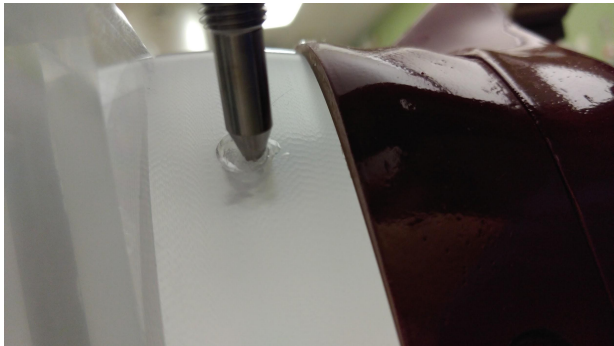
Blade width ~1mm



Designing the pin-phantom interface

- Large risk of fracture in placing pins into the bare Lucite and torqueing them down. Need an intermediate material.
- Drilled 6 mm diam X 16 mm depth holes into the Lucite slice at the point of contact with the GK post pins.
- Tested 3 “intermediate” materials. 1) Weldwood Contact Cement 2) J.B. Weld 2-part Epoxy 3) Castn’Craft “Liquid Plastic” acrylic with catalyst.
- Weldwood would not harden. Mounted the GK frame to the phantom with J.B. Weld, but under long duration and pressure, it bulged out of the hole. This movement between imaging and delivery invalidates the plan/data.
- Castn’Craft - Successful. No visible bulging between imaging and delivery. Chose this as the “intermediate”.






Weldwood
CONTACT CEMENT
ClearWeld
Quick-Setting
Epoxy
CLEAR
.85 FL. OZ. (25 mL)


Clear Polyester
Casting Resin
Resina de
poliéster
transparente
para coladas
Liquid Plastic
Plástico Líquido
DANGER: MAY BE HARMFUL BY BREATHING VAPORS OR BY SKIN CONTACT. MAY CAUSE BLINDNESS. EXPOSURE MAY CAUSE NERVOUS SYSTEM DEPRESSION. COMBUSTIBLE. KEEP OUT OF REACH OF CHILDREN.
PELIGRO: PUEDE SER DAÑINO SI SE INHALAN LOS VAPORES O SI ENTRA EN CONTACTO CON LA PIEL. PUEDE CAUSAR CEGUERA Y DEPRESIÓN DEL SISTEMA NERVIOSO. COMBUSTIBLE. MANTENGA FUERA DEL ALCANCE DE LOS NIÑOS.
Castin' Craft
Net 16 fl oz / Neto 16 oz fl / 473 mL

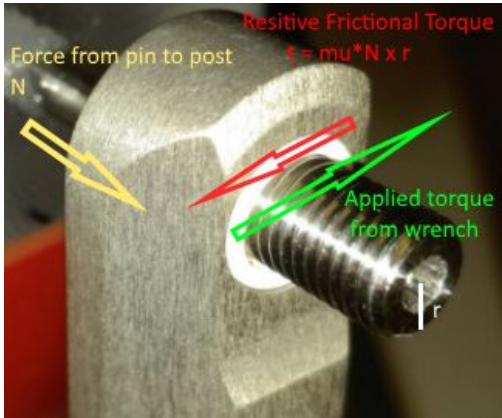
Physics of the interaction between the GK pins and the phantom

- Most important factor determining torque on the frame base: linear force from the phantom to the GK pin.
- $\vec{N}$ = Normal force from the pin to the frame post, directed away from phantom

$\vec{N}_t =$ integrated normal force from pin threads to post hole threads $\vec{N}_t = \vec{N}$

- $\vec{T_b}$ = torque about the frame base (for one post)

$$\vec{T}_b = \vec{r}_{\text{post}} \times \vec{N}$$

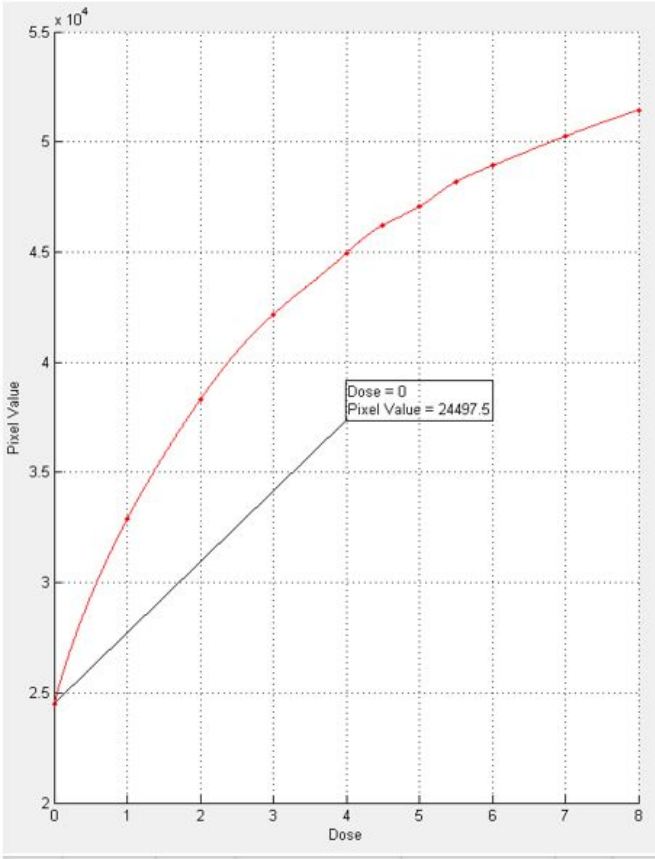


Physics of the interaction between the GK pins and the phantom

- Pins/posts are a dynamical system - torquing one pin down harder will influence the normal force on all pins.
- Nearly impossible to make the “true” physical torque match the torque wrench reading due to this
- The torque wrench reading only provides a *minimum* for the true amount of torque on the pin

Gafchromic Film

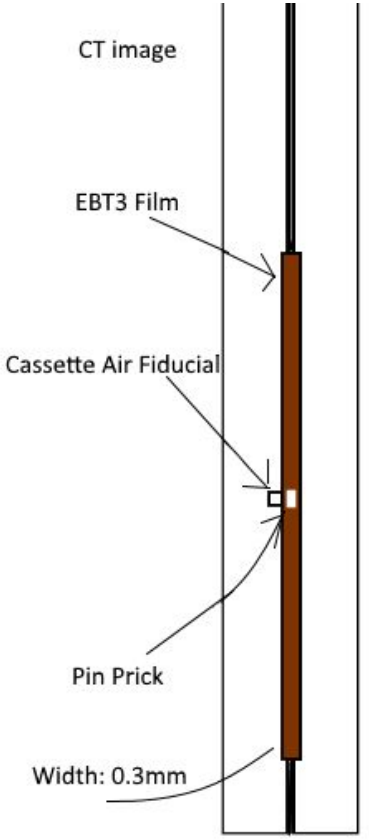
- 5x5 cm Gafchromic film was used to take the dose measurements
- Dose calibration curve was generated in RIT
- Not necessary for the project - only need spatial location of the center, not the dose value.
- The center of the FWHM of the net optical density is the point of maximum dose on the film
- Pin prick in the center of film, aligned to the cassette air fiducial marker.
- Check distance from pin prick to center of FWHM after dose delivery.



Film irradiation for a range of torque levels

Even torque workflow (4,6,8,10,12,14 inch-lbs):

1) CBCT the phantom with cassette and without film
2) CT the phantom with cassette and without film
3) Plan the CT dose delivery - target is the point on the film directly abutting the air fiducial marker. Record the mean and max reported error.
4) Deliver the CT plan.
5) Plan CBCT similarly.
6) Deliver CBCT plan.
7) Check distance between CBCT and CT target coordinates in Leksell Gamma Plan. (XY only!)
8) Scan gafchromic films, check distance between the pin prick (planned target) and the center of the FWHM (delivered target). This is the spatial error.



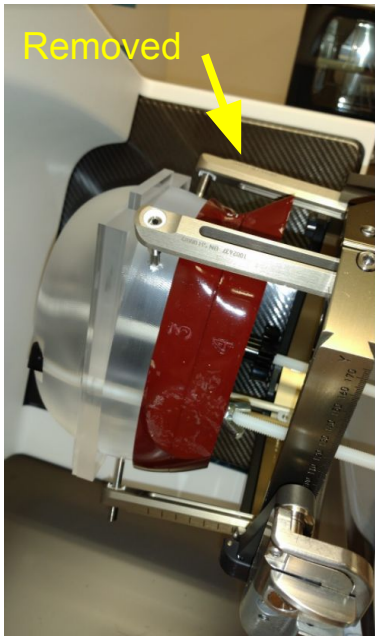
Film irradiation for a range of torque levels

Uneven (3-post) torque workflow (4,6,8,10,12,14 inch-lbs):

Same as the even torque workflow. Removed Anterior Left (AL) post and kept the other posts equal.

“Bonus” project: check spatial error caused by imaging the phantom with 4 posts and then removing one post and treating without re-imaging.

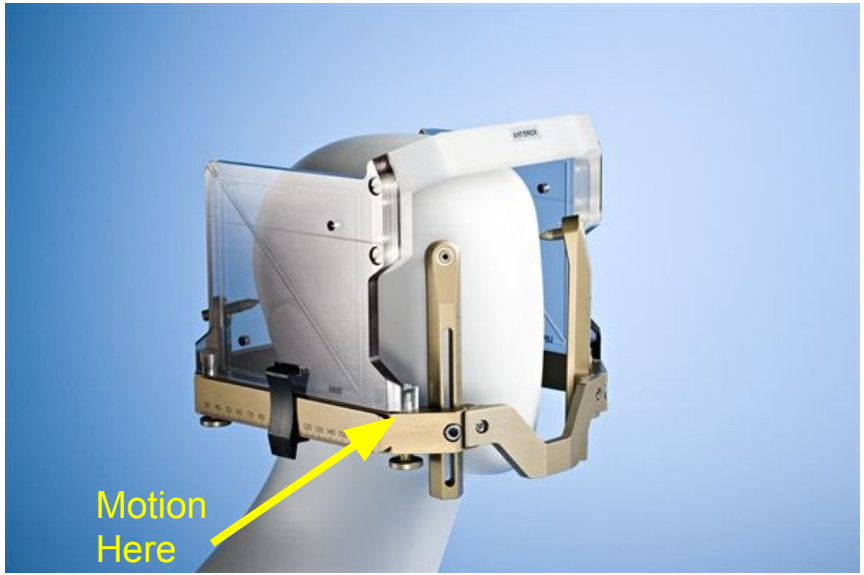
1) CBCT the phantom with all 4 posts torqued evenly
2) Remove the AL post
3) Deliver the dose
4) Check pin-prick to FWHM center distance



Issues

- After reaching 10 inch-lbs on the “3-post” uneven torque data, it became impossible to place the GK frame into the couch frame adapter.
- The 14 inch-lbs data was taken 10 days before, when the frame had been torqued to 14 inch-lbs evenly.
- 10 and 12 inch-lbs for uneven torque caused enough stress on the frame to make taking these data impossible.

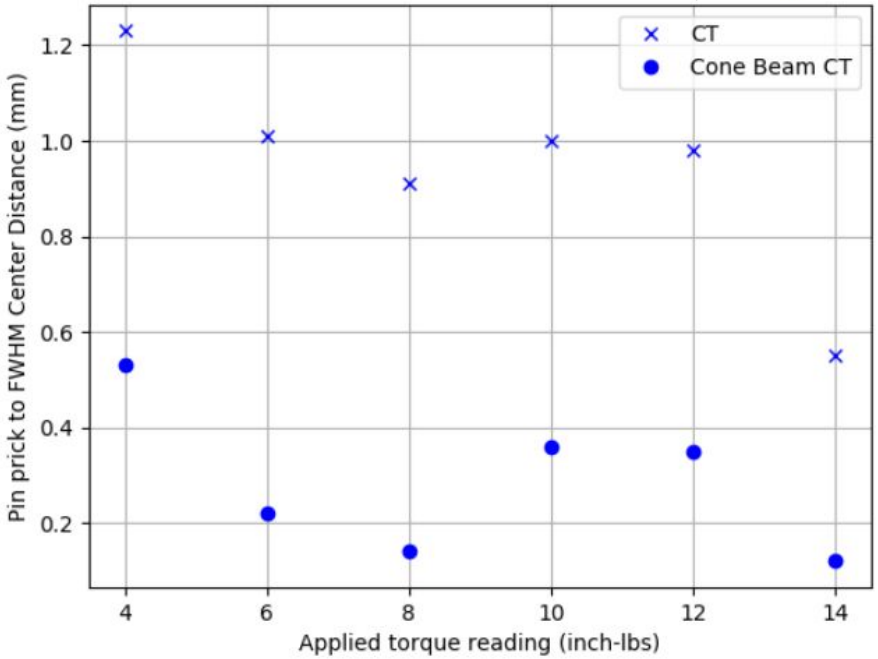
- At 10 through 14 inch-lbs on the even torque measurements, the CT fiducial box would not sit flush with the GK frame.
- This indicates warping of the fiducial box which means the fiducial markers are not in the correct position - affects the SD.



Results: Pin-prick data

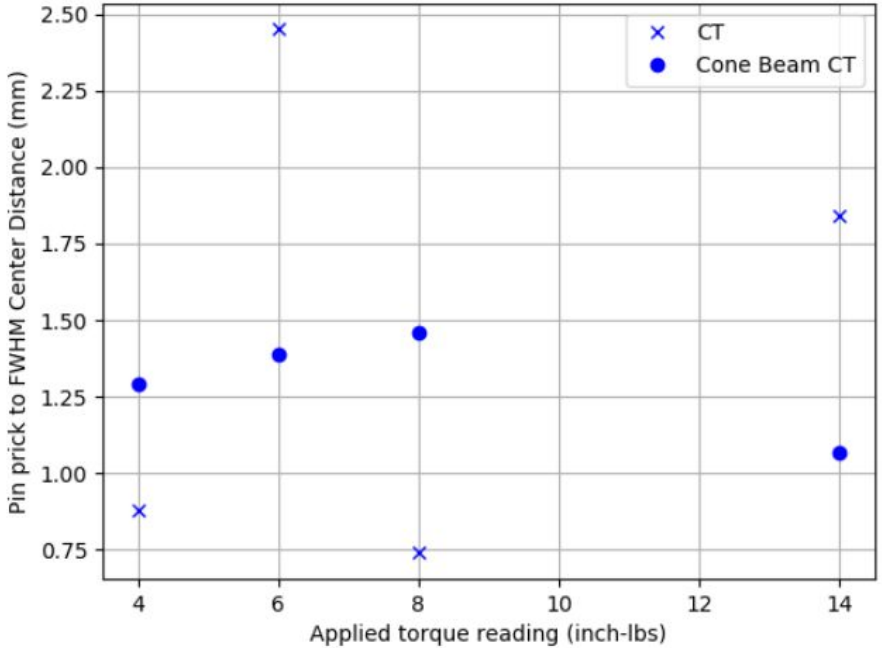
Difference (absolute value)
0.7
0.79
0.77
0.64
0.63
0.43

Even torque



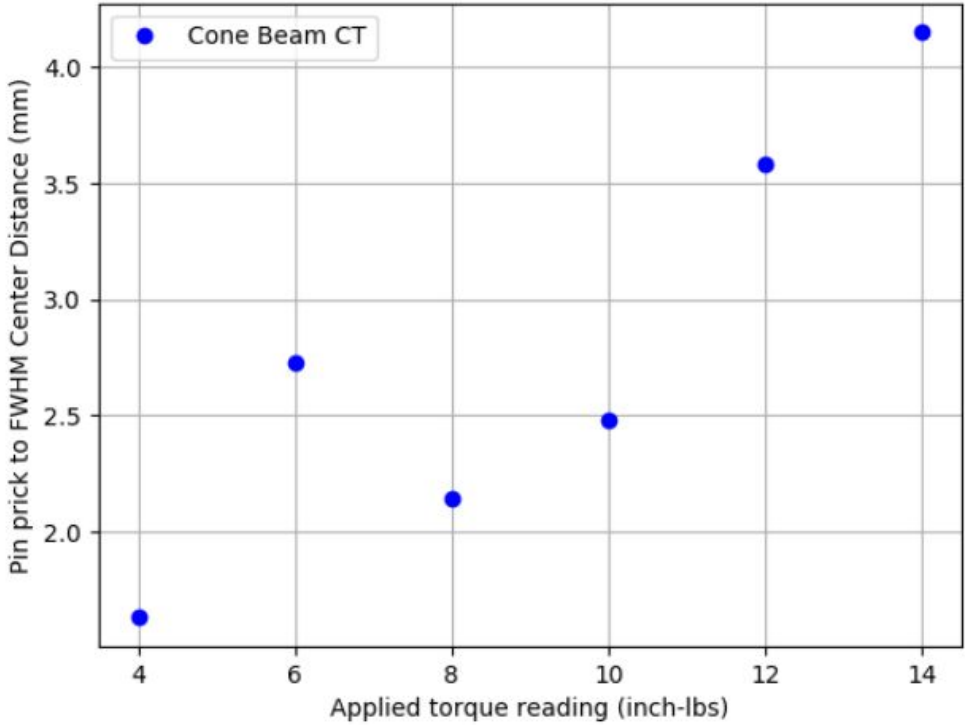
Difference (absolute value)
0.41
1.06
0.72
0.77

Uneven torque (3-post)



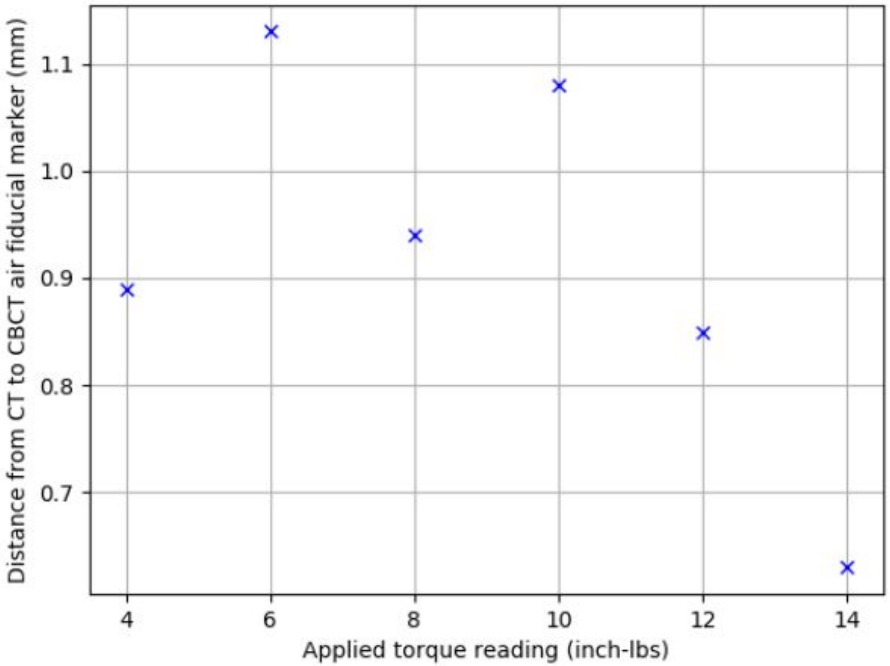
Results: Pin-prick data

Removing the AL post after imaging, then delivering the dose.

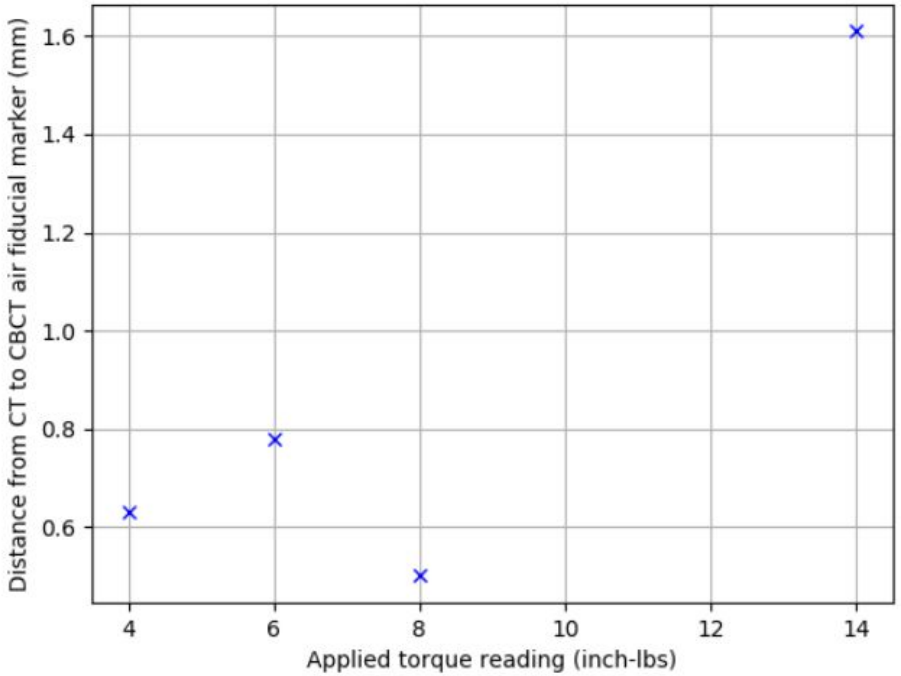


Results: CT-CBCT target coordinate distance

Even torque

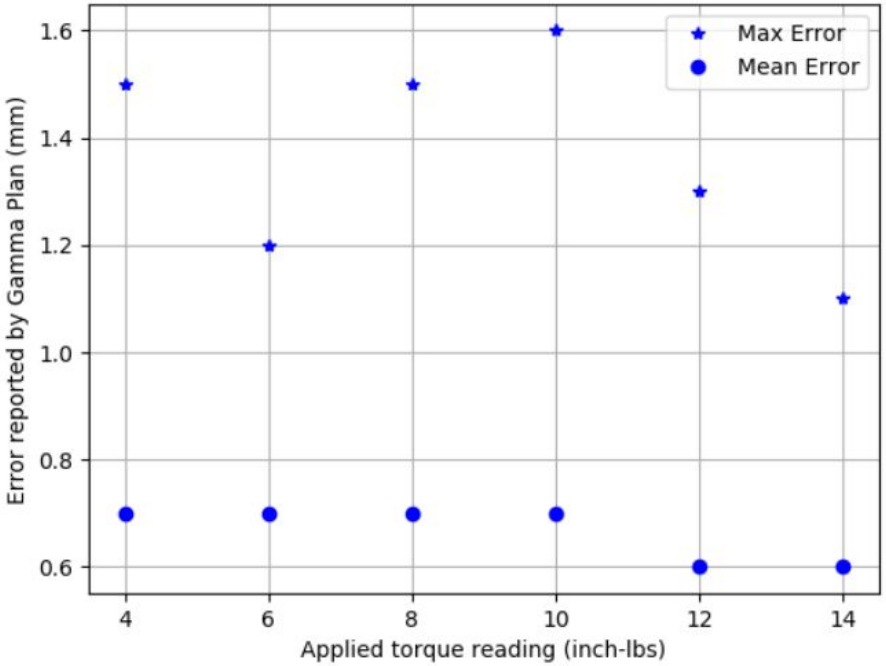


Uneven torque (3-post)

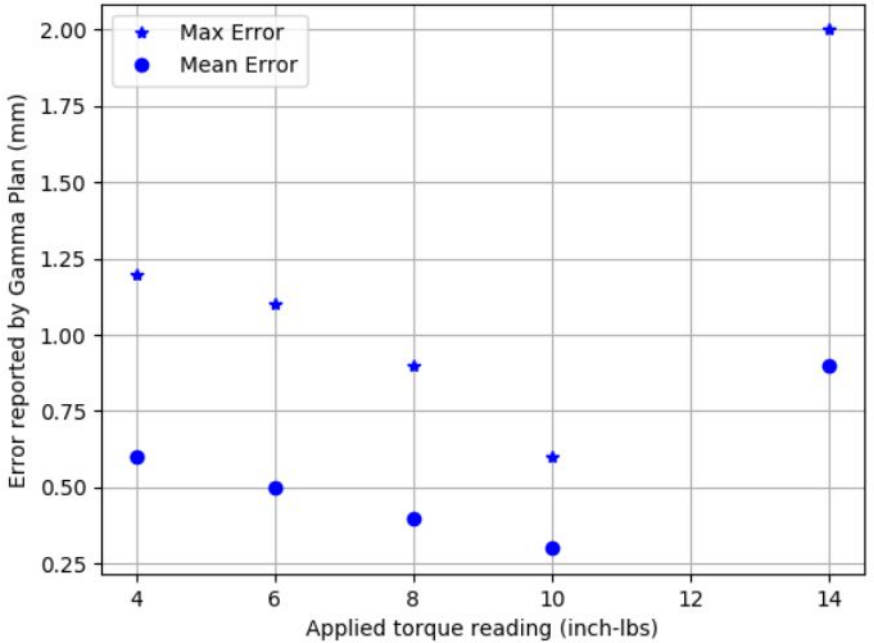


Results: Mean and Max reported error in LGP

Even torque



Uneven torque (3-post)



Discussion

- Apparent decrease in spatial error with increasing torque for even distribution.
- No clear relationship b/w spatial error and torque for 3-post torque distribution, although all but two of the data points are unacceptably high (> 1mm)
- Possible explanations for the “rising and falling” of CT and CBCT spatial error together:

1. “Settling in” of the pins may happening between imaging and delivery. Should affect CBCT more than CT due to larger time interval for CBCT.
2. CT and CBCT both experience the same baseline “torque-induced” error, but the CT experiences a further spatial error caused by problems with the fiducial box.

- The only consistent sub-mm accuracy workflow was stereotactic definition based on the CBCT with evenly distributed torque.

Conclusion

Conclusions / Recommendations based on the results of this project:

1) Need statistically significant number of repeat experiments to verify the downward trend of spatial error vs. torque. Even if true, increasing torque may not be possible due to tissue stress tolerance. Also, need to repeat at 4-inch lbs to verify the high CT error, since 4-inch lbs is the recommended value. Difficult to do since 1 data point = 30 minutes of clinic time with 2 people.
2) Avoid 3-post torque distribution if at all possible. Only 2 outliers produced sub-mm accuracy. Range of ~0.7mm to ~2.2mm. If unavoidable, decide whether the error is tolerable for patient welfare.
3) Imaging with 4 posts then removing 1 post should never be done. Always re-image the patient after removing the post.
4) Recommend that all GK ICON cases base the stereotactic coordinate system definition on a Cone-beam CT using the integrated CBCT arm. Consistently provides sub-mm accuracy with evenly distributed torque.

Future work

- Find out what is causing the high CT error, i.e. “pin settling” vs. fiducial box problems, both or neither?
- Repeat with 4 inch-lbs even torque to see if the high CT error is consistent across trials.
- Repeat entire experiment many times to verify downward correlation of error w/ torque
- Find out magnitude and direction of error as a function of torque → Develop “correction factor” or shift to implement in TPS after correlation is found?

Acknowledgements

Matt Giles: Advising and development of the project, gathering data.

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Dr. Hertel

References

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